https://ntrs.nasa.gov/search.jsp?R=19670029898 2018-07-24T20:13:42+00:00Z

NASA CONTRACTOR REPORT

NASA CR-61176

October 9, 1967

NASA CR-61176

THE PLASMA RADIATION SHIELD: CONCEPT, AND APPLICATIONS TO SPACE VEHICLES

Prepared under Contract No. NAS 8-20310 by
Richard H. Levy and Francis W. French

AVCO CORPORATION

GPO PRICE $ _____

CFSTI PRICE(S) $ _____

Hard copy (HC) 3.00

Microfiche (MF) .65

ff 653 July 65

FACILITY FORM 602

N67-39227 (ACCESSION NUMBER)

96 (PAGES)

CR-61176 (NASA CR OR TMX OR AD NUMBER)

(THRU)

1 (CODE)

31 [redacted] (CATEGORY)

For

NASA-GEORGE C. MARSHALL SPACE FLIGHT CENTER
Huntsville, Alabama

October 9, 1967

NASA CR-61176

THE PLASMA RADIATION SHIELD: CONCEPT, AND APPLICATIONS TO SPACE VEHICLES

(Contractor Report Dated April 1967)

By

Richard H. Levy and Francis W. French

Prepared under Contract No. NAS 8-20310 by

AVCO EVERETT RESEARCH LABORATORY
a division of
AVCO CORPORATION
Everett, Massachusetts

For

Space Sciences Laboratory

Distribution of this report is provided in the interest of information exchange. Responsibility for the contents resides in the author or organization that prepared it.

NASA - GEORGE C. MARSHALL SPACE FLIGHT CENTER

PRECEDING PAGE BLANK NOT FILMED.

ABSTRACT

The Plasma Radiation Shield is an active device using free electrons, electric and magnetic fields for the purpose of shielding astronauts from energetic solar flare-produced protons. The concept of Plasma Radiation Shielding is reviewed in the light of current studies. The available evidence indicates that the concept is physically sound, but important practical questions remain in at least two areas: these have to do with establishment and control of the extremely high voltages required, and with integration of the concept into a realistic space vehicle design.

PRECEDING PAGE BLANK NOT FILMED.

TABLE OF CONTENTS

		Page
	Abstract	iii
1.	PREFACE	1
2.	SPACE RADIATION SHIELDING	3
3.	THE PLASMA RADIATION SHIELDING CONCEPT	9
4.	VOLTAGE SELECTION IN THE PLASMA RADIATION SHIELD	35
5.	CONFIGURATION RESTRICTIONS	49
6.	SUPERCONDUCTING COIL SYSTEM	53
7.	VACUUM REQUIREMENTS	59
8.	OTHER SYSTEMS CONSIDERATIONS	69
9.	CONCLUSIONS	73
10.	ACKNOWLEDGMENTS	75
	APPENDIX	77
	REFERENCES	91

1. PREFACE

The Plasma Radiation Shield is an active device intended to protect astronauts on long missions in deep space from the penetrating proton radiation that follows large solar flares. The nature of the Plasma Radiation Shield is such that it is not by any means certain that it will be successful. However, if it is successful, it offers the prospect of radiation shielding at a comparatively low cost in weight, provided that certain features of the device prove to be compatible with broader aspects of the space mission profile. Research on the Plasma Radiation Shielding principle, although far from finished, has yielded encouraging results to the point that it seems worthwhile to consider in a preliminary way the broader problems that must be dealt with if the concept is to be useful in a practical sense. In this context, the present paper is intended to accomplish the following objectives:

1. To explain the fundamentals of the Plasma Radiation Shielding concept;
2. To outline the present status of research on basic aspects of the concept, with particular emphasis on the uncertainties still to be resolved;
3. To extract from the above a list of possible problem areas likely to arise in integrating the Plasma Radiation Shield with a realistic spacecraft design;
4. To discuss these problem areas in general terms, quantitatively where possible. These discussions are viewed as being essentially preliminary to a more thorough systems type study.

The organization of this paper is as follows: In Section 2 we give a very brief summary of the nature of the space radiation shielding problem. This summary points to the desirability of finding unconventional light-weight shielding methods. We discuss electrostatic and magnetic shielding, and conclude that neither of these schemes looks promising. This leaves the Plasma Radiation Shield as the only advanced shielding concept still in the

running; the basic principles of the Plasma Radiation Shield are thoroughly discussed in Section 3. The two basic design parameters in the Plasma Radiation Shield are the size and the voltage. The size is determined by such straightforward factors as the crew size, and compatibility with launch vehicles. The determination of the voltage is more complicated, and is the subject of Section 4. We conclude that the range from 30-60 million volts is likely to be of interest. The following sections (5 through 8) take up particular problems of importance in adapting the Plasma Radiation Shield concept to a space vehicle. These are, respectively, restrictions on the configuration, the superconducting coils, the vacuum requirements, and other miscellaneous problems. Section 9 offers our conclusions from the study; these are principally that we have succeeded in isolating the most difficult practical problems associated with the Plasma Radiation Shield, that these problems appear difficult but not insuperable, and that studies in greater depth are definitely required before firmer conclusions about the merits of the Plasma Radiation Shield can be reached. An appendix discusses the present status of research on the physics of the underlying concept. Here again, in spite of favorable initial results, much work remains to be done.

2. SPACE RADIATION SHIELDING

Manned space vehicles outside the geomagnetic field on lunar and interplanetary missions are subjected to the hazards of the unattenuated space radiation environment. Of the two principal components of this environment,* the galactic and the solar flare radiations, the latter is generally considered the more important because of the large fluxes associated with it.** The solar flare radiation hazard is compounded on long duration missions because of the integrated effects of the doses received over the extended mission. Vehicles orbiting the earth at high (e.g., synchronous) altitudes are subjected to much the same environmental components as well as to the protons and electrons associated with the outer edges of the trapped radiation belts. Since inadequate radiation protection can result in absorbed doses that cause discomfort, illness, and even (in extreme cases) death to the crew, it is apparent that provisions must be made to limit the anticipated radiation doses to acceptable levels.

There is a wide variation in opinion (e.g., Refs. 1 to 29) concerning the degree of hazard posed to astronauts by solar flares. This lack of agreement can be attributed to two factors. First, adequate quantitative data on the space radiation environment has only been obtained through one

---

*We restrict ourselves to considering the radiation hazard due to naturally occurring charged particles. On the one hand, the dangerous portion of the solar electromagnetic radiation spectrum (principally the far UV) is easily screened; on the other hand, there is no appreciable component of neutron radiation present in space.

**This is a fortunate accident, because the energies of the galactic radiation are so large that shielding against them is an order of magnitude more demanding than in the case of solar flares, and, for practical purposes, can be considered essentially impossible. Astronauts in the foreseeable future will have to live with the galactic radiation; this situation is not ideal, but, in quantitative terms, is probably acceptable.

solar cycle. This data suggests that it will be very difficult to make a useful art out of forecasting the occurrence of major flares. Further, the wide range in intensity of different flares makes it difficult to predict the confidence levels appropriate to the more intense flares. Thus, postulation of radiation conditions to be encountered on future flights based on this modest experience is questionable. Second, information on the response of the human body to the type of radiations encountered in space is limited. This deficiency is due to the lack of experience with a natural source of protons on earth, difficulties in simulating the fluxes of high energy particles in the laboratory, and humanistic considerations which preclude the use of human subjects for hazardous experiments.

The simplest method of providing radiation protection is to use bulk shielding material to stop the incident radiations. For solar flare protons and alpha particles, the most appropriate materials have low atomic numbers (e.g., water, polyethylene). For long-duration missions, the amount of shielding required can be reduced if the recovery capacity of the human body is taken into consideration. However, there are many uncertainties involved in formulating a radiation tolerance criterion on this basis,[27, 30] and the shielding requirements, while reduced, are still substantial. As an example, the amounts of polyethylene shielding required on a two-year Martian mission are given in Ref. 27 to be 17 gm/cm^2 using a cumulative dose criterion and 7 gm/cm^2 using a criterion that takes into account biological recovery. On the other hand, much larger figures have recently been suggested,[26, 31] depending on the desired probability of not exceeding some stated dose and the phase of the solar cycle. Some of these figures are given in Table 2.1.

If it is desired to completely shield a cylindrical vehicle 15 ft ($\sim$4.6 m) in diameter by 25 ft ($\sim$7.6 m) long with 7 gm/cm^2 of material, the shielding material would weigh about 22,000 lbs ($\sim$10,000 kg). An alternate procedure to shielding the entire vehicle is to shield only a minimum-size storm cellar to which the crew can retire in the event of severe solar flares. This approach, however, severely restricts the activities of the crew and probably rules out normal flight and scientific duties for the duration of the flare. This restriction could be particularly compromising to the success

TABLE 2.1

Current Estimates of Shielding Thicknesses Required on Interplanetary Flights*

Dose to the blood-forming organs (rem)	Reliability	Phase of the Solar Cycle	Material	Shielding Thickness	
				380 days Venus orbiter mission	650 days Mars fly-by
100	99%	Minimum	Polyethylene	1 gm/cm^2	2 gm/cm^2
		Maximum		15 gm/cm^2	21 gm/cm^2
		Minimum	Aluminum	3 gm/cm^2	4.5 gm/cm^2
		Maximum		22 gm/cm^2	30 gm/cm^2
	99.9%	Maximum	Aluminum	105 gm/cm^2	
200	99%	Maximum	Polyethylene	8.5 gm/cm^2	10 gm/cm^2
			Aluminum	12 gm/cm^2	17 gm/cm^2
	99.9%		Polyethylene	37 gm/cm^2	54 gm/cm^2
			Aluminum	51 gm/cm^2	73 gm/cm^2

*The data in this table was supplied by A. Reetz (Ref. 31), and is based on the work of J. Snyder and A. Hardy of the Manned Space Craft Center, Houston, Texas.

of the mission if a solar flare occurs during a crucial phase of the flight. What is clearly needed, then, is a system that will provide adequate radiation protection, not interfere with the normal functioning of the spacecraft, and be relatively light in weight.

From this brief survey of the space radiation shielding problem as a whole, we wish only to draw the following conclusion: a large uncertainty presently exists concerning the shielding that will ultimately be required. It is therefore manifestly worthwhile to consider whether, by unconventional means, the degree of protection afforded by a given weight can be substantially increased. This conclusion launches us into a brief review of advanced concepts in radiation shielding. To the knowledge of the present authors, all advanced radiation shielding schemes so far put forward have depended on the fact that the solar flare protons (and alphas) which constitute the hazard are charged particles and can therefore be acted upon by electromagnetic forces. The first of these schemes is "Pure Magnetic Shielding."

2.1 Pure Magnetic Shielding

It has long been known that the spectrum of cosmic rays or solar flare protons measured near the top of the atmosphere exhibits a low-energy cut-off which is a strong function of geomagnetic latitude.[32] This phenomenon is due to the fact that charged particles are able to cross a quantity of magnetic field lines that increase with their energy; it is clearly possible for a particle to arrive at either magnetic pole without crossing a single field line; on the other hand, the equatorial regions are strongly protected by the geomagnetic field. "Equatorial" in this sense means within, say, 45° of the geomagnetic equator. These equatorial regions have, therefore, been the scene of all U. S. manned space flights so far. It is clearly possible to achieve a protective effect of this type for space vehicles far from the earth by carrying an appropriate magnetic field coil; this possibility (known as pure magnetic shielding) has been studied a good deal.[33-42] We note first that the method is equally valid for charged particles of either sign. It appears that the method has a certain promise[43,44] when it is desired to shield against electrons in the energy range up to several MeV; these occur in the form of trapped particles at certain locations in

the geomagnetic field, but are essentially unknown in deep space. Magnetic radiation shielding of the type in which the field extends to "infinity" is particularly attractive in this application since the radiation hazard caused by the electrons is not due so much to the penetration of the primary electrons, as to the comparatively long range of the secondary x-rays and γ-rays produced by stopping the electrons. These secondaries are absent in the magnetic radiation shield.

Whereas pure magnetic radiation shielding against trapped electrons looks attractive today, the same cannot be said of using pure magnetic radiation shielding against solar flare protons in deep space. The reasons for this situation are strictly quantitative; the solar flare protons against which it is desired to shield have higher rigidities than the trapped electrons, and therefore require more intense magnetic fields to do the job. The situation has been studied both roughly and carefully; the conclusion is always that except for cases where it is desired to stop very energetic (~ 1 BeV) protons from penetrating into large volumes, the weight advantage of pure magnetic shielding over solid shielding is not great enough to compensate for the substantially reduced reliability and increased complexity of the active system. This conclusion can probably be regarded as definitive.

2.2 Pure Electrostatic Shielding

There are two forms of pure electrostatic shielding, and neither is sound. In one scheme,[35] the space vehicle is pictured as being constructed of two concentric shells, these shells to act as a charged capacitor. In this arrangement the space vehicle as a whole is electrically neutral. In the other arrangement,[45] the space vehicle is considered as a charged conductor at some potential relative to "infinity."* Without going into great detail the difficulty with the first scheme is technical; the largest steady voltages produced on earth between conductors are found in Van de Graaff machines. The massiveness of these machines, which nevertheless cannot attain voltages as high as 20 MV, speaks for itself. It is virtually certain

*The meaning of this is explained in detail in connection with the Plasma Radiation Shield.

that the insulators that would be required by an electrostatic space shielding system would weigh far more than the solid material required to do the same shielding job.

The difficulty with the second scheme is, perhaps, slightly less obvious. It might be thought in the first instance that the very high vacuum prevailing in deep space would itself be a very good insulator. This is not the case, however, since the solar wind fills the planetary system with free protons and electrons to a density of about 10/cc. These charges are free to respond to an electric field of the type here considered and would discharge any substantial potential of either sign in a very short time. This is particularly true if (as is always the case) one tried to maintain the space vehicle positive as a protection against energetic protons. The free electrons in space would discharge the potential in a time so short that the scheme becomes quite unrealistic.

From the foregoing it is clear that (in our opinion) neither pure magnetic nor pure electrostatic radiation shielding looks attractive; furthermore, the limitations on both these methods are of a sufficiently fundamental character that it is very unlikely that our conclusions could be substantially modified by technological developments. This situation leaves the field of "active" radiation shielding open to the only other scheme of this type which has been put forward. This is the so-called "Plasma Radiation Shielding" scheme which is the principal subject of this paper and to which we now turn our attention.

3. THE PLASMA RADIATION SHIELDING CONCEPT

3.1 Plasma Radiation Shielding

The Plasma Radiation Shield[46, 47] involves the use of both electric and magnetic fields, but the specific purposes of the two fields are as follows: the electric field is the direct means of providing the shielding against energetic protons, while the magnetic field has the sole purpose of supporting the electric field. It follows that the electric field that is required for the Plasma Radiation Shield is just the same as that required for the pure electrostatic shield. We therefore require the establishment of a voltage on the order of 30-100 MV, i.e., higher than has ever been achieved on earth. Now, while the achievement of such voltages must obviously remain in doubt until positively demonstrated, we hope to show in this paper that under the special conditions of deep space there are sound reasons to hope that such voltages are in fact attainable.

In the remainder of this section, we will present the basic features of the Plasma Radiation Shield. The sections that follow are devoted to preliminary discussion of various aspects of the Plasma Radiation Shield viewed as a single system in an integrated space vehicle. An appendix describes the current status of research on the problems associated with the basic physics of the Plasma Radiation Shielding concept.

3.2 Electrostatics

We consider first the electrostatic meaning of "potential of a space vehicle with respect to infinity." Now engineers in general are used (for good reasons) to considering virtually any electrical device in terms of the voltages applied or induced between pairs of terminals. In view of this, it is a surprising fact that the concept of a voltage between a conductor and infinity is normally the very first subject introduced in elementary electrostatics. We generally consider a conducting sphere of radius a carrying a positive charge Q on its surface; the electric field produced by this arrangement (in the absence of other charges) is radially outwards from the

surface of the sphere. The magnitude of this radial electric field at radius $r(> a)$ is $E = \frac{Q}{4\pi\epsilon_0 r^2}$ and this field can be derived from a potential

$$\phi = \frac{Q}{4\pi\epsilon_0 r} \tag{3.2.1}$$

In defining the potential an arbitrary constant may always be added; in this case we have assumed that $\phi = 0$ at a large distance from the sphere. It follows that the sphere is at a potential

$$\phi(a) = \frac{Q}{4\pi\epsilon_0 a} \tag{3.2.2}$$

above the potential of distant space. A way of interpreting this statement in terms relevant to the Plasma Radiation Shield is as follows: the work necessary to bring a proton (of charge $+e$) from infinity to the surface of our sphere is just $e\phi(a) = \frac{eQ}{4\pi\epsilon_0 a}$. In space the only source of this energy is the kinetic energy of the proton when at infinity; only if this exceeds the quantity $e\phi(a)$ will the proton be able to reach the surface of the sphere. Measuring this kinetic energy in electron volts we find (since the charges on an electron and a proton are of equal magnitude) that the sphere is electrostatically shielded against protons having less than $\phi(a)$ electron volts. If we wish to exclude protons up to 50 MeV, $\phi(a)$ must have the value 5×10^7 volts.

For a capacitor of capacitance C, the charge and the voltage are related by the formula

$$Q = C\phi \tag{3.2.3}$$

Comparing this with the formula (2) we see that the capacitance of the isolated sphere is $C = 4\pi\epsilon_0 a$. Thus, a two-meter radius isolated sphere

has the capacitance 222×10^{-12} farads = 222 picofarads. It follows that if we wish $\phi(a)$ to be 5×10^7 volts, the charge Q must be 11.1×10^{-3} coulombs = 11.1 millicoulombs.

Now, as was explained in connection with pure electrostatic radiation shielding, the arrangement described is not, as it stands, satisfactory. This is because a positive charge of the magnitude being considered would attract electrons from the surrounding space plasma at a rate so large as to make the whole concept useless. In the Plasma Radiation Shield, the vehicle is surrounded by a cloud of free electrons, the cloud being held in place by a magnetic field. Now the voltage across the electron cloud is always fixed by shielding considerations, but the details of the way in which the electron cloud is distributed are quite difficult to calculate. However, any given distribution can be characterized by a capacitance C, which, through (3.2.3) will determine the required charge. In this section we shall discuss briefly two geometrical arrangements which are intended to convey a general picture of the electrostatic arrangement of the Plasma Radiation Shield, without simulating the geometrical details.

Consider first the situation that arises if the sphere of the previous example is surrounded by a larger concentric conducting sphere of radius b'. The capacitance between the two spheres is

$$C = \frac{4\pi\epsilon_0 ab'}{b' - a} = 4\pi\epsilon_0 a \frac{1}{1 - \frac{a}{b'}} \tag{3.2.4}$$

If $b' = 4$ meters and a remains 2 meters, this is 444 picofarads. To maintain a potential difference of 5×10^7 volts between the spheres requires a charge of 22.2 millicoulombs. Now, if the large sphere carries a charge of - 22.2 millicoulombs, the combination of two spheres carries no <u>net</u> charge, and it follows that the electric field is entirely confined to the space between the two spheres. Thus it does not attract electrons from the surrounding space plasma and thereby overcomes the objection to the single sphere model. In terms of the Plasma Radiation Shield the inner sphere is

not only at a potential 5×10^7 volts higher than the outer sphere; it is also 5×10^7 volts above the potential of "infinity". Suppose that the outer sphere is transparent to protons; then a proton of 50 MeV kinetic energy approaching the arrangement from a large distance will be unaware of the existence of the spheres until it penetrates the outer one. Then, as it travels into regions of higher potential its kinetic energy will fall until it is brought to rest at the surface of the inner sphere. At this point, it will start to fall back towards the outer sphere. When it recrosses the surface of this sphere, it will have reacquired its initial energy of 50 MeV and will retain this energy in its further travels.

The example just discussed is in many ways a fair idealization of the electrostatic aspects of the Plasma Radiation Shield, even though the spherical geometry is not representative of the Plasma Radiation Shield. If we continue to ignore this difference, we can regard the inner sphere as representing the space vehicle. But we have already (in the discussion of pure electrostatic radiation shielding) dismissed the possibility that the outer sphere could be a solid electrode for the reason that the insulators separating the spheres would surely weigh more than a solid material radiation shield. In the Plasma Radiation Shield the outer sphere is replaced by a distributed cloud of electrons held in place by a magnetic field of moderate intensity. Therefore, in our second example, we imagine a cloud of electrons to be distributed around the inner sphere in such a manner that their number density n_e (i.e., the mean number of electrons per cubic meter) is a function only of r. For the moment we shall just suppose that they are held in place by "magic". Later we shall discuss this obviously vital question in detail. Clearly, the electron cloud is completely transparent to incoming protons in the sense of the discussion of proton reflection given earlier.

Poisson's equation connects the potential with the charge density. In the present spherically symmetric situation we have:

$$\frac{1}{r^2} \frac{d}{dr} \left[r^2 \frac{d\phi}{dr} \right] = \frac{n_e(r)e}{\epsilon_0}$$

Now for simplicity, suppose that the electron distribution is one of constant density n_e extending between the surface of the inner sphere (radius a) and some larger radius b . This distributed electron cloud represents the outer sphere of the previous example; the electron cloud therefore contains a total charge $-Q$ given by:

$$Q = \frac{4}{3}\pi (b^3 - a^3) n_e e \tag{3.2.5}$$

The appropriate solution of Poisson's equation, valid for $a \leq r \leq b$ can now be shown to be:

$$\phi(r) = \frac{Q}{4\pi\epsilon_0 r} \frac{(b-r)^2 (b + r/2)}{(b^3 - a^3)} \tag{3.2.6}$$

The potential at $r = b$ is zero, as is also the potential of all points $r > b$. The electric field at $r = b$ is also zero because there is no <u>net</u> charge inside this radius. The electric field also vanishes for $r > b$. It follows now that the potential of the "space vehicle" is higher than the potential at "infinity" by the amount

$$\phi(a) = \frac{Q}{4\pi\epsilon_0 a} \frac{(b-a)(b+a/2)}{b^2 + ab + a^2} . \tag{3.2.7}$$

For a given value of $\phi(a)$, $\phi(r)$ can be written in the form:

$$\phi(r) = \phi(a) \cdot \frac{(1 - r/b)^2 (1 + 2b/r)}{(1 - a/b)^2 (1 + 2b/a)} \tag{3.2.8}$$

For various values of b/a , this variation in $\phi(r)$ across the electron

cloud is shown in Fig. 3.1.

Formula (3.2.3) allows the calculation of an equivalent capacitance for the system of sphere plus electron cloud given by:

$$C = 4\pi\epsilon_0 a \frac{b^2 + ab + a^2}{(b - a)(b + a/2)} .$$

Comparing this with (3.2.4), we see that our arrangement is equivalent electrically to the concentric sphere arrangement discussed earlier where the radius of the outer sphere is given by:

$$b' = \frac{2}{3} \frac{b^2 + ab + a^2}{b + a} .$$

If, for example, the distributed electron cloud extends from $a = 2m$ to $b = 5.46\,m$ ($= 2\sqrt{3} + 2$) m , it follows that $b' = 4$ meters. Thus an electron cloud of uniform density extending over a radius ratio of 5.46 : 2 corresponds electrostatically to the example quoted before of two concentric spheres with a radius ratio of 4 : 2 . For this example we also calculate the required electron density in the cloud; this follows from the fact that $Q = 22.2$ millicoulombs and from equation (3.2.4) we find: $n_e = 2.1 \times 10^{14}$ electrons/m.^{3} $= 2.1 \times 10^8$ electrons/cc. The total number of electrons in the cloud is just Q/e . This is $N_e = 1.38 \times 10^{17}$ electrons. The support of such an enormous number of electrons is obviously not a trivial matter, and we shall come to this question after taking one more number out of the present analysis. The value of the radial electric field at the surface of the sphere is $E(a) = \frac{Q}{4\pi\epsilon_0 a^2}$. For the numbers quoted, this has the value 5×10^7 volts/meter or .5 million volts/cm. This large value of the electric field raises questions of its own to which we shall return (in 3.5). For the moment we observe that the density of positive charge on the outside surface of the "Plasma Radiation Shield" is $Q/4\pi a^2 = .44 \times 10^{-3}$ coulombs/m^2. The electric field just calculated exerts a force on this charge layer equal to

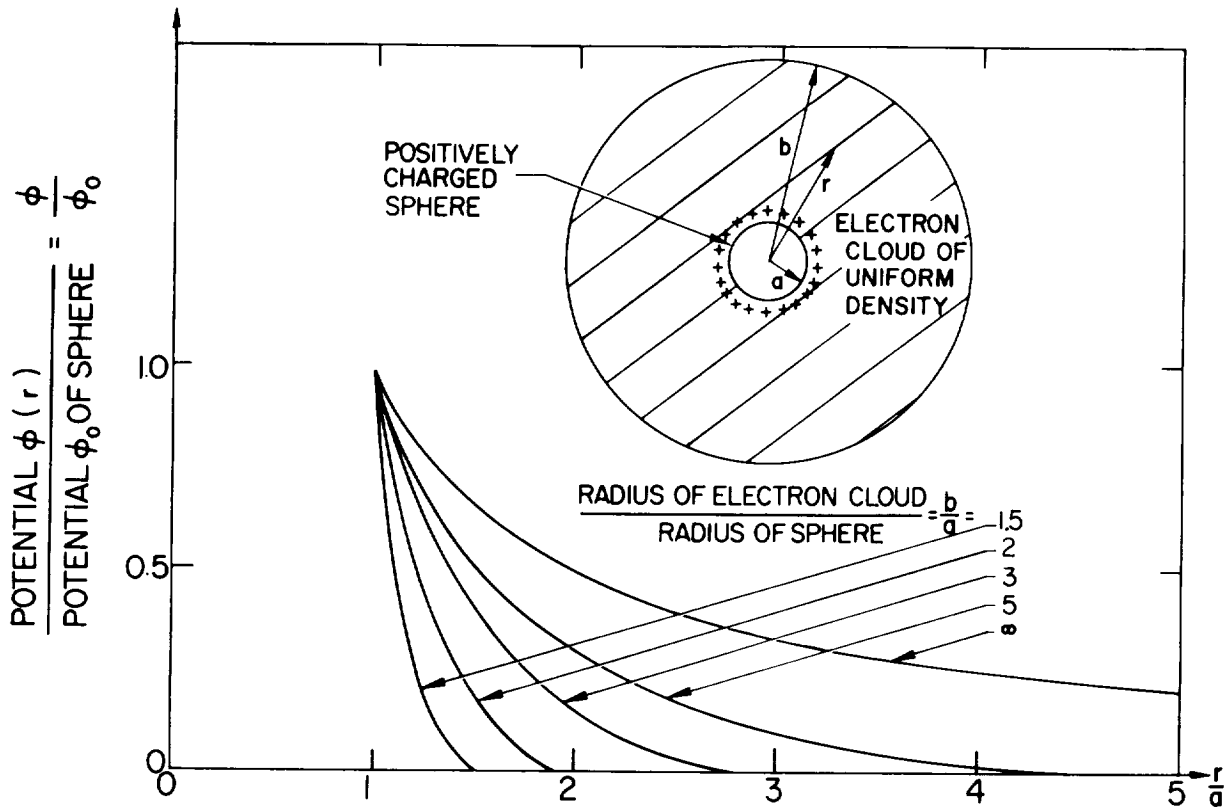


Fig. 3.1 Distribution of potential outside a charged sphere in the presence of an electron cloud of uniform density extending from the sphere (radius a) to radius b . The negative charge in the electron cloud is equal in magnitude to the positive charge on the sphere.

A5731

$.11 \times 10^5$ newtons/m^2 $\approx$ .11 atmospheres. This force can also be thought of as the force of attraction between the positive charge $+Q$ on the inner sphere and the negative charge $-Q$ in the electron cloud. The nature of this force is the same as that of a gas atmosphere at this pressure inside the sphere; the magnitude would not be such as to cause much of a structural problem.

The preceding discussion of the electrostatic situation near a "Plasma Radiation Shield" of spherical geometry gives an idea of the way in which the electric fields are distributed around the space vehicle, and also gives a preliminary indication of the orders of magnitude of the quantities involved; we turn next to the means by which a magnetic field can be used to hold the electron cloud in place.

3.3 The Magnetic Field

The force exerted on an electron of charge $-e$ moving with velocity $\underline{v}$ in a magnetic field $\underline{B}$ is $-e(\underline{v} \times \underline{B})$. This force has no component parallel to $\underline{B}$, and from this observation follow important consequences. For, should there be any electric field in the direction of the magnetic field, the electrons will respond immediately by flowing along it until it is essentially nullified. It follows that after a very short time magnetic field lines (or at least those portions of the magnetic field lines on which there are electrons) will have no electric field along them, or, what is the same thing, they will become equipotentials. Now, since "infinity" and the space vehicle are supposed to differ in potential by 5×10^7 volts, there can be no lines of force which in one place are near the space vehicle and in another place far away from it. There is really only one kind of magnetic field geometry that satisfies both this requirement and the additional requirement that the field be <u>outside</u> the space vehicle, and that is, in its simplest form, the magnetic field due to loop of current, illustrated in Fig. 3.2. To be more precise, one would like to make the surface of the vehicle correspond in form to a given magnetic field line. This can be accomplished in a large variety of ways, but all these are <u>topologically</u> the same as the single loop coil shown in Fig. 3.2. Thus, the simple observation that $\underline{v} \times \underline{B}$ is perpendicular to B leads us to reject the possibility of a spherical Plasma Radiation Shield

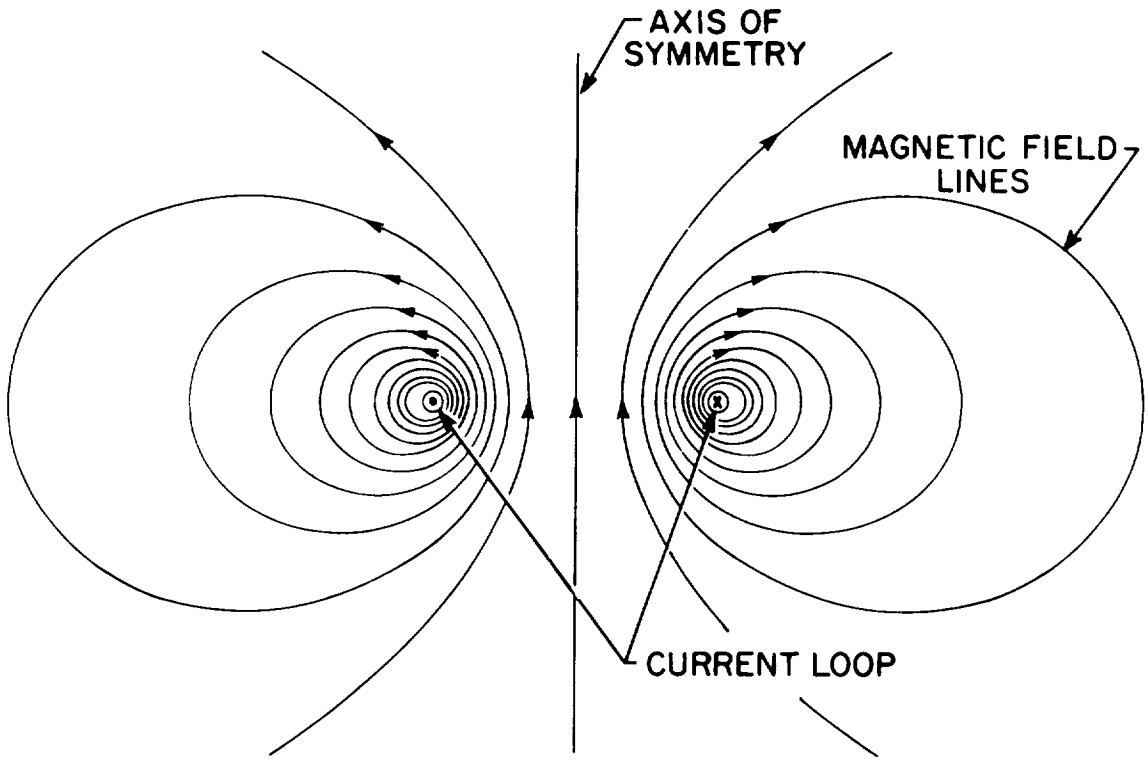


Fig. 3.2 A loop current is the simplest form of magnet giving a field shape satisfying the requirements of the Plasma Radiation Shield. This illustration shows the general shape of the magnetic field lines surrounding such a loop.

A7422

in favor of a topological torus. The condition that a space vehicle utilizing the Plasma Radiation Shield be a topological torus is on examination not as restrictive as one might suppose, although it does rule out direct adaptation of shapes not satisfying this condition. There are an unlimited number of ways in which a topological torus can be deformed; two examples are shown in Figs. 3.3 and 3.4. Of these two, the first represents a more substantial departure from current thinking about the shape of space vehicles than the second. Several other possibilities are discussed in Section 5 under the general heading of Vehicle Configuration Possibilities. For the present, we note that the configuration of Fig. 3.4 may have important advantages, although, pending further study, these remain uncertain. A brief discussion of these advantages is given in Section 3.6.

A second observation of considerable importance also follows directly from the form of the expression $(\underline{v} \times \underline{B})$ for the force exerted on an electron by a magnetic field. That is that the force is zero when the electron is stationary. But since a force is obviously required to counteract the electric field, the electrons must be (on the average) in motion. Thus, we are seeking a dynamic rather than a static equilibrium. The electron cloud must be permanently in motion of a rather complicated kind, and this motion must be so accurately perpendicular to the electric field that the electrons do not reach the space vehicle in a time comparable to the duration of a solar flare (i.e., about 48 hours). The nature and present state of understanding of this dynamic equilibrium are briefly discussed in Section 3.4 and in the Appendix. For the present we note only that the dynamics of the electron cloud poses many problems concerning which our present knowledge is incomplete.

One further conclusion to be reached on the basis of the force expression is quantitative. The magnitude of the magnetic force is evB. The electric force which this is supposed to counterbalance is eE. Equating these yields

$$B = E/v = \frac{E}{\beta c}, \quad \text{where} \quad \beta = v/c \tag{3.3.1}$$

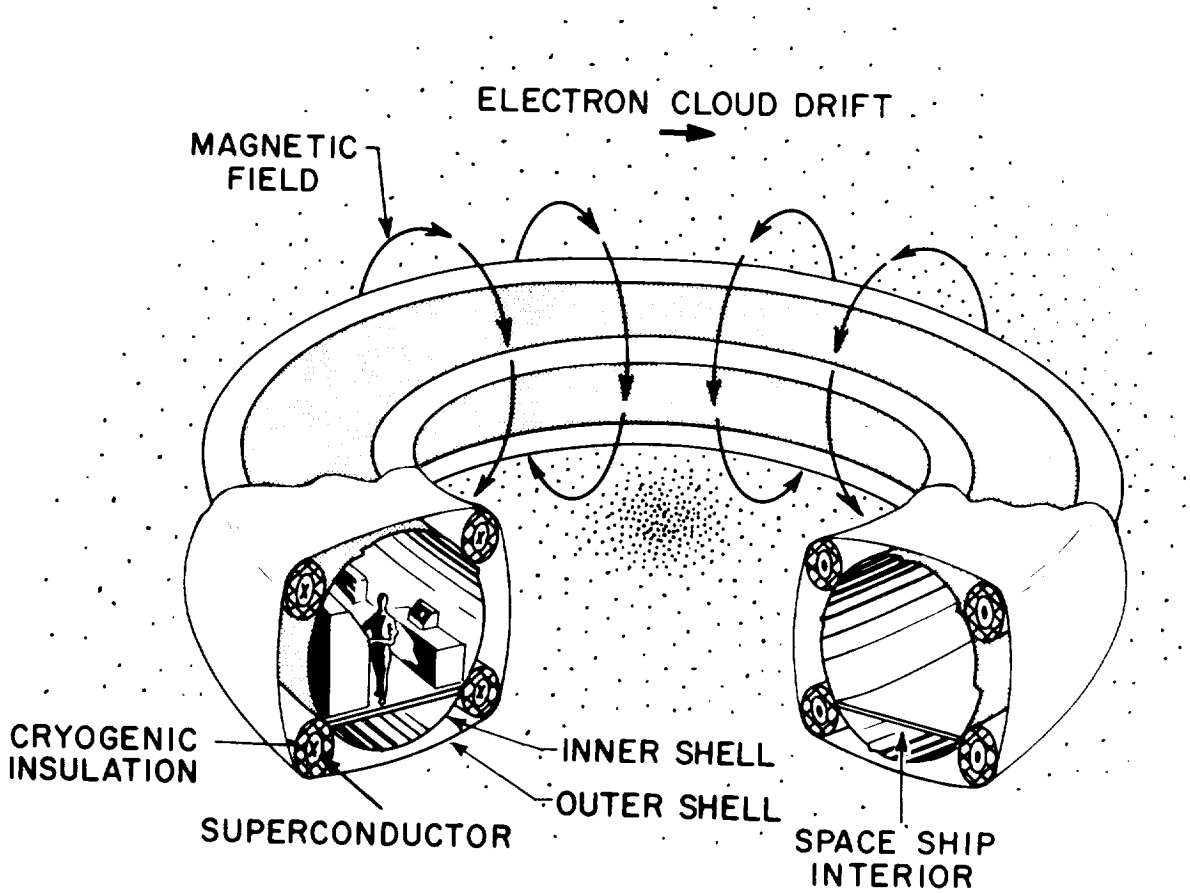
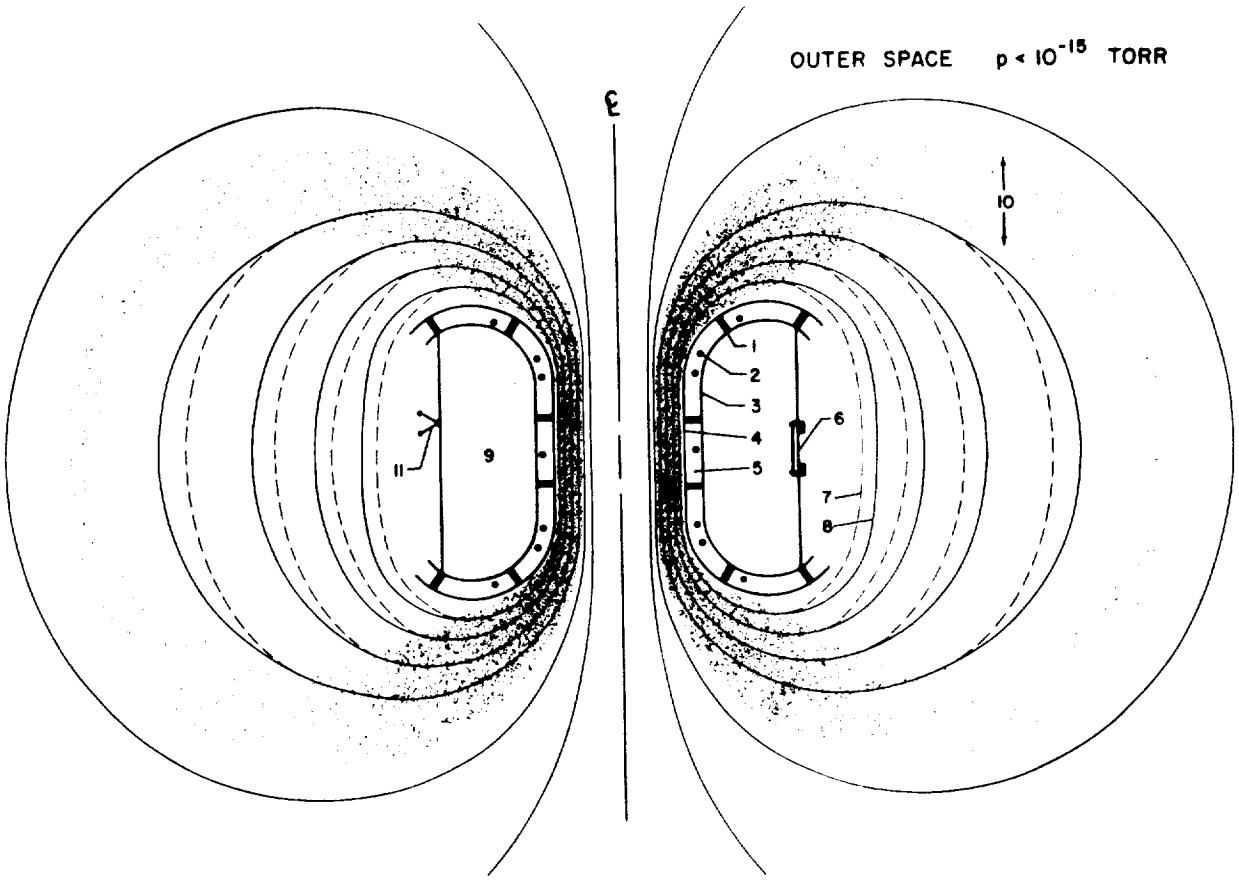


Fig. 3.3 Shows how the simple loop current shown in Fig. 3.2 can be adapted to a space vehicle. In this particular realization, the vehicle is symmetric in azimuth around the axis of the loop. Also shown are the electron cloud with its associated direction of drift, and a possible 4-coil arrangement for the superconducting magnet. The double-walled construction is discussed in Section 7. Of the many other realizations of the Plasma Radiation Shield that are possible, one more is shown in Fig. 3.4.

A2089



1 - INSULATING STRUTS
2 - MAGNETIC FIELD COILS
3 - NON-BAKEABLE INNER SKIN
4 - BAKEABLE OUTER SKIN
5 - INNER SPACE, $p \approx 10^{-9}$ TORR
6 - EXIT PORT WITH VITON "O" RING SEAL
7 - EQUIPOTENTIAL SURFACES
8 - MAGNETIC FIELD LINES
9 - LIVING & WORKING SPACE $p \approx 5$ psi
10 - LIMITS OF ELECTRON CLOUD
11 - ANTENNAS ETC.

Fig. 3.4 Possible alternate conceptual configuration for a Plasma Radiation Shielded space vehicle. This speculative configuration could utilize a cylindrical launch vehicle. The relative merits of this approach are discussed in Section 3.6. The equipotentials follow magnetic field lines in the interior of the electron cloud, but are distinct outside of the cloud.

A7807

and if we knew v this would determine B since E is fixed by the electrostatics of the situation. But an absolute upper limit to v is given (by the theory of relativity) as the speed of light $c = 3 \times 10^8$ m/sec. Using the value of $E = 5 \times 10^7$ volts/m and assuming that the electron velocity can be one-half of its maximum value (i.e., $\beta = 1/2$), we find a characteristic magnetic field of .33 webers/m^2, or 3.3 k gauss. This magnetic field is far below what would be required for a pure magnetic radiation shield. Note also that it depends directly on our assumption about the electron velocity. Here again is a case where necessary basic knowledge is lacking; in this case if the β chosen to be 1/2 had been in fact 1/10, the magnetic field would have been 5 times more intense than the 3.3 k gauss quoted. This would give a magnetic field comparable in strength to that required for a pure magnetic shield, and we already know that the weight of these devices makes them unattractive. On the other hand, it may be permissible to go the other way; perhaps β can be as high as 0.9, giving a magnetic field of only 1.9 k gauss. This large uncertainty has a considerable effect on the calculated weight of the Plasma Radiation Shield, since the superconducting magnetic field coil (with its structure, insulation, power supply, controls, etc.) is the only massive item in the Plasma Radiation Shield. Up to the present, it has been guessed that $\beta = 1/2$ and all estimates have been based on this guess. The factors that determine the largest achievable $\beta (< 1)$ are not yet fully understood.

A final point to consider in connection with the magnitude of the magnetic field is the following: although low values of the mean magnetic field appear attainable, this by itself does not necessarily represent an optimum design. A more meaningful quantity is the total magnitude of the magnetic field energy. Now this total energy varies as the square of the mean magnetic field, and the cube of some linear dimension. It may very well turn out to be desirable to utilize larger mean magnetic fields over smaller volumes. Study of this trade-off is likely to be an important element in a deeper systems study of the Plasma Radiation Shield. In particular, the configuration illustrated in Fig. 3.4 (and briefly discussed in Section 3.6) would probably operate with rather substantial fields

(10-30 k gauss) in the relatively small interior volume. The most important unknown in this trade-off is the way in which the shielded volume varies with magnetic field energy.

3.4 Containment of the Electron Cloud

The fundamental idea underlying the concept of the Plasma Radiation Shield is certainly sound in principle. However, although a magnetic field as described is capable of holding the electron cloud in place, many difficult problems must be solved before it can be stated with assurance that this capability can actually be realized. The basic problem is that the electron cloud has a strong tendency to collapse onto the Plasma Radiation Shield; from the thermodynamic point of view this tendency is due to the very large free energy associated with the electric field. The Plasma Radiation Shield will work if it turns out that all the means available to the electron cloud of giving up its free energy operate at acceptably low rates.

The quantitative definition of "acceptably low" turns out to be very restrictive. Specifically, the electrons in the cloud are held at a distance from the space vehicle by the magnetic field; various mechanisms will allow the electrons to cross the magnetic field at appropriate speeds, and to fall into the space vehicle. Such motion constitutes a loss current. Plainly, this loss current must be extremely small if all the electrons (and hence the protective electric field) are not to be lost in a time short in comparison with the duration of a solar flare. If we take this time to be 2 days $\approx 2 \times 10^5$ seconds, and take the total charge in the cloud to be .022 coulombs, the loss current due to all losses should be substantially less than $.11\mu$ amps. A current of this magnitude crossing a voltage of 5×10^7 volts yields a maximum acceptable loss power of 5.5 watts. Put somewhat differently, at a speed of 1/2c, an electron will drift around the Plasma Radiation Shield in a time of about $.1\mu$ secs. Thus the mean direction of drift must be perpendicular to the magnetic field to an accuracy of roughly 1 part in 10^{12} (or 10^5 secs/$.1\mu$ secs).

3.4.1 Instabilities

By far the most dangerous possibility is that the electron cloud would be unstable. By this we mean that some collective effect in the

electron cloud could cause the cloud to fall across the magnetic field on a large scale. But the times associated with inherent instabilities of the usual kind would be expected to correspond to the inherent time scales of the electron cloud. These time scales are typically on the order of the time it takes an electron to drift around the device (i.e., .1μ sec), or, even shorter, the electron plasma period, or even the electron cyclotron period. These times are so extremely short that it is vital for the success of the concept that the electron cloud be exceedingly stable. It is a fortunate fact that prolonged and careful study of the question of stability has yielded consistently encouraging results. The details of these studies are given in Ref. 48 to 53; but a summary of the results suggests that if the inner edge of the electron cloud is maintained very close to the surface of the space vehicle, stability can be attained. There is also empirical evidence that a small-scale device (the Vac-Ion Pump)[54] which is closely related to the Plasma Radiation Shield is successful only because electron clouds of our type are in fact very stable. Our own experiments have also suggested the same, but there is an important proviso: no experiments have been done in the geometry demanded by the Plasma Radiation Shield concept. Since certain possible modes of instability are strongly dependent on geometrical factors, it will ultimately be necessary to test the stability of the Plasma Radiation Shield in a direct manner. At present, all that we can say is that experimental, empirical, and theoretical evidences are all sufficiently encouraging to proceed to other (generally slower) forms of loss on the assumption that the hoped for stability is in fact present. The question of stability is discussed in somewhat greater detail in the Appendix.

3.4.2 Classical Diffusion

These other, slower forms of loss come generally under the heading of "classical diffusion" caused by close collisions of the electrons with (1) other electrons; (2) ions; (3) neutral atoms and (4) particulate matter. We deal with these possibilities in order.

(1) Electron-electron collisions. Collisions between like particles cause only a very weak form of diffusion, when there is a gradient of density or temperature. Calculations indicate that losses from this source are less than 0.1 watts, and are

therefore well within the allowable maximum diffusion rate.

(2) Electron-ion collisions. These are no problem in the Plasma Radiation Shield for the following reasons: positive ions are strongly expelled from the electron cloud by the electric field and are sufficiently massive that the magnetic field cannot restrain them. The residence time for a typical ion in this field is on the order of 10^{-7} seconds, and this time is so short that the ion will generally have no close collisions with electrons of the cloud. This is true of the solar flare ions, and also of any other ions that from time to time might be present in the system. In particular, ions coming from outside the cloud (i.e., from space) are reflected elastically by the electric field with no net exchange of energy.

(3) Electron-neutral collisions. Due to solar UV radiation and other effects, the ambient density of neutral atoms in deep space is negligible, but there will be atoms coming out of the space vehicle due to leaks from the pressurized cabin, and to outgassing from exposed surfaces. The Plasma Radiation Shield concept puts a very severe restriction on the flux of these atoms, for the following reasons: an atom coming off the space vehicle will generally be moving at a speed corresponding to the temperature of the surface from which it came. These speeds are generally moderate, and the atom is at once exposed to the circulating flux of electrons in the cloud. If these electrons have a density of $10^8/cm^3$, and a speed of 10^{10} cm/sec, and if we take the cross section for ionization as $10^{-18} cm^2$, the length of time that elapses before the atom is ionized will generally be about 1 sec. This suggests that a non-negligible fraction of the neutral atoms coming off the space vehicle will be ionized during their passage across the electron cloud. Now, after ionization an electron and a positive ion are formed; the electron will become just part of the electron cloud, but the ion, unrestrained by the magnetic field on account of its greater

mass, will be ejected into deep space by the electric field in the time 10^{-7} seconds previously quoted. But the transport of a positive ion from some point near the surface of the space vehicle to infinity is just as much a loss as is the transport of electrons from the outer regions of the cloud to the surface of the space vehicle. In the worst case, all the ions are formed right at the surface of the space vehicle and subsequently ejected across the full 5×10^7 volts. In this case the limit on the current of ions is about $.1\mu$ amps. This represents a maximum allowable number of such ions on the order of 10^{12}/sec, and this is also the maximum allowable rate of escape of neutral atoms from the active space vehicle. If this is a leak of oxygen from the cabin, it corresponds to an allowable leak rate of about 10^{-6} grams of oxygen in two days! In fact, the mean potential at which neutrals are ionized can be considerably lower than 5×10^7 volts, since in the 1 sec mean free time estimated above the neutrals would cover a distance like 100 m. or more. Suppose, for instance, that the mean potential of ionization is only 1% of the full voltage, or 5×10^5 volts. The tolerable current is then 10μ amps corresponding to a flux of 10^{14}/sec, or 10^{-4} gms in 2 days. However, even with these figures, it is obvious that the cabin pressure vessel must be a high quality vacuum vessel; if it is double-walled, however, this low leak rate should be attainable. There is also a severe restriction on the amount of outgassing of the whole surface that can be permitted; this corresponds roughly to a pressure over the surface of about 10^{-12} mm Hg, again a very low but not unattainable level. It must be remembered that ample time is generally available to bake and thoroughly clean all exposed surfaces before activation of the Plasma Radiation Shield. We shall return to this question in Section 7.

(4) Particulate matter. If the surface of the Plasma Radiation Shield is clean, no dust particles should be present on it;

preliminary activation of the electric field should help to achieve the required degree of cleanliness. There remains, then, the flux of micrometeorites from space. If, as is believed,[55] this flux is less than 10^{-8} gm/cm^2/year outside the immediate neighborhood of the earth, there should be no problem from this source. A large meteorite might shut off the electric field, and reactivation would take perhaps an hour or less, but the probability of such an event coinciding with a solar flare is reasonably low.

This completes our discussion of problems of classical diffusion; by far the most important difficulty to have arisen is the control of leakage and outgassing. Although difficult, it cannot be stated that this problem is insuperable; the actual constraints that it is likely to impose are reviewed in Section 7.

3.5 Achievement of Very High Voltages

It was mentioned in Section 2 (in connection with electrostatic shielding) that the required voltages are higher than any yet achieved on earth, and the same comment applies to the Plasma Radiation Shield. It is natural to ask, in these circumstances, how it is that we can contemplate reaching these voltages in the Plasma Radiation Shield. At this stage we can do no more than explain why the effects that limit the voltage in present-day machines do not apply to the Plasma Radiation Shield. This lack of applicability of known limitations is encouraging, but is obviously not a guarantee that the required voltages can be reached. This is an area in which there can be no substitute for an experiment.

In general, the achievement of high voltages in the laboratory has been limited by problems of breakdown.[56-64] The particular breakdown experiments which are most relevant are those having to do with breakdown between parallel electrodes in high vacuum conditions. It seems that the best available theory[56] of how this occurs is as follows: at the negative electrode (or cathode) the electric field points in such a direction as to draw electrons out of the surface. A current is actually drawn by the quantum-mechanical mechanism known as field emission. This current depends

exponentially on the electric field and is therefore concentrated at microscopic projections on the cathode where the electric field is intensified. Next, the current through these projections heats them by Ohmic dissipation. At a certain field strength this heating is sufficient to evaporate the projections altogether; breakdown then occurs in the gas thus formed. Now, if this is indeed the true mechanism of breakdown, there is reason to be optimistic where the Plasma Radiation Shield is concerned, for in our case, there is no material cathode at which field emission can occur. The only material electrode is the space vehicle itself, and this is the anode (positive electrode); that is the direction of the electric field is such that it tries to extract positive ions. From a quantum-mechanical viewpoint, the extraction of positive ions by field emission is virtually impossible. The evidence as regards anode field strength limitations is from the working of the positive ion microscope,[65] a device in which a large cathode and a tiny anode produce an enormous electric field at the surface of the latter. This device draws a satisfactory ion current only when the electric field is on the order of 100 million volts/cm, a field some 100 times greater than that contemplated for the Plasma Radiation Shield. Furthermore, this field strength produces electrostatic forces on the order of 3,000 atmospheres, that is, on the order of the yield strength of most materials. Microscopically, it is 1 volt/angstrom. Taking 1 angstrom as a typical spacing between ions in a lattice, and 1 volt as a typical binding energy, it is again plain why an ion current can be drawn by an electric field of this strength. To sum up this subject, the Plasma Radiation Shield should not be subject to high vacuum breakdown as it is presently understood, and should not lose appreciable ions at the field strengths contemplated. As stated before, these hopes can only be proved sound by an appropriate experiment.

3.6 Possibilities for the Configuration of Fig. 3.4

The configuration of Fig. 3.4 may turn out to be very advantageous. The reasons for this possibility must for the moment be regarded as speculative, but nevertheless it is worthwhile to offer herewith some discussion of these reasons. This discussion accomplishes two purposes, of which the first is specific and the second general. The first purpose is that if the

anticipated advantages of this configuration hold up under further study, the Plasma Radiation Shield will be substantially simpler to achieve than might otherwise have been the case. The second purpose is to show, by means of an example, that there is still a large amount of room for the application of imaginative ideas to the Plasma Radiation Shield. The concept is still far from complete definition; further study on a broad front can still be expected to yield large as well as small changes in its overall desirability.

It was stated in Section 3.2 that magnetic field lines on which there were electrons must be equipotentials. This statement may not be strictly true, for the following reasons: in axially symmetric magnetic fields (as, for instance, that shown in Fig. 3.2) magnetic field lines that pass close to the axis of symmetry (say, at a radial distance r_{small}) close at a very large radial distance, roughly $r_{large} = V/(2\pi r^2_{small})$, where V is a representative volume of the magnet. But since the electrons of the cloud are attracted to the positive charge on the space vehicle, the electrons may not wish to locate themselves quite so far away from the vehicle as r_{large}. This suggests that the electron cloud might be confined to some region near the space vehicle, of characteristic volume V, and that the remainder of the magnetic field is largely, or even entirely, free of electrons. The interpretation of the statement in Section 3.3 about magnetic field lines being equipotentials is then as follows: throughout the electron cloud, magnetic field lines are indeed equipotentials, but in regions of the magnetic field where there are no electrons, there is no such requirement. Thus, it is possible to imagine that the equipotentials follow the magnetic field lines in the region near the axis of the magnetic field, but that outside of some contour defining the boundary of the electron cloud, the electrostatic potential satisfies Laplace's equation. In this case the equipotentials would fall inside the magnetic field lines in the vacuum region, but would become tangent to the magnetic field at the boundary of the electron cloud. This situation would not affect the basic shielding properties of the configuration.

It is not known for sure whether such an electron cloud is possible, but, on the assumption that it is, the configuration of Fig. 3.4 would have important advantages, as follows:

1. The shape of the magnetic field is roughly that of a long solenoid; in such a magnetic field, the field lines close at larger distances than they would, say, for the loop current of Fig. 3.2. Thus, the electron cloud should be substantially confined to the interior of the solenoid.
2. The general shape of the space vehicle is cylindrical, in accordance with many current ideas about such vehicles; such a shape is naturally compatible with launching rockets.
3. The construction of a solenoidal magnet is a simpler task structurally than the construction of the four-coil magnet of Fig. 3.3. Also, the stray magnetic fields in the shielded volume would be very small indeed.
4. Since there is essentially no electron cloud outside the vehicle, gas atoms coming from the vehicle will not be ionized, and will therefore constitute no electrical loss. Thus, the vacuum problem (discussed briefly in Section 3.4.2, and in detail in Section 7) would be confined to the relatively small area of the space vehicle facing the electron cloud. In particular, ports, doors, antennas, etc. could be located on the exterior surface without the necessity for special sealing.
5. The electric field on the outside of the space vehicle would be quite low. Thus protuberances of various sorts could easily be tolerated, and would have essentially no effect on the electron cloud.
6. The injection of the electrons could be accomplished in the low field region outside the vehicle; these electrons would then quite naturally proceed to the high magnetic field region inside the solenoid. Such an injection procedure might be extremely simple.

In conclusion, we must emphasize that the existence of the type of equilibrium we are considering has not yet been demonstrated. Even less is known about possible instabilities of such equilibrium configurations. In particular, we do not yet know how to calculate the shielded volume

associated with such a configuration, i.e., what outer radius of the space vehicle can be tolerated. An important effect of this ignorance is that calculations of the weight of such a Plasma Radiation Shield are irrelevant to the extent that we cannot associate them with definite values of the shielded volume. Lastly, the extent of these uncertainties can be taken as a rough measure of the present degree of definition of the Plasma Radiation Shielding concept.

3.7 Basic Design Parameters

The most basic design parameters of the Plasma Radiation Shield are, first, the size and shape, and second, the overall voltage. The voltage is set by considering such questions as the actual frequency and spectra of solar flares, and allowable radiation doses to the crew. This subject is discussed in some detail in Section 4. The size is set fundamentally by the nature of the mission to be undertaken, especially the crew size and the mission duration, but the shape is set (as discussed in Section 3.3) by the requirement that the Plasma Radiation Shield be essentially toroidal. Two possible configurations are shown in Figs. 3.3 and 3.4, but these suggestions are far from exhausting the possibilities.

Now a principal object of any analysis of the possibilities inherent in the Plasma Radiation Shield must be a curve showing the relation between the shielded volume and the systems weight. However, we are not yet in a position to calculate either of these quantities with any precision. The uncertainty associated with the shielded volume was discussed briefly in Section 3.6 in connection with the configuration of Fig. 3.4, but stems basically from lack of definition of the overall configuration of the space vehicle, magnetic field and electron cloud. The uncertainty associated with the systems weight stems basically from a lack of definition of the attainable value of β (Eq. 3.3.1), since this parameter determines the level of the required magnetic field. The weight of a Plasma Radiation Shield resides primarily in the superconducting coil. The weight of the superconductor itself is proportional to β^{-1}, while the weight of its power supply and structure scale with β^{-2}. The weight of the cryogenic system (including refrigerator) depends strongly on the coil configuration. Lack of certainty

about the configuration also makes it difficult to assign a weight to other components of the system, such as penalties associated with vacuum requirements.

The net result of these considerations is that it is not possible, at the present time, to calculate the weight of a Plasma Radiation Shield with any more precision than was done in Ref. 44. The curve of weight vs. shielded volume of that paper is reproduced here, as Fig. 3.5, and indicates clearly the advantages that may be possible with a Plasma Radiation Shield. Since this curve was drawn, the physical basis for the concept has been placed in a much sounder framework. Thus it is now possible to take up again the question of systems integration; as stated in the Preface (Section 1), it is the purpose of this paper to lay the basis for such a systems study, rather than to accomplish it. This being the case, in calculating system weights, we leave our results for the most part as formulas, showing the dependence of the weights of different components on characteristic parameters such as the magnet current. In particular, we do not attempt to establish a sample design for which weights can be calculated, as this does not seem presently to be justified.

3.8 Summary

To sum up, the basic features of the Plasma Radiation Shield are as follows:

1. A cloud of electrons of total charge $-Q$ is held away from the space vehicle (which has a positive charge $+Q$) by a magnetic field. The magnitude of Q is determined roughly by a knowledge of the required voltage of the space vehicle and its size and shape, and (to a smaller extent) by the details of the distribution of the electron cloud. Potentials from 10 to, say, 200 million volts are considered. Characteristic electric fields are on the order of 1 million volts/cm.
2. The space vehicle is necessarily toroidal; it carries a large current (generally several million ampere turns) around its major radius, and its shape in the meridional section must coincide with some line of force of the magnetic field.

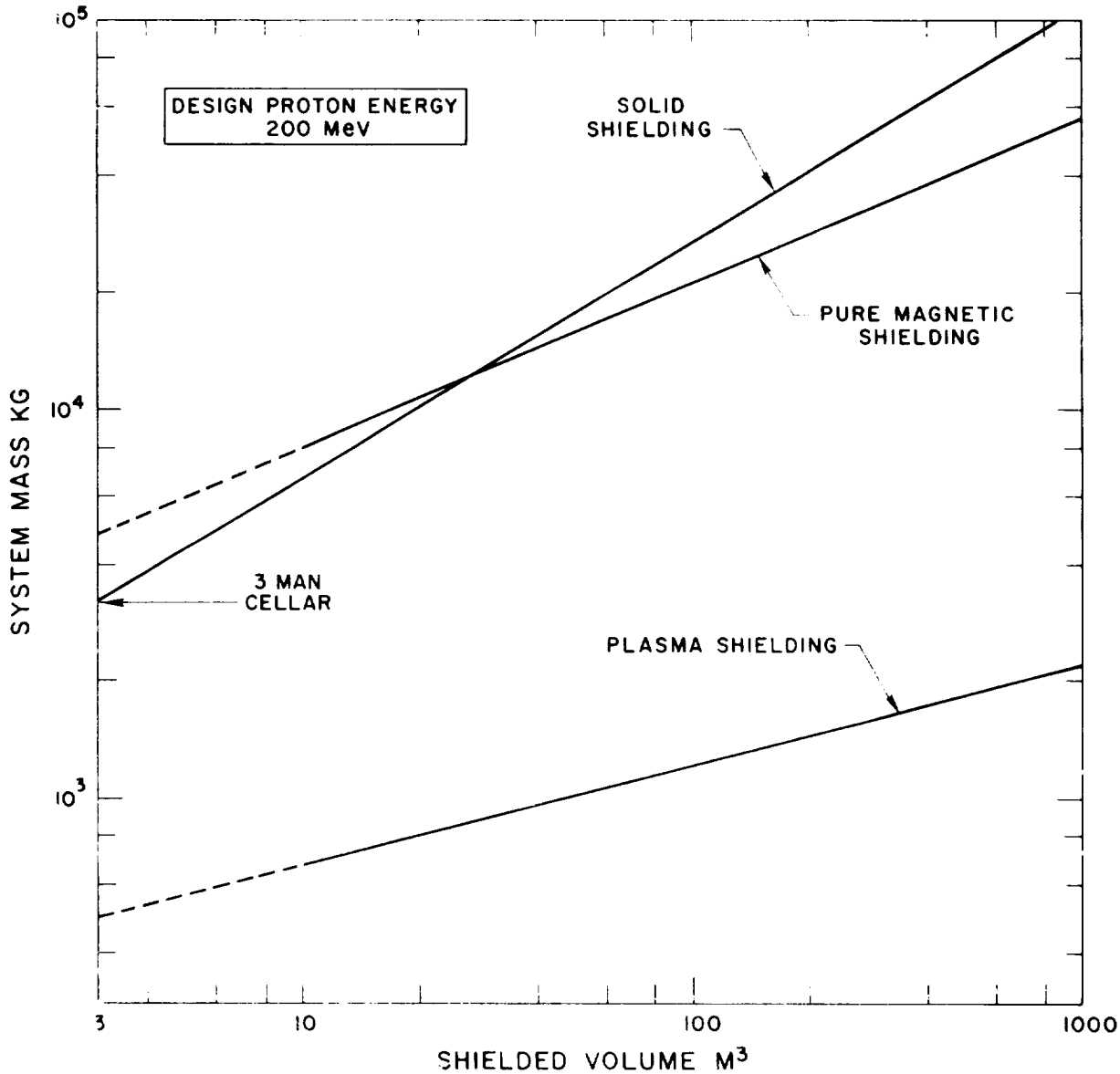


Fig. 3.5 The weight of a Plasma Radiation Shield as a function of the shielded volume. This curve, reproduced from Ref. 44, remains the most reasonable estimate of the weight of a Plasma Radiation Shield, pending more detailed systems studies. Thus it must be regarded as subject to large uncertainties. Shown for comparison are estimated weights for solid and pure magnetic shields, for 200 MeV design energy.

2090

Magnetic fields required are on the order of several thousands of gauss.

The whole concept of Plasma Radiation Shielding is associated with two large unknowns; these are as follows:

1. It is not certain that under any conditions the electron cloud around the Plasma Radiation Shield will function satisfactorily, although there are at present grounds for being guardedly optimistic on this score. Some of the questions that arise, and the reasons for our guarded optimism are discussed later in the paper, and especially in the Appendix.
2. Even if all the questions that arise under the above topic are satisfactorily resolved, it will still remain true that to incorporate a Plasma Radiation Shield in an actual space vehicle would involve very far reaching design "boundary conditions" affecting the space vehicle as a whole. Whether these conditions are acceptable or not will certainly be a question of balancing in detail all the various pro's and con's. In particular, it is important to know exactly what concessions in terms of weight would be demanded by the provision of adequate solid shielding. If the weights are large, it could well be worthwhile to adapt the over-all space vehicle design to the demands of the Plasma Radiation Shielding concept. We are not yet ready to undertake a detailed study of the relative advantages of this concept; however, we are in a position to be fairly specific about the demands of the Plasma Radiation Shield. To the extent presently possible, these demands are discussed in the following sections.

4. VOLTAGE SELECTION IN THE PLASMA RADIATION SHIELD

The two most basic parameters of the Plasma Radiation Shield are the over-all size and shape, and the magnitude of the voltage. In this section we discuss the considerations which enter into the selection of the voltage.

The starting point is a consideration of the maximum permissible dose to which the crew may be subjected. In Table 8 of Ref. 30 are listed the biological doses sustained behind various bulk shielding configurations for all the principal solar flare events from February 1956 to October 1962. If one stipulates some sort of dose tolerance criterion – e.g., a maximum acute dose or a maximum cumulative dose over some time period – one can then determine the thickness of bulk shielding that will just satisfy this criterion. One can then enter proton range-energy tables, such as Ref. 66, and determine the maximum energy of proton that is stopped by this thickness. As a first approximation we may consider that a Plasma Radiation Shielding system should be capable of stopping this same proton. For example, Ref. 30 shows that the maximum surface dose behind 10 gm/cm^2 of aluminum for any single event (actually three separate events in one week) was 66 rad. Also, the same source shows that the maximum cumulative dose during any two-year period for the same shielding configuration was 151 rad. If it is assumed that these dose figures are tolerable, then the required bulk shielding thickness is 10 gm/cm^2 of aluminum. Reference to range-energy tables[66] shows that this thickness is adequate to stop 100 Mev protons.

Now, the rate of loss of energy of fast particles in matter is a strongly decreasing function of energy. Thus, at high energy, the use of solids to stop protons is relatively wasteful. Conversely, at low energy, the use of solid shielding is relatively efficient. Further, any space vehicle configuration will possess a certain amount of solid shielding in the form of its skin and other equipment. This shielding may be estimated roughly at

2-4 gm/cm^2 aluminum.* Suppose, for example, that it is required to stop 100 MeV protons. If the skin thickness is 2 gm/cm^2, reference to the range-energy tables shows that this thickness will just stop a 40 MeV proton. It is therefore only necessary to provide 60 million volts of potential in the Plasma Radiation Shield in order to achieve the desired effect. The incident 100 MeV proton crosses the Plasma Radiation Shield voltage, losing 60 MeV. The remaining 40 MeV are then absorbed in the 2 gm/cm^2 of skin. If the skin thickness is 4 gm/cm^2, reference to the range-energy tables shows that this thickness will stop a 60 MeV proton. Thus a 40 MV Plasma Radiation Shield outside of 4 gm/cm^2 of skin would also suffice to stop 100 MeV incident protons. Proceeding in this way, one can, using the range-energy tables, construct a graph showing the different combinations of Plasma Radiation Shield voltage and solid shielding thickness that will stop a given proton. This graph is presented in Fig. 4.1. From it we can, by looking along the line marked "Proton Energy 100 MeV," find the two examples just discussed of a vehicle skin of 2 or 4 gms/cm^2, with Plasma Radiation Shield voltages of 60 and 40 million volts respectively. Another way to look at Fig. 4.1 is to consider the relative effectiveness of, say, a 40 million volts Plasma Radiation Shield against protons of various energies. For example, to stop a 100 MeV proton requires 10 gm/cm^2 of solid shielding. But we saw above that 40 MV Plasma Radiation Shielding ahead of 4 gm/cm^2 of skin will also stop a 100 MeV proton. In a sense, the 40 MV Plasma Radiation Shield is the equivalent of 6 gm/cm^2 of solid shielding. Again, to stop a 150 MeV proton requires 19 gm/cm^2 of solid shielding. But a 40 MV Plasma Radiation Shield will cut a 150 MeV proton down to 110 MeV, and to stop a 110 MeV proton requires only 12 gm/cm^2. At this level, the 40 MV Plasma Radiation Shield is the equivalent of 7 gm/cm^2 of solid shielding.

We have assumed that one need only determine the total stopping power of any shielding combination in order to calculate its shielding

*For a space vehicle having a surface area of 4 x 10^{6}cm^2, 2-4 gm/cm^2 corresponds to total weights of 8,000 and 16,000 kg respectively.

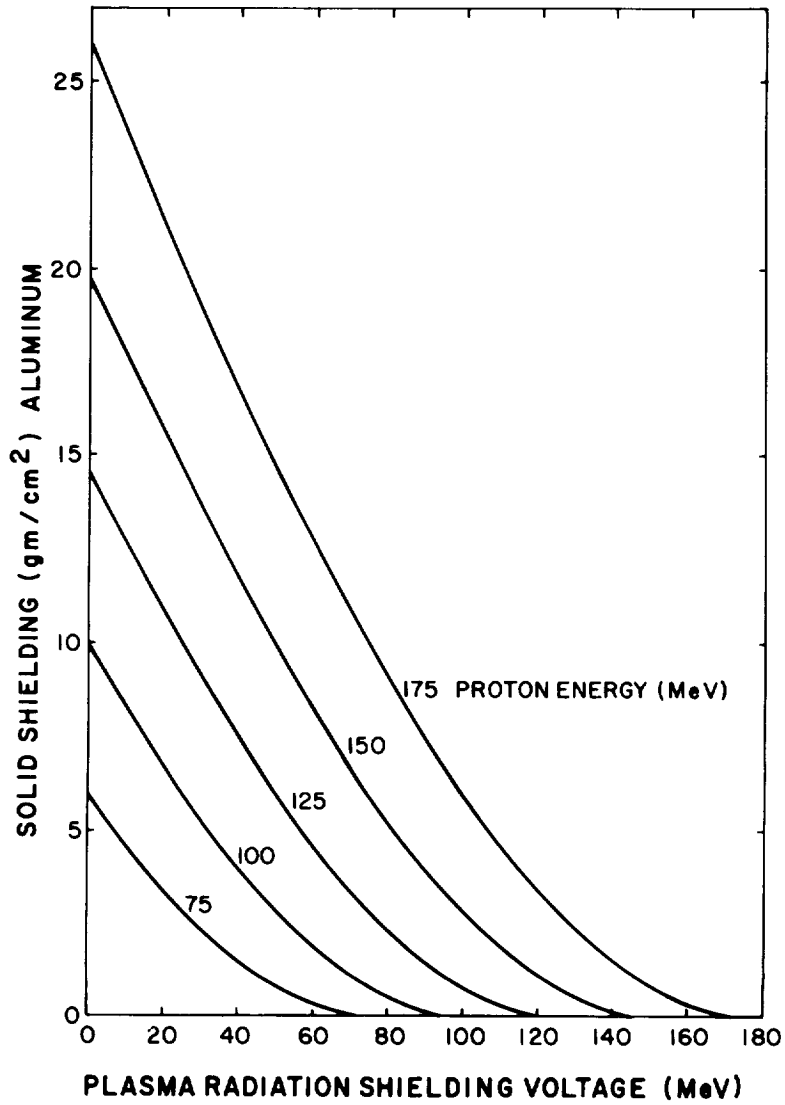


Fig. 4.1 "Range-Energy Tables" appropriate to a combination of electrostatic and solid shielding. Following the curves corresponding to a given proton energy, one may read off the different proportions of the two shielding components required to stop the proton. Note the great relative advantage of the first 20 or 30 MV of electrostatic shielding. Note also that the graph assumes the electrostatic potential is outside the solid matter. Reversing the order of the shields greatly reduces the effectiveness of a given combination.

A7431

effectiveness. This will, in general, be true where the incident spectrum is soft, because in this case nearly all the dose delivered at any point is given (since the spectrum is soft) by those particles which just arrive. However, it is not strictly true since different shielding combinations will differently affect the spectra of protons above the cut-off energy. This effect is exhibited in Fig. 4.2, and in Table 4.1. We consider, for example, a 60 MV Plasma Radiation Shield ahead of 2 gm/cm^2 of aluminum. Both these shields just stop 100 MeV protons; their different effects on more energetic protons are listed in Table 4.1. At energies above 100 MeV the composite shield removes more energy from the incident protons than the solid shield, but this effect is relatively small for very high energies.

To make these considerations more specific, consider an incident flux of protons having an integral spectrum in free space given by

$$I_0(>E_0) = I_{REF}\left[\frac{E_{REF}}{E_0}\right]^n \tag{4.1}$$

E_{REF} is any convenient reference energy (in MeV), and I_{REF} is the integrated flux of particles per sq. cm^2 having energies greater than E_{REF}. Later on, for a specific case, we shall choose $E_{REF} = 100$ MeV, and $I_{REF} = 10^8$ protons/cm^2, but these choices have no special validity.

The flux of particles in free space having energies between E_0 and $E_0 + dE_0$ is

$$-\frac{dI_0}{dE_0}\,dE_0 = n\,I_{REF}\left[\frac{E_{REF}}{E_0}\right]^{n+1}\frac{dE_0}{E_{REF}} \tag{4.2}$$

Let the Plasma Radiation Shield have a voltage V. There will then be no flux of particles behind the Plasma Radiation Shield whose energy E_0 in free space was less than V. The simplest model would be to consider the flux of particles with energy E_1, behind the Plasma Radiation Shield, to

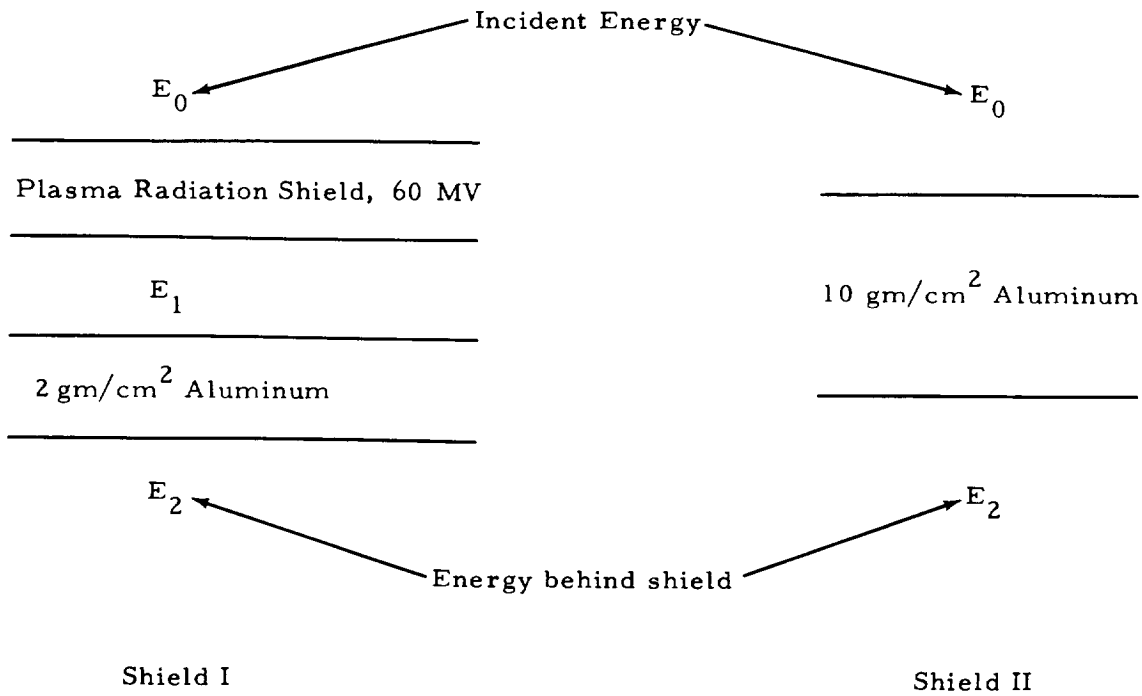


Fig. 4.2 Schematic diagram of two shields each having the ability to stop 100 MeV protons. Shield I consists of a 60 MV Plasma Radiation Shield ahead of 2 gm/cm^2 of aluminum. Shield II consists of 10 gm/cm^2 of aluminum. The different effects that these shields have on protons >100 MeV, and on the spectra of such protons are discussed in the text.

A7681

TABLE 4.1

Comparison of Shield Effectiveness

	Shield I		Shield II
E_2 Mev	E_1 Mev	E_0 Mev	E_0 Mev
0	40	100	100
20	47	107	102
50	67	127	115
100	110	170	149
150	158	218	190
200	206	266	232
500	502	562	522
1000	1001	1061	1020

equal the flux of particles with energy $(E_1 + V)$ in free space. However, this approach would yield a finite flux of particles with low energy behind the Plasma Radiation Shield and does not do justice to the properties of the electrostatic shield. Particles having an energy just greater than V in free space will be strongly deflected by the electric field, and can only penetrate it if their initial motion is accurately parallel to some electric field line. An estimate of the strength of this effect is that the flux of particles of energy $E_0 (> V)$ is reduced by the factor $(E_0 - V)/E_0$ in passing through the field. This factor is strictly correct for simple geometries and is probably at least representative for more complicated ones. It has the right general trend of emphasizing the deflection, or scattering phenomenon for particles with free space energy E_0 just greater than V. When E_0 is much greater than V, the deflection is insignificant, and the factor goes to unity. Use of this factor yields a differential flux behind the Plasma Radiation Shield given by:

$$- \frac{d I_1(E_1)}{dE_1} \, dE_1 = n I_{REF} \left[\frac{E_{REF}}{E_1 + V} \right]^{n+2} \frac{E_1 dE_1}{E_{REF}^2} \qquad (4.3)$$

For the present purposes we can roughly simulate the loss of energy of protons in matter by the equation

$$- \frac{dE}{dx} = \frac{k}{E} \qquad (4.4)$$

where x is in gm/cm^2. k is a constant, representative of the stopping material, and having the dimensions $(MeV)^2 cm^2/gm$. If the thickness of the solid shield in the composite arrangement is x_I, it will just stop protons of energy $E_1 = \sqrt{2kx_I}$. If E_1 is higher than this, the energy E_2 on emerging from the solid shield is $E_2 = \sqrt{E_1^2 - 2kx_I}$. The total stopping power of the arrangement is $V + \sqrt{2kx_I}$. The spectrum of energies

emerging from the solid shield is:

$$- \frac{dI_2(E_2)}{dE_2} dE_2 = n I_{REF} \left[\frac{E_{REF}}{\sqrt{E_2^2 + 2kx_I} + V} \right]^{n+2} \frac{E_2 dE_2}{E_{REF}^2} \tag{4.5}$$

If the thickness of Shield II is x_{II} gms/cm^2, the differential spectrum behind it is

$$- \frac{dI_2(E_2)}{dE_2} dE_2 = n I_{REF} \left[\frac{E_{REF}}{\sqrt{E_2^2 + 2kx_{II}}} \right]^{n+2} \frac{E_2 dE_2}{E_{REF}^2} \tag{4.6}$$

and the shields are comparable if

$$V + \sqrt{2kx_I} = \sqrt{2kx_{II}} \tag{4.7}$$

Choosing for Shield I $\sqrt{2kx_I}$ = 40 MeV and V = 60 MeV , and for Shield II $\sqrt{2kx_{II}}$ = 100 MeV, the differential spectra (4.5) and (4.6) are shown in Fig. 4.3. We have chosen two values of n , n = 2 (a hard spectrum), and n = 4 (a soft spectrum). We have also shown the differential spectrum (4.2) in free space. All these spectra are normalized to the quantity I_{REF}/E_{REF} , and we have chosen E_{REF} = 100 MeV, so that I_{REF} is the total flux of particles in free space with energies greater than 100 MeV. We observe that the composite shield passes less flux than the solid shield at all energies, and that the effect is more pronounced for the softer flare. This is because the electrostatic scattering factor $(E_0 - V)/E_0$ is more effective for the softer flare.

These flux calculations can also be converted into dose calculations if we neglect the variation of the RBE with energy. Using the assumption

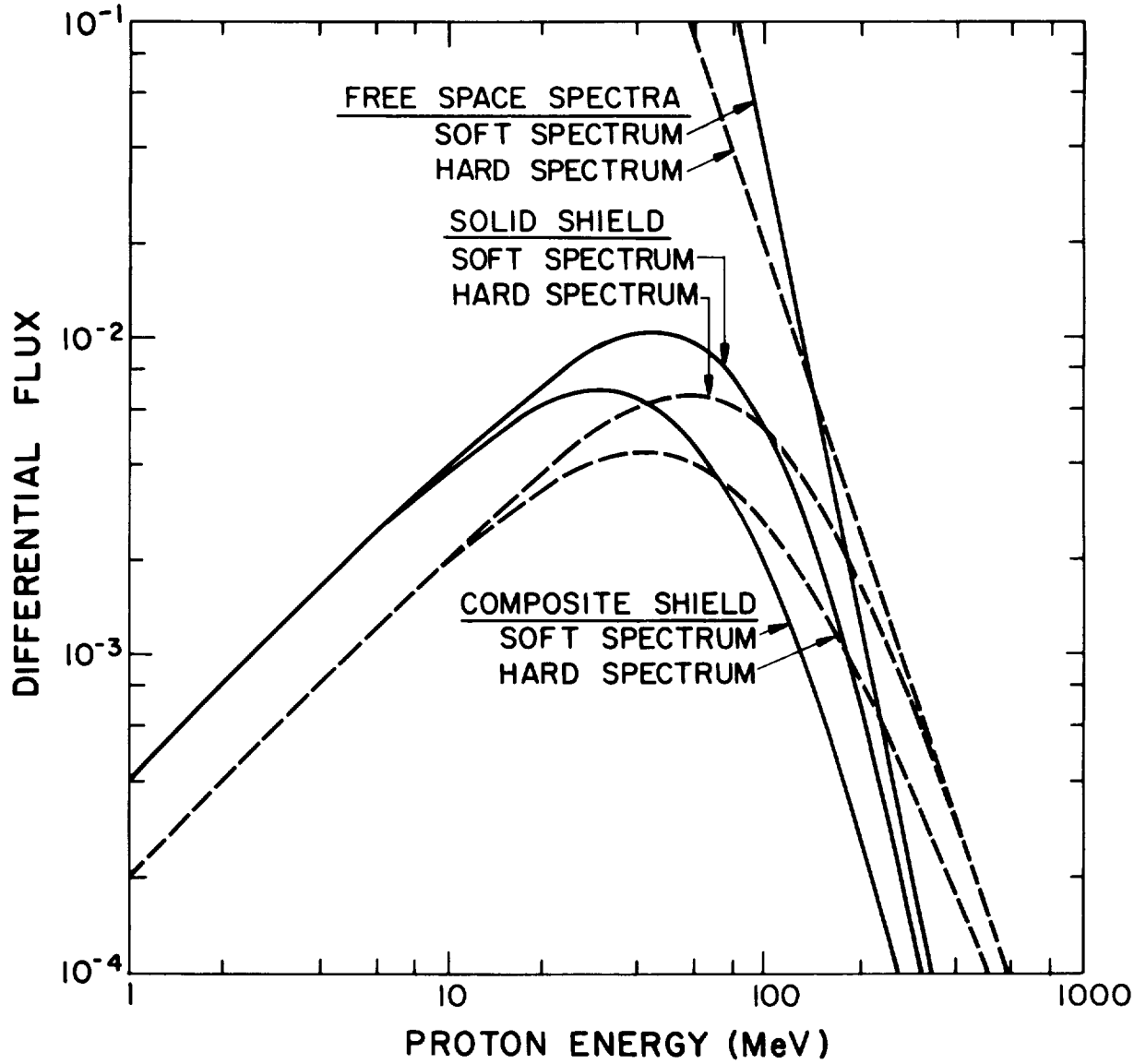


Fig. 4.3 Differential flux spectra behind the two shields illustrated in Fig. 4.2. The units of flux are protons/cm^2/MeV divided by the total flux of particles I_{REF} above 100 MeV. Two free space spectra are considered, a soft spectrum having $I(>E) \propto E^{-4}$ and a hard spectrum having $I(>E) \propto E^{-2}$. Both spectra are assumed to have the same total flux above 100 MeV.

A7454

(4.4) on the rate of energy loss of the protons, the total energy deposition per unit mass at the back of Shield I (composite) is just:

$$D = \frac{k}{E_{REF}} I_{REF} \int_0^\infty n \left[\frac{E_{REF}}{\sqrt{E_2^2 + 2kx_I} + V} \right]^{n+2} \frac{dE_2}{E_{REF}} \qquad (4.8)$$

Doses calculated in this way can be shown to be the point dose at the center of a sphere of radius x_I, and charged to a potential V, provided the flux in space is isotropic, with intensity $I_0/4\pi$ per steradian.

The energy deposition per unit mass of equation (4.8) is (owing to the units in which k is defined) in units of MeV/gm. However, this is easily converted, first to ergs/gm, and thence to rads, so that D is a measure of the radiation dose. To give an idea of the magnitude of the dimensional factor in Eq. (4.8) we can take $E_{REF} = 100$ MeV, I_{REF} (which is the number of protons above 100 MeV) $= 10^8$ protons/cm^2, and k appropriate to the range of 100 MeV protons in aluminum, i.e., 500 MeV^2 cm^2/gm. In this case the dimensional factor kI_{REF}/E_{REF} is, after changing units, approximately 8 rads. We introduce the notation

$$\sqrt{2kx_I} = E \qquad (4.9)$$

so that E is the thickness of the solid shield measured in MeV, we find:

$$\frac{D}{(kI_{REF}/E_{REF})} = n \int_0^\infty \frac{dy}{\left[\sqrt{y^2 + (E/E_{REF})^2} + V/E_{REF}\right]^{n+2}} \qquad (4.10)$$

Using this formula, we have calculated the dose as a function of E/E_{REF}, V/E_{REF}, and n. E_{REF} is just an arbitrary normalizing constant, so that the true parameters are E (the equivalent thickness, in

TABLE 4.2

$D/(k I_{REF}/E_{REF})$	E/E_{REF}	V/E_{REF}	$(E + V)/E_{REF}$
n=2 (Hard Spectrum)			
.021	0	3.175	3.175
.021	1.941	1.941	3.882
.021	4.225	0	4.225
.167	0	1.587	1.587
.167	0.971	0.971	1.941
.167	2.112	0	2.112
1.33	0	0.794	0.794
1.33	0.485	0.485	0.791
1.33	1.056	0	1.056
n=4 (Soft Spectrum)			
.005	0	2.737	2.737
.005	1.605	1.605	3.209
.005	3.397	0	3.397
.167	0	1.369	1.369
.167	0.802	0.802	1.605
.167	1.699	0	1.699
5.33	0	0.684	0.684
5.33	0.401	0.401	0.802
5.33	0.849	0	0.849

energy terms, of the solid absorber part of a composite shield), V (the voltage of the Plasma Radiation Shield part of a composite shield), and n , the spectrum index. As indicated at the beginning of this section, the most important parameter of any shield is the energy of the particle it will just stop. In our case, the composite shield will just stop a proton of initial energy (E + V) MeV. We have therefore shown, in Fig. 4.4, contours of constant dose D (non-dimensionalized as indicated in Eq. 4.10), on axes representing the total stopping power of the shield (E + V), and the Plasma Radiation Shield voltage V . On such a graph straight lines can be drawn to indicate constant values of the ratio of E to V . When $E \gg V$, the solid shield is thick and the Plasma Radiation Shield voltage is low, and vice-versa.

As expected, the dose is overwhelmingly a function of E + V , and only to lesser extent is it affected by the proportions of E and V going to make up E + V . Thus, for the soft spectrum (n = 4) , a factor of 2 change in E + V yields a factor of 32 change in D . For the hard spectrum (n = 2), a factor of 2 change in E + V yields a factor of 8 change in D . In spite of this basic dependence on E + V , however, there is a distinct reduction in the dose if, at constant E + V , the Plasma Radiation Shield voltage is raised and the solid shielding thickness reduced. Thus, for the soft spectrum at constant E + V , the dose for <u>pure</u> Plasma Radiation Shielding is 66% lower than the dose for <u>pure</u> solid shielding. But, since the skin of the vehicle is not negligible, this is an extreme case. If, instead of going to pure Plasma Radiation Shielding (E = 0) we go only as far as E = V, the dose is only 25% below the pure solid (V = 0) case — always at constant E + V . For the harder spectrum, these percentages are respectively 58% and 22%. But for the harder spectrum, the dose is not quite such a strong function of (E + V), so that these differences can be more significant. The differences are chiefly of importance in evaluating the skin dose just behind the skin of the space vehicle. The dose to organs located deep in the body is likely to correspond to $E \gg V$, so that the total stopping power (E + V) of the shield is the only parameter of significance. Some of the numbers calculated from Eq. (4.10) are listed in Table 4.2.

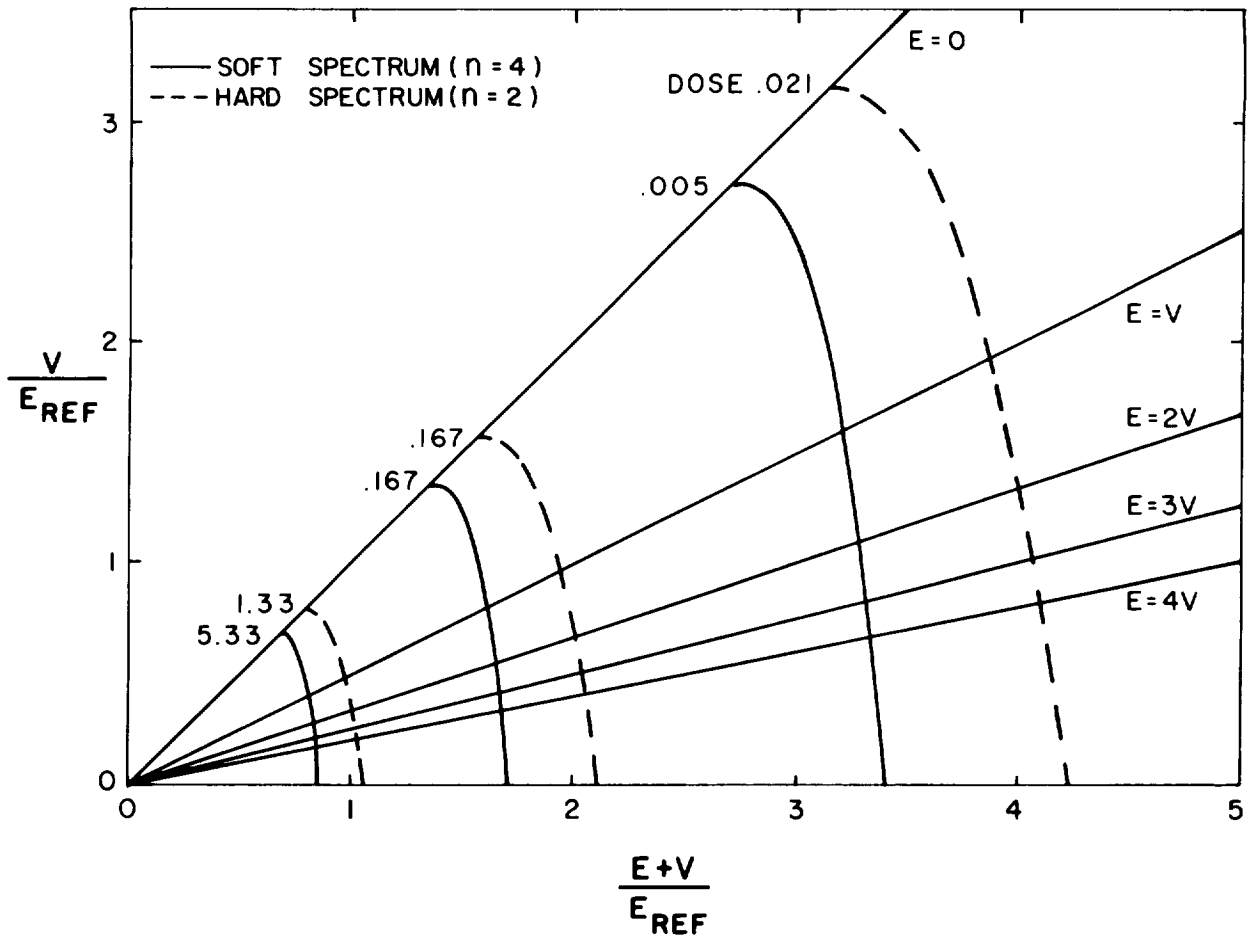


Fig. 4.4 Contours of constant dose behind shields having varying proportions of Plasma Radiation Shielding (at voltage V) and absorber (measured by the energy E of the proton which it will just stop). The doses are given in arbitrary units, which depend on the choice of a reference energy (E_{REF}) and a reference integrated flux (I_{REF}) of protons $> E_{REF}$. For E_{REF} = 100 MeV, $I_{REF} = 10^8/cm^2$, the unit of dose is roughly 8 rads. The two spectra used have the same total flux of particles above the energy E_{REF}. The dose is principally determined by the total stopping power (E + V) of the combination, but this is truer for the soft spectrum than for the hard one. The straight lines represent constant proportions of Plasma Radiation Shielding voltage V and absorber thickness E.

A7437

A point of unknown importance is the effect of the Plasma Radiation Shield on the production of secondary radiations. Although the efficiency with which energetic protons produce secondaries is a strongly increasing function of energy, the steep spectra associated with solar flares are thought to result in the lower energy particles producing the bulk of the secondaries. If this is true, the Plasma Radiation Shield will exhibit a further advantage, since the low energy protons will be deflected electrostatically and have no opportunity to produce secondaries. The relative magnitude of the dose due to secondaries in solid shields has been estimated[7] at 10% of the direct dose for thick shields.

Another factor whose importance remains to be evaluated is the effect on the flux of protons of the magnetic field. There may be a further reduction of the flux of particles of energy just greater than V due to this effect, but the magnitude of this reduction will depend on the configuration, and is presently unknown.

In conclusion, we have attempted to bring out the principal factors governing the choice of Plasma Radiation Shielding voltage. By far the most important parameter, from the dose point of view, is the total stopping power $(E + V)$ of the shielding system, including the vehicle skin. Final selection of the voltage must involve consideration of the total weight of a shielding system of given $(E + V)$, as E and V vary. It is likely that an optimum combination will be found, but it is too early to be precise about its location. In numbers our conclusion from Fig. 4.1 is that voltages in the general range 30-60 MV are likely to be attractive for shielding purposes.

5. CONFIGURATION RESTRICTIONS

As previously discussed, conditions on the magnetic field dictate that the shape of a space vehicle that utilizes the Plasma Radiation Shielding concept be a topological torus. However, this requirement is not as restrictive as one would initially suppose, and we will discuss some possible approaches that may be explored to satisfy this requirement. It should be borne in mind that the following discussion is intended to be heuristic rather than definitive, and it is hoped that this brief exposition will stimulate further ideas in this area.

Shown in Figs. 5.1A to F are some possible spacecraft designs that would satisfy the configuration requirements. It should be noted that their common feature is that they all contain a hole someplace. Fig. 5.1A shows a single element toroidal vehicle that is suitable for a small space station or interplanetary vehicle. Such a vehicle could have a maximum diameter of about 33 feet to fit the diameter of a Saturn S-II stage. This type of vehicle could be made from rigid material, with a minimum number of joints, and checked out for leaks on the ground. These last considerations are of particular importance for the Plasma Radiation Shielding concept for, as will be discussed in Section 7, the need for an extremely tight pressure vessel favors configurations with a minimum number of joints and a low wall porosity.

The maximum allowable size for the vehicle should not be limited by the diameter of the launch vehicle. One way of attaining growth potential while still retaining the basic toroidal shape is to use an inflatable torus that can be packaged into a small volume and deployed in orbit. Such a device, however, is probably not too practical as it would lack the requisite structural strength and rigidity, as well as probably being prone to leakage. A second way of attaining growth potential that appears more attractive is to use rigid modules to construct a large vehicle. One such possibility is illustrated in Fig. 5.1B which shows a larger space vehicle constructed from two rigid toroidal modules. The modules could be stacked up, for instance, on a

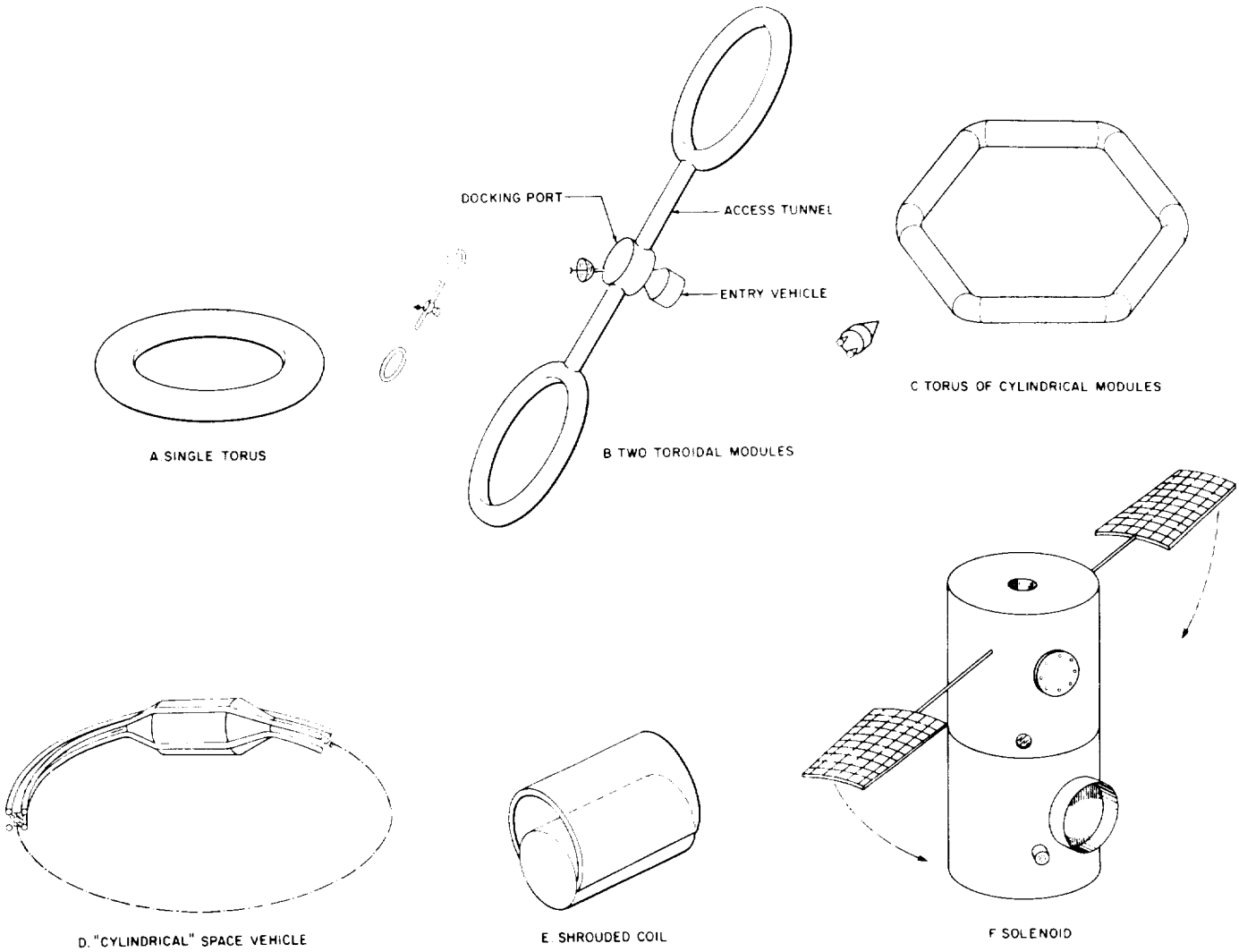


Fig. 5.1 Some possible configurations of spacecraft that utilize the Plasma Radiation Shield concept. In 'A' is shown the basic toroidal shape that may be most appropriate for small vehicles. In 'B' and 'C' are shown growth versions that may find application for intermediate and very large size vehicles. Configurations that are not geometrical toruses but which are acceptable from a topological point of view are shown in 'D' through 'F'. In 'D' is shown a design that utilizes a cylindrical vehicle with a coil that can be deployed in orbit, while in 'E' is shown a cylindrical vehicle with a coil contained in a rigid shroud-like structure. Illustrated in 'F' is a vehicle that utilizes the solenoid principle discussed in Section 3.6; such a configuration, if feasible, offers several potential design advantages.

A7789

Saturn S-II and assembled in orbit. The docking port and access tunnels could be of conventional construction, and detached from the systems when the Plasma Radiation Shield is activated. This configuration has the same advantages as the single module shown in Fig. 5.1A, with the additional advantage of a redundant shelter for crew safety in the event of a failure in one of the modules. If it is desired to use the system for a high altitude, earth-orbiting station, this configuration would provide some gravity gradient stabilization.

Another version of the multi-module approach is shown in Fig. 5.1C which shows several cylindrical elements joined together to form a six-sided torus. The cylindrical elements could be launch vehicle upper stages, and this configuration could serve as a very large space station. It may be noted that the vehicle in Fig. 5.1C is not too different from several designs that have previously been suggested, with the exception that the latter have generally included a central docking hub and access spokes to the toroid. However, because of the requirement that no magnetic field lines intersect the vehicle, such a variant is unacceptable here. The vehicle shown in Fig. 5.1C has the ability to provide a measure of artificial gravity for the crew by rotation about its axis.

There are also allowable spacecraft configurations that do not look like conventional toruses but still meet the requirements imposed by the Plasma Radiation Shielding concept. Three of these are shown in Figs. 5.1D to F. In Fig. 5.1D is shown a cylindrical type spacecraft with a field coil deployed from it. Such a coil could be deployed in orbit from a vehicle that may be similar to proposed MOL or Apollo Applications-type vehicles. Such an approach, however, presents several difficult problems in storing and erecting the coil in space, as well as in adequately supporting it once it is erected. This concept also does not make the most effective use of the field. The vehicle shown in Fig. 5.1E is a variation of that shown in Fig. 5.1D, with a shrouded coil replacing the deployable coil. This design eliminates the coil storage and deployment problems, and provides better support for the coil.

An interesting possibility is illustrated in Fig. 5.1F where the vehicle has many of the characteristics of a solenoid. (See also Fig. 3.4.)

The feature of this design is that the preponderance of electrons are concentrated in a relatively small hole through the center of the vehicle. Because of the low density of electrons along the field lines exterior to the vehicle, the outer surface may have less stringent requirements for leak prevention and protuberance control. Thus, as shown in Fig. 5.1F, the outer surface could contain solar panels, antennas, hatches, docking ports, telescopes, etc., and be of more conventional construction. The inner surface, however, would still require careful control of its leakage characteristics and surface smoothness. Although this approach has many attractive features, it should be emphasized that it is speculative, being dependent on the unproven assumption of electron concentration in the hole.

It has been mentioned above that the outer surfaces of the vehicles (with the possible exception of that shown in Fig. 5.1F) should be relatively smooth and free of protuberances. Just what constitutes an acceptable degree of smoothness requires further study, and this criteria might well strongly influence vehicle design and construction. Also influencing the configuration is the requirement for a structure to resist the magnetic field forces (a topic that will be discussed in Section 6).

6. SUPERCONDUCTING COIL SYSTEM

It is clear that our whole concept depends on the hope that large scale superconducting coils can be operated in space. It is easily demonstrated that the power requirements of any room temperature or cryogenic (not superconducting) electromagnet would be prohibitive for our application. Superconductors, however, have the property of dissipating no heat at all through resistive losses but they must be maintained at very low temperatures. To achieve very high magnetic fields, it is desirable to work at $4.2^{\circ}K$ (boiling point of liquid helium). But the Plasma Radiation Shield may be operated with relatively small fields over relatively large volumes. In this case it might be adequate to operate around $13^{\circ}K$* and use liquid hydrogen. It is quite possible that a space vehicle would have a liquid hydrogen system in connection with its propulsion. Thus this possibility may be quite attractive.

In the absence of ohmic dissipation in the field coils, the only requirement for power arises from the necessity of removing the heat that leaks through the thermal insulation. These powers are generally low, but since heat must be removed at very low temperatures and rejected at almost room temperature, refrigeration efficiencies are low. Notice, however, that the Carnot efficiency of a refrigerating cycle operating between $13^{\circ}K$ and room temperature is three times greater than the efficiency of a cycle operating from $4.2^{\circ}K$.

The current that must be carried by the coil is proportional to the required level of the magnetic field B, times a characteristic radius R of the magnet. From Eq. (3.3.1) the magnetic field intensity B is proportional to E/β. But the voltage V of the Plasma Radiation Shield is a more basic parameter than the level of the electric field, and scales as

*For example, Niobium-Tin has a critical temperature of over $18^{\circ}K$.

ER . Thus

$$I \propto \frac{BR}{\mu_0} \propto \frac{ER}{\mu_0 \beta c} \propto \frac{V}{\mu_0 \beta c} \tag{6.1}$$

and in a first approximation the current is independent of the size of the vehicle, although there is a dependence on the shape which it is not yet possible to calculate with much precision. For $V = 50 \times 10^6$ volts and $\beta = 1/2$, Eq. (6.1) yields a current of 3×10^5 amperes, but the actual current required might be several times this value. In particular, the attainable value of β is quite uncertain. In the rest of this section we shall use a total current of 3×10^6 ampere turns as a typical value, allowing a factor of 10 for the various uncertainties in Eq. (6.1).

Present-day superconductors are characterized by maximum current densities of about 10^4 amp/cm^2, but this figure has been increasing as a result of technical progress. If it is assumed that by the time the Plasma Radiation Shield is built current densities of the order of 10^5 amp/cm^2 will be available, then the cross-sectional area of superconductor required, $A_{s.c.}$, will be $10^{-5} I \, cm^2$. If $I = 3 \times 10^6$ amps, $A_{s.c.} = 30 \, cm^2$. The associated mass of superconductor, $M_{s.c.}$, is then

$$M_{s.c.} = 2 \pi R \rho_{s.c.} A_{s.c.} \tag{6.2}$$

$\rho_{s.c.}$ is the density of the superconducting material, and may be taken as 10 gms/cm^3 . The value of R depends on the coil configuration but will probably be in the neighborhood of 5 meters. Thus $M_{s.c.} \approx 930$ kg., subject to the uncertainty in I . The characteristic magnetic fields are several thousands of gauss.

The weight of the cryogenic system (insulation, refrigeration machinery, power supply and waste heat radiator) is directly proportional to the coil surface area, and inversely proportional to the absolute

operating temperature. For a single turn coil (Fig. 3.2), the area of the cryogenic surface is

$$A_{cry} = .7R(I/10^6)^{1/2} \ m^2 \tag{6.3}$$

For $I = 3 \times 10^6$ amps, $R = 5$ m. this is 6.6 m^2, and is less sensitive to the uncertainty in I than $M_{s.c.}$. The four-coil arrangement of Fig. 3.3, having one quarter the current in each of four coils, would have twice the cryogenic area, about 13.2 m^2. If the configuration of Fig. 3.4 used a winding distributed along the length of the solenoid, A_{cry} might be as much as 50 m^2. For a system operating at 4.2°K, the mass of the cryogenic system and the refrigerator power may be estimated from data presented in Fig. 6.1 (based on Ref. 36). From this figure it is seen that if $A_{cry} = 50$ m^2, the power required is 42 kw, and the mass of the system 750 kg. The weight of the power supply has been estimated using a figure of about 10 kg/kw. Operating at 13°K, the same system would require a power of 8 kw, and would weigh about 250 kg.

The third component in the superconducting magnet system, in addition to the superconducting coil and the cryogenic components, is the support structure necessary to contain the energy stored in the coil. The structural mass is determined by requirements to resist both tangential (or hoop) and meridional stresses in the torus (Ref. 36). The magnitude of the characteristic magnetic field has a strong influence on the structural weight since the weight varies as the square of the field strength. The stress level in the magnet is approximately equal to the magnetic pressure $B^2/2\mu_0$. For a magnetic field strength of about 3300 gauss, such as considered herein, the equivalent magnetic pressure is about 5 psi. Since this pressure is of the same order of magnitude as the cabin atmosphere pressure, the required structural problems are not contemplated to be severe. The actual stress pattern in a configuration like that of Fig. 3.3 would be quite complex and it is difficult to arrive at an accurate estimate for the structural weight. The structure of the solenoidal field coil

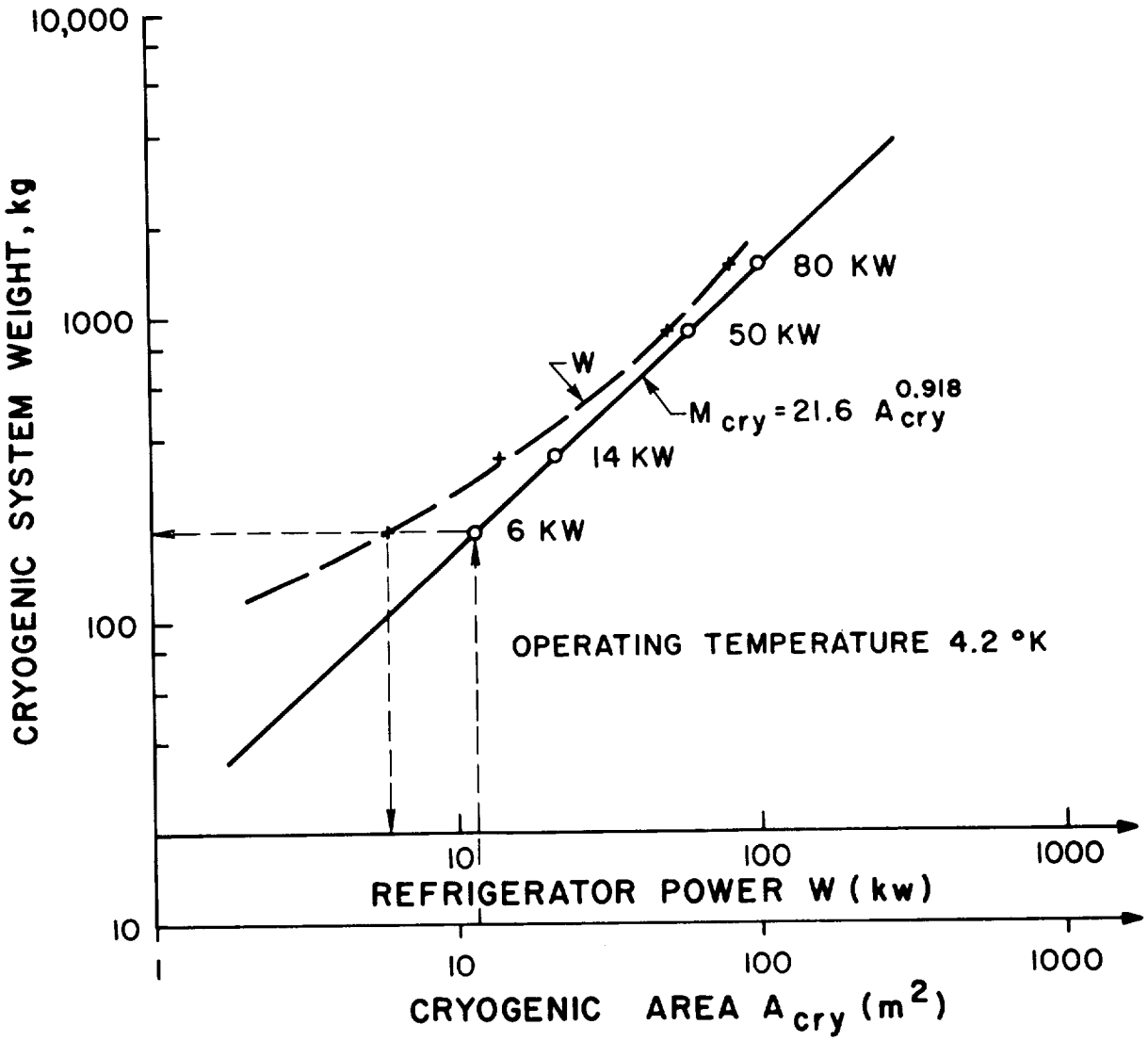


Fig. 6.1 Mass and required power for a cryogenic system comprising insulation, refrigerator, power supply and waste heat radiator. The weight of the last two was estimated using a conversion figure of about 10 kg/kw. The graph is for an operating temperature of 4.2°K. At 13°K, all powers and weights would be reduced by a factor of about 3 . The data is based on Ref. 36. As an example, suppose A_{cry} = 10.2 m^2. The solid line then indicates a system weight of 200 kg. Also, reading horizontally to the dashed line, and then down, the room temperature refrigerator power required is 7 kw.

A7590

associated with the configuration of Fig. 3.4 would be relatively simple. Only a small amount of work has been carried out in this area and much more remains to be done.

One last problem needs to be mentioned in connection with the design of the magnetic field. In general, one would like to design the coils so that the vast majority of the magnetic flux is where it is needed, that is, in the electron cloud and hence outside the space vehicle. In general, however, any particular coil design will have a certain level for the stray fields inside the space vehicle. These stray fields must be kept at low levels if they are not to interfere with the function of equipment sensitive to magnetic fields within the space vehicle; such things as cathode ray tubes, magnetic tape recorders and ferrites come to mind. The need to keep stray fields low would tend to produce a diffused coil design, such as the four-coil scheme shown in Fig. 3.3 or the solenoid of Fig. 3.4. Such designs, however, would entail a penalty in surface area (and hence refrigeration).

7. VACUUM REQUIREMENTS

It was pointed out in Section 3 that the ionization of neutral atoms by the electron cloud can constitute a serious source of loss; control of this source of loss requires that the outward flow of neutral gas originating in the space vehicle must be held to extremely low levels. The two primary sources of such gas are: 1) Outgassing from the outer surface of the space vehicle, and 2) Leaks from the interior. In this section we discuss first the factors determining allowable loss rates, and second, the effect of these rates on the design of the Plasma Radiation Shield.

7.1 Factors Controlling Allowable Leak Rates

In Section 3 we made a preliminary estimate of the allowable leak rate, but this was based on the most pessimistic assumption, namely, that each neutral emitted by the space vehicle was ionized right at the wall. When this happens, the ion thus formed carries away an energy corresponding to the full voltage of the Plasma Radiation Shield. On the other hand, our estimate of the mean free time of the neutral before ionization was 1 second; in this time the neutral is capable of crossing the electron cloud many times. For example, let the speed of the neutral be 10^5 cm/sec and let the size of the electron cloud be 10^3 cm. In this case, the mean potential at ionization will be on the order of 1% of the full potential; this results in a vacuum requirement 100 times less stringent than the most pessimistic case discussed above. To resolve the uncertainties arising in this way, it is necessary to take account of a number of factors. These factors are listed below, but, except for the last one (influence of the overall geometry), it is felt that the individual uncertainties are not very large. Later on, in the interest of offering definite numbers, we shall guess that the combined effect of all the factors does not amount to more than an order of magnitude, but additional work is required to justify this guess. The factors are:

1. The actual velocity of the neutrals. Here it is reasonable to assume that the neutrals leave the surface of the space vehicle with a Maxwellian distribution of velocities corresponding to the temperature of the surface. If the temperature of the surface is $15^{\circ}C = 288^{\circ}K$, the mean value of the velocity component normal to the surface for some typical gases is:

H	1.2×10^5 cm/sec
H_2	$.87 \times 10^5$
He	$.60 \times 10^5$
N	$.32 \times 10^5$
N_2	$.23 \times 10^5$
O	$.3 \times 10^5$
O_2	$.21 \times 10^5$

2. The spatial distribution of the electrons. The mean free time of 1 sec quoted above was a very rough average. In order to calculate this time correctly, we require (among other things) to know whether the electrons are in a dense layer near the space vehicle, or spread out over a considerable distance. The ratio of the size of the electron cloud x to the mean free path of the neutrals is roughly $xn\sigma v_e/v_n$ where the symbols stand for the size of the electron cloud, the electron number density, the ionization cross section, the electron velocity, and the neutral velocity. But xn_e is roughly proportional to the electric field at the wall of the vehicle, and this in turn is roughly proportional to ϕ_0/x, where ϕ_0 is the potential of the Plasma Radiation Shield. For a given potential, the ratio in question is smaller when x is relatively large. A more important ratio is that of the mean potential at ionization to the potential ϕ_0. However, to a first approximation, this ratio is similar to the ratio of lengths calculated above.

3. The distribution of electron velocities. This quantity has an important effect on the product σv_e which occurs in these calculations.

For electrons having kinetic energies significantly large compared to the ionization energy, the product σv_e varies roughly as

$$\sigma v_e \propto \frac{1}{v_e I} \ln \frac{\frac{1}{2} m v_e^2}{eI}$$

where I is an appropriate ionization energy. In general, the electron energies will be well above the ionization energy so that

$$\sigma v_e \propto \frac{1}{v_e}$$

roughly. Hotter electrons are therefore less efficient producers of ionization, and hence more desirable from our point of view. To a first approximation, the electron velocity is simply E/B, but superposed on this drift motion there is likely to be a "thermal" distribution at an unknown temperature. This thermal component is likely to be especially important near the outer edge of the electron cloud, where E/B is low. However, the effect of ionizations which occur near the outer edge is also low. Its magnitude is at present quite uncertain; this lack of knowledge may eventually require experimental study.

4. The species of neutral. This not only affects the expected neutral velocity, but also the ionization cross-section through the quantity I occurring in the above formula. In general, the heavier gases not only move more slowly through the electron cloud, but also have larger ionization cross-sections. However, it is easier to control the leakage of the heavier gases.

5. The overall geometry. The electric and magnetic field, the potential and the electron density have characteristic values, but can also vary quite widely as a function of position around the space vehicle. For

example, the electric field and the number density on the outside of the Plasma Radiation Shield (facing away from the axis) are substantially lower than those on the inside (facing towards the axis). The extreme possibility here is the solenoidal configuration of Fig. 3.4. If, as we hope, it turns out that the electron cloud is entirely confined to the region inside the solenoid, the whole vacuum problem becomes very much easier. For leaks from those parts of the surface not facing the electron cloud (i.e., the outer surface) are of no consequence, and we only have to restrict leakage from the inside of the solenoid. Thus, one would place all access doors, antennas and other protuberances on the outside. As stated in Section 3.6, the existence of this type of confined electron cloud has not yet been demonstrated.

The factors discussed above are not likely to achieve substantially better definition in the immediate future. It is therefore appropriate, in the spirit of this paper, to consider the effects of our rough estimates of allowable leak rates on the design of the Plasma Radiation Shield.

The allowable leak rates were estimated in Section 3, on the basis of two different assumptions, as the equivalent of 10^{-6} and 10^{-4} gms of oxygen in two days. Except for the configuration of Fig. 3.4, it is probably not reasonable to imagine that more than a further factor of 10 could come out of detailed consideration of the various factors enumerated above. This could give an upper limit to the leak rate of 10^{-3} gms in two days. To appreciate the magnitude of these figures let us compare them with comparable figures for past and planned manned vehicles. The Mercury vehicles experienced a leak rate of 2.24 lb/day = 1 kg/day (of air at 5 psia).[67] The internal volume of the Mercury vehicles was small, about 30 ft^3 (.85 m^3), so the leak rate per unit volume was about 7.5×10^{-2} lb/day/ft^3 (1.2 kg/day/m^3). It is anticipated that the latter figure for the Apollo vehicles will be improved by an order of magnitude to about 7.5×10^{-3} lb/day/ft^3 [68,69] (.12 kg/day/m^3). However, this vehicle will have a much larger internal volume so that the leak rate itself will not be an order of magnitude less than Mercury's. Clearly the Mercury-Apollo type construction would yield leak rates that are many orders of magnitude too large for the application in mind. However, for these vehicles no

particular attempt was made in the design to obtain low leak rates, for the principal penalty was to carry along a few extra pounds of air. At the very least it is obviously unreasonable to contemplate losses on the order of 1 kg/day for missions lasting several hundred days. Current thinking indicates that it is possible to obtain much lower leak rates than those quoted through careful design and a pre-launch program of leak detection.

7.2 Outgassing

If we suppose that the principal source of neutrals near the space vehicle is due to outgassing from the walls, then we can estimate an allowable effective pressure over the walls. The permitted current of atoms may be in the range 10^{12} to 10^{15} atoms/sec. Assuming a surface area of 3×10^6 cm^2, this gives a mean allowed flux of from 10^6 to 10^9 atoms/cm^2sec. By way of example, these fluxes correspond to a partial pressure of oxygen of 10^{-15} to 10^{-12} mm Hg at 15^oC. These levels imply that it will be necessary to apply very high quality vacuum technology to the design of the Plasma Radiation Shield. However, there are certain factors which make the environment in deep space exceptionally suitable for the application of this technology. There will, for example, be ample time to clean the surface thoroughly in the hard vacuum of outer space. This could be accomplished by baking out the entire surface while in space, to above 400^oC. On the basis of present knowledge, these procedures, if applied in space, should be extremely effective and should indeed result in outgassing rates of the right order of magnitude. Many metal materials are compatible with bakeout procedures of this type, and bakeout of the outer metal wall could be accomplished in earth orbit, before departure for deep space. It could also be accomplished before the vehicle was manned, although there need be no requirement for the temperature inside the vehicle to reach the bakeout temperature. Hydrocarbon or teflon seals cannot be baked to 400^oC, but ceramic seals can. It would be desirable to have more information on the achievement of very clean, outgassed surfaces in the space environment, but preliminary ideas suggest that this environment is uniquely suitable to our purposes.

7.3 Leaks from the Interior

At room temperature and pressure, the flux of oxygen through a small plane hole into a vacuum is roughly 10 gms/cm^2 sec or 1.7 x 10^6 gm/cm^2 in two days. On this simple-minded basis, it would appear necessary to restrict leaks to a total area of 10^{-12} to 10^{-9}cm^2, but several factors render this estimate unreasonably pessimistic. Principally, leaks generally involve long and narrow paths which offer considerable resistance to any flow. Possibly more important is the fact that the use of high quality seals and good high vacuum techniques should result in an essential elimination of leaks.

In spite of these possibilities it seems that it would be highly desirable to use a double-walled construction technique for the space vehicle. The inner wall would contain the atmosphere in which the crew would live, while the space between the two walls could be evacuated to a rather low pressure, say between 10^{-6} and 10^{-9} mm Hg. With pressures of this order in the space between the two walls, the leak through an aperture in the outer wall would be reduced to 2.3 x 10^{-3} gm/cm^2 to 2.3 x 10^{-6} gms/cm^2 in a period of two days. Thus, in the best case (allowable loss of 10^{-3} gms, and an inter-wall pressure of 10^{-9} mm Hg), it would be permissible to have holes in the outer vessel amounting to 1000 cm^2! In the worst case (allowable loss of 10^{-6} gms, and an inter-wall pressure of 10^{-6} mm Hg), plane holes in the outer vessel should not exceed 10^{-3} cm^2. The comment above on long, narrow leakage paths also applies here.

The double-walled construction suggested above has several very attractive features:

1. Double-walled construction is highly favored as a protection against puncture of the pressure vessel by large micrometeorites. In addition to contributing materially to the stopping power of the wall, the construction provides some degree of fail-safe protection of the cabin atmosphere.

2. Pumping in the space between the walls to maintain a low pressure in this region would in any event not be difficult. It is particularly assisted in the present case by the presence of the cryogenic system associated with the superconducting coils. This system normally comprises

a liquid nitrogen container surrounding the liquid helium; surfaces at liquid nitrogen temperatures should effectively trap all the heavy gases leaking out through the inner wall, and reduce the pressure of all other gases that might be present.

3. Double-walled construction with inter-wall pumping relieves the problem of leaks to such an extent that the use of standard polymer or teflon seals should be quite satisfactory for the inner vacuum barrier.

Although any form of high vacuum pump could be used to keep the pressure low between the walls, a particularly attractive prospect might be to utilize the existing magnetic field to turn part of the space between the walls into a sort of Vac-Ion Pump. This would involve maintaining a moderate electric potential between a cathode and an anode, and using a circulating electron beam to ionize and pump any residual neutrals. A particularly attractive possibility associated with the configuration of Fig. 3.4 is that the outer wall need only cover that part of the surface facing the electron cloud, i.e., the interior. Thus, if the outer wall were not continued on the outside part of the surface, the infinite pump of outer space would be available to pump from the inter-wall region on the inside surface.

7.4 Summary

The Plasma Radiation Shield will require a clean outgassed outer surface and a double-walled pressure vessel with a pressure of roughly 10^{-6} to 10^{-9} mm Hg in the space between the walls. The exact requirements cannot yet be stated with much precision, but do not appear excessively difficult. The space environment is especially favorable to the achievement of clean surfaces and high vacuum, and the double-walled construction has subsidiary advantages. On the other hand, this construction presents many novel design problems to the space vehicle designer. The requirements for low permeability walls and ground detection of leaks indicate that a welded, metal construction will be necessary. Such a construction is rigid and places limitations on packaging within the launch vehicle as well as on the manner in which the system can grow. It will also require careful consideration of the placement and design of cutouts in the pressure vessel

walls, and in the design and selection of material for the seals around these cutouts.

In addition to the prevention and careful control of leaks, care must be exercised in allowing no other type of expirations from the vehicle during a solar flare. This has ramifications in design of such systems as power supply, attitude control, propulsion, life support, etc. Such systems should either be chosen to not have an exhaust or, if they do, to be inoperative during a solar flare. A possible exception to these considerations is the configuration of Fig. 3.4.

A preliminary conception of the double-walled construction is shown in Fig. 7.1.

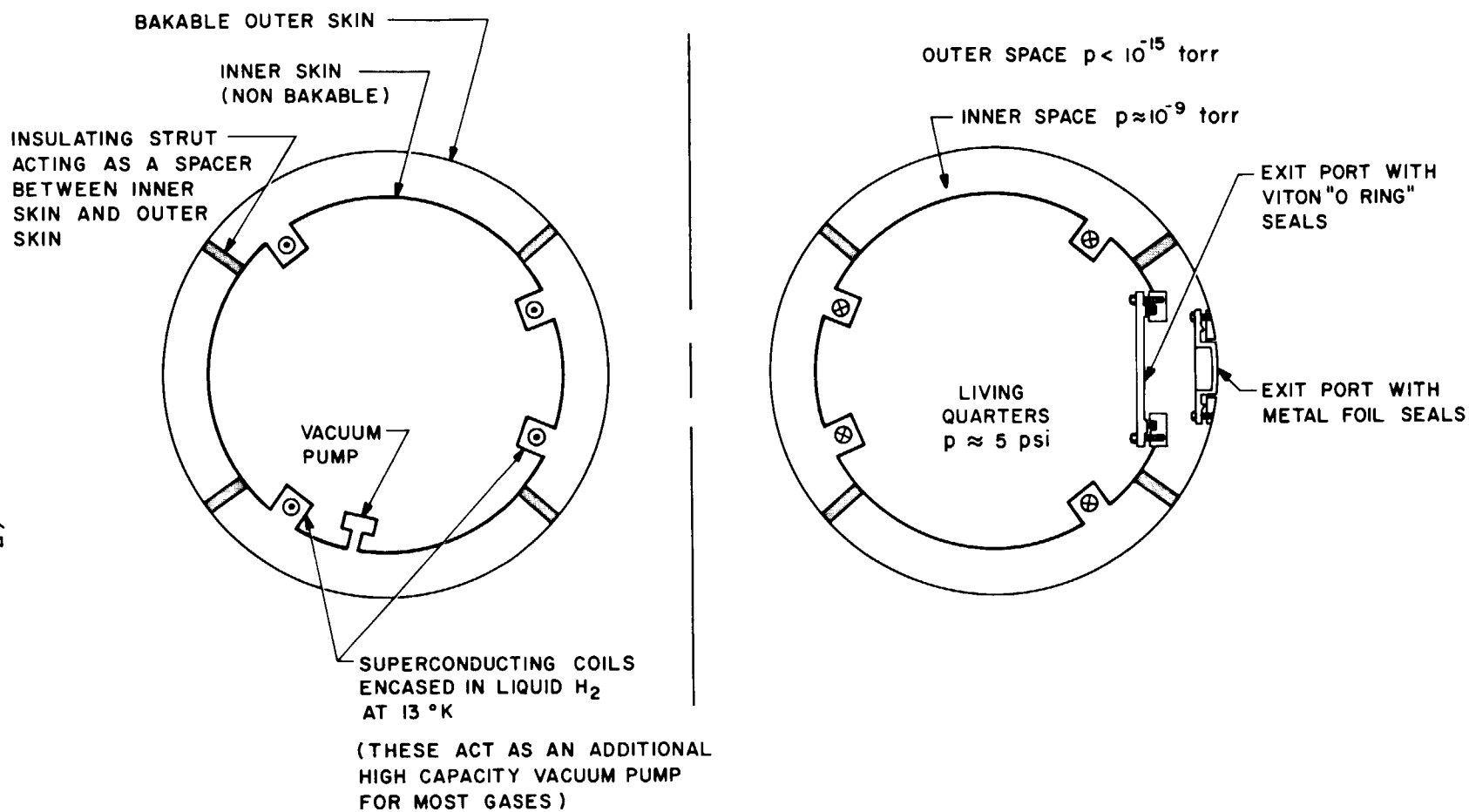


Fig. 7.1 Shows schematically one out of the many possible ways in which the double-wall concept could be applied to a toroidal space vehicle using a Plasma Radiation Shield. The space between the walls is kept at a pressure like 10^{-9} torr by a combination of vacuum pumps pumping into the interior and the low temperature environment of the superconducting coils.

A7647

8. OTHER SYSTEMS CONSIDERATIONS

The design of other subsystems that go into the total spacecraft system will also be influenced by the requirements imposed by the Plasma Radiation Shield. Several of these systems that are most obviously influenced will now be discussed, and possible design approaches suggested.

8.1 Magnet Charging Power Supply

The total electric field energy is $\frac{1}{2} CV^2$ where C is the effective capacity of the space vehicle and electron cloud. If we guess that C is 10^{-9} farads, the stored electric energy at 50×10^6 volts is 1.25×10^6 joules. The magnetic energy is larger than this by roughly β^{-2}, so that if $\beta = \frac{1}{2}$ the magnetic energy is 5×10^6 joules. These total figures are subject to considerable uncertainty both as regards the capacity and the value of β. We shall suppose, for purposes of illustration, that the uncertainty is a factor of ten, and take a representative magnetic field energy as 50×10^6 joules.

The maximum time allowable to energize these fields is of the order of the time interval between first detection of the flare and the first arrival of appreciable particle flux. If this time is taken as 1-1/2 hr, the power that must be supplied during this time is about 10 kw for a 50 MV 50 M joule system. (This figure is in addition to steady power requirements for the cryogenic system, and typically about 5 to 10 kw for other spacecraft needs.) The power source for field energization must be operative during every major solar flare (maybe ten times during a mission) and must not (except possibly in the configuration of Fig. 3.4) vent exhaust gases to the exterior during its operation. The latter requirement rules out several otherwise likely candidates, and a very large solar cell array is ruled out because it would cut through magnetic field lines. A class of power sources that meet these requirements and can be available in the time period of interest is the fuel cell. Two types of fuel cells may be considered for the application discussed here – the hydrogen-oxygen and the lithium-chlorine

types. The hydrogen-oxygen fuel cell is currently available for powers of a few kilowatts. These devices give off easily-storable water as a by-product of the reaction, and operate optimally at a relatively low temperature (90°C). A 2 kw unit will soon be available that weighs 146 lbs.[70] If more power is necessary, the power supply should have a lower specific weight. Taking hydrogen and oxygen consumption rates of 0.1 and 0.8 lb/kw-hr, respectively, the weight of the fuel cell reactants for the mission is then

$$w_f = (0.1 + 0.8)\,\frac{\text{lb.}}{\text{kw.hr.}} \times 1.5\text{ hr} \times 10\text{ kw} \times 10\text{ applications} = 135\text{ lbs.}$$

Including the tankage, the total weight of the power supply using hydrogen-oxygen fuel cells should be around 1500 lbs for the 10 kw level, and would scale roughly as the field energy. Lithium-chlorine fuel cells are still in development but offer the promise of high power levels for short times at low weight. Aside from their present unavailability, a disadvantage to this type of fuel cell is their high operating temperature, 650°C. A reasonable energy density figure to be expected from these cells for a 10 kw system with an operating time of 1-1/2 hr is about 200 w-hr/lb.[71,72] Using 10 of these units for the mission would result in a total power supply system weight of about

$$W = \frac{10{,}000\text{ w} \times 1\text{-}1/2\text{ hr}}{200\text{ w-hr/lb}} \times 10\text{ applications} = 750\text{ lbs.}$$

In summary, it appears feasible to use hydrogen-oxygen or lithium-chlorine fuel cells for the power supply with system weights of less than 1500 lbs. Integration of the magnet charging power supply with the general spacecraft power system would result in a lower weight assignable directly to the Plasma Radiation Shield, because the specific weight of such power systems is smaller for larger powers.

8.2 Communications

It is very desirable, if not essential, for the crew to be able to communicate with the outside while the Plasma Radiation Shield is in operation. With the exception of the configuration of Fig. 3.4, this must be accomplished by transmission through the electron cloud that surrounds the space vehicle, and without the use of lengthy antennas. To do this in the radio range requires a frequency above the plasma frequency, ν_0, given by $\nu_0 = 9 \times 10^{-3}(n_e)^{1/2}$ with ν_0 expressed in megacycles per second, and n_e, the electron density, in electrons per cubic centimeter. For $n_e = 2.1 \times 10^8$ per cm^3 (Section 3.2), the plasma frequency is 130 Mc/s. Thus, transmissions at higher frequencies (such as commonly-used S-band) would be possible. Another means of communication that could be considered is by laser beam, since it is anticipated that this type of communication, with its promised high data rate, will be available in the time period of interest.

8.3 Attitude Control and Propulsion

The attitude control and the propulsion systems are constrained not to have an exhaust while the Plasma Radiation Shield is in operation. If it is necessary to change vehicle attitude during a solar flare, such a change could possibly be affected by the use of devices such as momentum wheels. If chemical or nuclear rockets are used as the main propulsion system on the space vehicle, it would seem that the probability of having to fire them during a solar flare would be somewhat small. If, however, the propulsion unit is a system that depends on attaining a desired impulse by a small thrust applied over a long time, the system would be required to be shut down while the Plasma Radiation Shield is in operation.

8.4 Life Support

In regard to the crew and their life support, the ecological system must be of the closed-cycle type, at least for the duration of the flare. Although the Plasma Radiation Shield concept requires the magnetic field to be external to the spacecraft, it is fairly certain that some stray, extraneous fields are bound to exist within the spacecraft interior. While the level of these stray fields can be reduced arbitrarily, stringent requirements on the allowable level will cause the magnet weight to rise. It is therefore

worthwhile to examine the effects of these fields on the crew and on internal equipment.

Medical evidence has been negative as to the effects of magnetic fields, at least of the magnitudes anticipated in the spacecraft, on human beings.[73] The effects of magnetic field gradients are somewhat more obscure but it is felt that gradients of the magnitude occurring in the spacecraft will also be safe for humans.

8.5 Effect of Stray Magnetic Fields on Electronic Equipment

With respect to the effects of these stray magnetic fields on internal electronic devices, the situation is not so optimistic. It is anticipated that field strengths could conceivably be strong enough to require shielding or careful positioning of devices such as tape recorders and oscilloscopes.

9. CONCLUSIONS

We have reviewed in some detail the various features of the Plasma Radiation Shield concept likely to be important in any systems analysis of a space vehicle using the Plasma Radiation Shield. In summing up our findings, the point of departure must be the following observation: there still remains a wide range of opinions on the magnitude of the threat posed by solar flare protons to astronauts. Our premise is that a substantial problem exists. Since estimates of the solid shielding required are high, the possibility of reducing shielding weight by using the Plasma Radiation Shield is attractive.

Pending the satisfactory resolution of several questions, the possibility of realizing the advantages offered by the Plasma Radiation Shield must remain in doubt. The outstanding questions fall into two distinct categories:

1) Questions associated with the fundamentals of the concept itself, such as the attainability of very high voltages, and the stability of the electron cloud.

2) Questions associated with the integration of a Plasma Radiation Shield into a space vehicle. The Plasma Radiation Shield makes demands on the vehicle design in areas of overall configuration, power supply, and leak control, to name only the most important.

At this point, it is possible to be guardedly optimistic about the questions in the first category. No insuperable difficulties have been found, but affirmative statements cannot be made without further experimental and theoretical studies. It is particularly important to establish the maximum permissible value of $\beta = E/cB$, since this parameter determines the strength of the magnetic field and hence the weight of the magnet. In estimating the weight of a Plasma Radiation Shield, the magnet is by far the most important component.

As regards the second category of questions, these reduce to definite quantitative requirements which must be met by any space vehicle incorporating the Plasma Radiation Shield. The most important questions are those of overall configuration, and control of leaks.

It was stated in the preface that this paper was regarded as preliminary to a deeper systems analysis of the Plasma Radiation Shield. It is therefore appropriate to make some remarks here on the basic problems likely to be encountered in such an analysis. Now a primary goal of such a systems analysis will be a reliable graph of weight vs. shielded volume. This is because unless such a graph can be developed, the advantages of the Plasma Radiation Shield over solid shielding cannot be exhibited in a quantitative manner. It was explained above that the weight will remain uncertain until the allowable value of β can be established. However, it is also true that the shielded volume of different configurations cannot yet be given with much accuracy; it is even more true that for a given configuration, the dimensions cannot be optimized to yield a minimum magnet weight per unit shielded volume. We are now in a position to calculate the shielded volume for a variety of configurations, but the calculations are difficult and have not yet been undertaken. Clearly, such calculations must constitute the first step in a detailed systems analysis.

In summary, the Plasma Radiation Shield still appears to offer the promise of substantial reductions in shielding weight. More work in several areas will be required in order to show that these reductions can be realized.

10. ACKNOWLEDGMENTS

It is a pleasure to acknowledge the assistance of G. S. Janes and J. D. Daugherty in connection with several parts of this paper. We are indebted to Dr. John C. Helmer of Varian Associates, Palo Alto, California for permission to use Figs. A.1 and A.2, and to Mr. A. Reetz of NASA, Washington, D. C. for supplying the figures appearing in Table 2.1.

Appendix

Status of Work on the Electron Cloud

A.1. Introduction

The current status of work on the electron cloud is as follows:

1. Theoretical work[47-53] has thus far failed to find any reason why a stable dynamic equilibrium for the electron cloud should not exist. This "double negative" statement is the best that can be made, since, in a problem as complicated as that of the electron cloud, a positive theoretical proof of stability is virtually impossible. There have, nevertheless, appeared certain conditions that the electron cloud must satisfy if it is to be stable. The most important of these are:

   a) the number density n of the electrons, and the magnetic field strength B must satisfy the condition

$$\frac{ne}{\epsilon_0 B^2} \lesssim \frac{1}{30} \tag{A.1.1}$$

   b) the inner edge of the electron cloud must be rather close to the surface of the Plasma Radiation Shield.

2. It has been observed that the electron cloud in the Plasma Radiation Shield closely resembles the electron cloud in a high vacuum pump (the Vac-Ion Pump). Encouraging conclusions may be drawn from the apparent stability of the electron cloud in this pump.

3. Several experiments[49, 74] have been performed to study the electron cloud, although none has been in the geometry of the Plasma Radiation Shield. One of the objects of these experiments has been the demonstration of high voltages using the inductive charging system. In an electron cloud 10 cm. in radius, voltages in excess of 80,000 have been

demonstrated; the achievement of higher voltages presently awaits development of the means to measure them.

A.2 Theoretical Work

It is a relatively easy matter to find dynamic equilibria for the electron cloud under the assumption that the motions of the electrons are adequately represented by the "guiding center" approximation:

$$\underset{\sim}{v}_e = \underset{\sim}{E} \times \underset{\sim}{B}/B^2 . \qquad (A.2.1)$$

In configurations with axial symmetry, both the electric and magnetic field vectors lie in the meridional plane, so that the velocity vector is in the azimuthal direction. Then, if the number density of electrons is independent of the azimuth (the symmetrical situation) the condition

$$\text{div } \underset{\sim}{j} = - \text{div } n_e e \underset{\sim}{v}_e \qquad (A.2.2)$$

on the current is trivially satisfied. It is necessary, however, to require that the electric potential be such that the magnetic field lines are equipotentials. This can be done as follows: since $\text{div } \underset{\sim}{B} = 0$ we can write (in r, θ , z coordinates)

$$B_r = \frac{1}{r} \frac{\partial \psi}{\partial z} \qquad B_z = -\frac{1}{r} \frac{\partial \psi}{\partial r} \qquad (A.2.3)$$

the surfaces $\psi(r, z) = \text{constant}$ are then the field lines since along such a surface

$$O = d\psi = \frac{\partial \psi}{\partial r} dr + \frac{\partial \psi}{\partial z} dz = -r [B_z \, dr - B_r \, dz] \qquad (A.2.4)$$

$$\frac{B_r}{B_z} = \frac{dr}{dz} \quad . \tag{A.2.5}$$

If we then require the potential $\phi(r, z)$ to have the form

$$\phi(r, z) = F[\psi(r, z)] \tag{A.2.6}$$

where F is an arbitrary function, all the necessary conditions are satisfied. The number density can be obtained from (A.2.6) through Poisson's equation. It is then only necessary to restrict the range of functions F by the condition that the number density be everywhere positive.

Inasmuch as the equation (A.2.1) is a very good approximation to the electron dynamics in the Plasma Radiation Shield, it is expected that equilibria derived by the method just described will be very close to true equilibria of the whole electron cloud.

Having exhibited the possibility of equilibria, we turn next to the much more difficult problem of stability. As stated in the introduction, stability analysis can in general only arrive at negative statements. Thus, one can prove that such and such a mode is stable, but, in complicated systems, one can never be sure that all the important modes have in fact been dealt with. With these reservations, we can make the following general statements: In general, we expect stability trouble to occur at or near characteristic frequencies of the medium. For our electron plasma there are three such frequencies, namely, the electron gyro frequency

$$\omega_c = eB/m \tag{A.2.7}$$

the electron plasma frequency

$$\omega_p = (ne^2/\epsilon_0 m)^{1/2} \tag{A.2.8}$$

and the frequency with which the electrons circulate around the space vehicle

$$\omega_0 = E/BR \quad . \tag{A.2.9}$$

In view of the connection between the electron number density and the electric field, these frequencies are related by the following approximate formula:

$$\omega_p^2 = \omega_0 \omega_c \quad . \tag{A.2.10}$$

A convenient non-dimensional number is the ratio

$$q = \frac{\omega_p^2}{\omega_c^2} = \frac{nm}{\epsilon_0 B^2} \quad . \tag{A.2.11}$$

In terms of this ratio, our frequencies can be ordered as follows:

$$\omega_0 : \omega_p : \omega_c \equiv q : \sqrt{q} : 1 \tag{A.2.12}$$

Now for the Plasma Radiation Shield q is a small number, on the order of 10^{-3}. It follows that the frequencies listed in (A.2.12) are in ascending order, with a factor ~ 30 between each pair.

All these frequencies are high, however, ω_0 being in the range of 3Mc/sec or so. Hence any instability having a growth rate of even a fairly

small fraction of these frequencies would be disastrous.

Our findings for the three frequency ranges are as follows:

a) The gyro frequency: Here there is apparently always an instability. However, the growth rate of this instability is on the order of $\omega_0 \cdot e^{-2/q}$. For $q = 10^{-3}$ and $\omega_0/2\pi = 3$ Mc/sec., this gives an exponentiating time longer by far than the age of the universe! This is not a "fairly" small fraction of ω_0 and represents a growth so slow as to be quite unreasonable. This instability is of interest only for $q \gtrsim 1/30$.

b) The plasma frequency: Analysis in this region is not yet complete, but it appears that there is no important instability here.

c) The frequency $\omega_0 = \omega_p^2/\omega_c$: The instability that is important in this range is called the "diocotron instability." It appears, on the basis of a considerable amount of work, that this instability can be avoided in the Plasma Radiation Shield configuration provided that there is not too large a gap between the inner edge of the electron beam and the conducting wall of the Plasma Radiation Shield.

Thus, the results of our stability analysis, while not conclusive, are encouraging. We turn next to the empirical and experimental evidence in favor of the stability of low-q crossed-field electron beams.

A.3 Empirical Evidence

Two important devices depend upon crossed-field electron beams — the microwave magnetron and the low density Penning discharge as applied, say, in the Vac-Ion Pump.[54,75] These devices are geometrically rather similar: both have cylindrical anodes and axial magnetic fields. It is a striking fact that while both devices are thoroughly successful, the magnetron works because an inherent instability of the electron beam makes it possible to extract considerable microwave power, while the Vac-Ion Pump works because the beam is extremely stable; this stability results in long containment times for the electrons which are therefore quite effective at pumping.

It can be shown that the principal difference between these devices are the value of q. For the magnetron, q is characteristically a few tenths.

For the Vac-Ion Pump, q is generally $\sim .07$ or less. The instability described in the previous section having a growth rate $\omega_0 e^{-2/q}$ is of the utmost importance for the magnetron and is altogether negligible for the Vac-Ion Pump. Naturally, at still smaller values of q this instability is "even more negligible." It appears that the Plasma Radiation Shield can be considered as a scaled-up Vac-Ion Pump. As such, it may be hoped that it will exhibit the same remarkable degree of stability.

Fig. A.1 is a schematic drawing of the Vac-Ion Pump, taken from an article by Helmer and Jepsen.[54] Fig. A.2 is characteristic of the calibration curves associated with these pumps. The most striking feature of Fig. A.2 is the roughly linear relationship existing between the gas pressure in the device and the current drawn. This linear relationship is an indication that nothing other than classical diffusion of the electrons by collisions with the neutrals is taking place. Knowing the voltage applied across the device and its characteristic size, it is possible to estimate the total number of electrons contained in it. Then, on dividing by the current, one obtains an estimate for the containment time. At a pressure 10^{-6} mm Hg, this containment time is approximately 10^{-3} secs. For the Plasma Radiation Shield, in the vacuum of space, a pressure of 10^{-14} mm should lead to the required containment time of 10^5 secs, or about a day.

A.4 Experimental Work

A number of experiments related to the Plasma Radiation Shield have been carried out. However, none of these has been in the geometrical shape of the Plasma Radiation Shield, for the following reason: the topology of the Plasma Radiation Shield (see, for example, Fig. 3.3) cannot be used in a simple way in a laboratory experiment, since the supporting strut which must necessarily be used is certain to interrupt the drift of the electron cloud.

The first experiments on the containment of electron clouds are described in Refs. 49 and 74. Here, we shall give a very brief description of the most recent experiment. This is an "inside out" torus, shown schematically in Fig. A.3, and photographically in Fig. A.4. The object of the experiment is to exhibit the containment of electron plasmas for

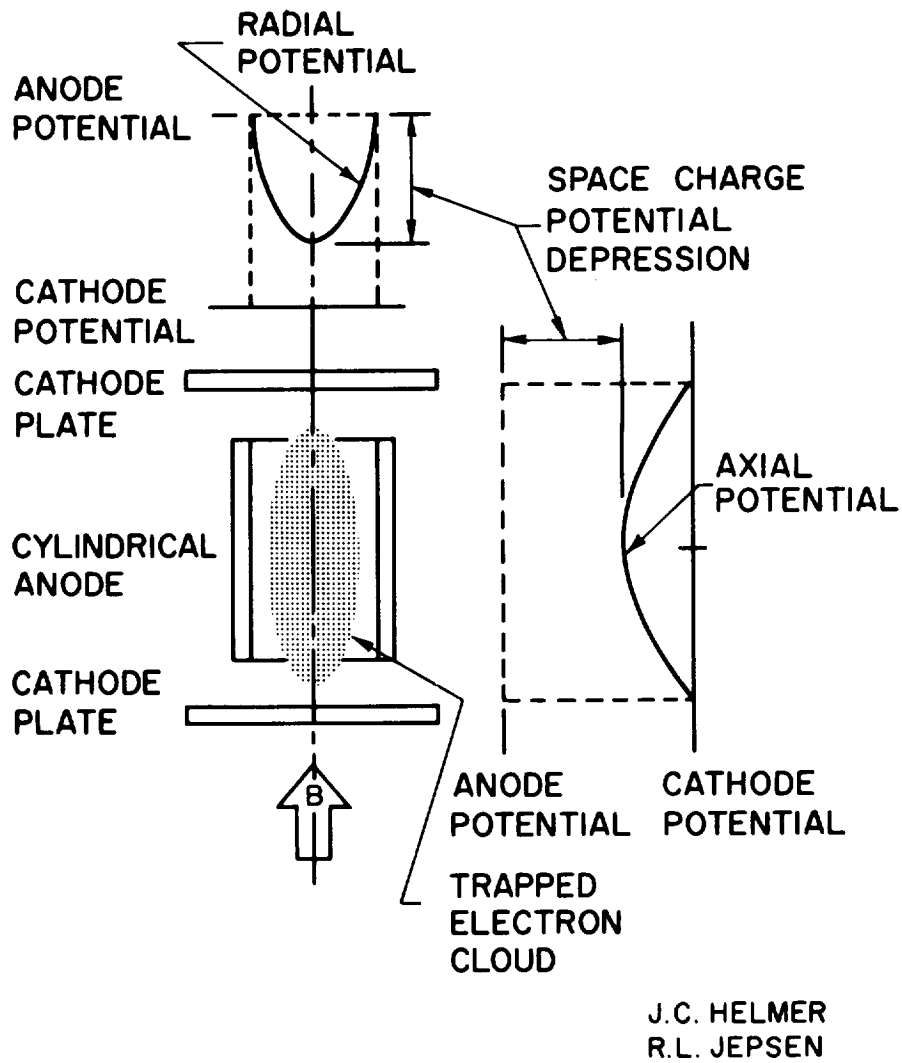


Fig. A.1 Schematic diagram of a Vac-Ion Pump taken from Ref. 54. The dynamics of the electron cloud in this device are very similar to the dynamics of the electron cloud in the Plasma Radiation Shield, since the value of $q = \omega_p^2/\omega_c^2 \lesssim 1/30$. The stability of the electron cloud in this device is clearly implied by the calibration curve shown in Fig. A.2.

A5474

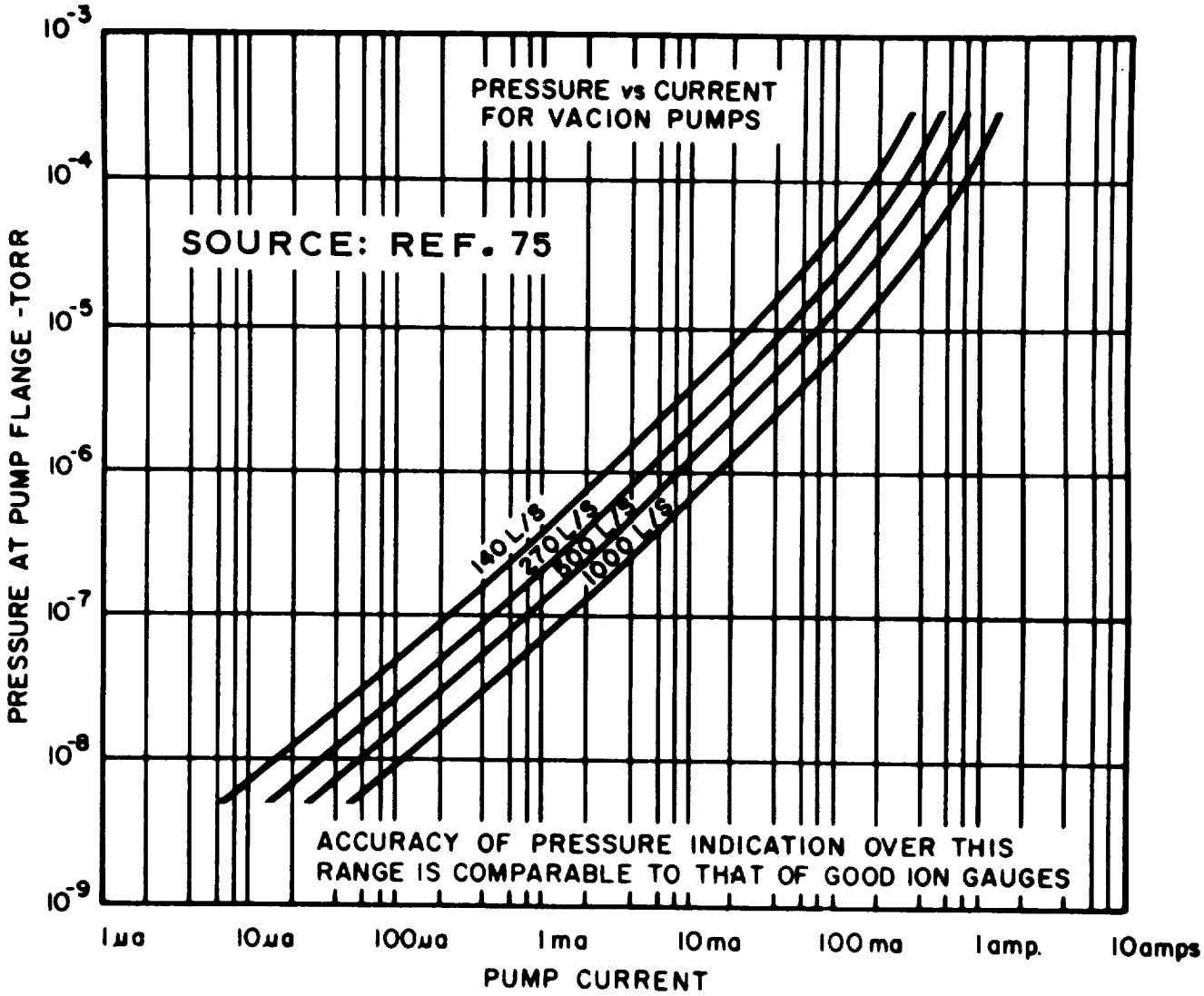


Fig. A.2 Calibration curve of a Vac-Ion Pump taken from a Varian catalog (Ref. 75). Note the roughly linear relationship between the pressure and the output current over a very wide range of the variables. This linear relationship can only be the result of classical diffusion of the electrons to the anode by means of collisions with the neutrals. Other pumps of this character have operated down to pressures like 10^{-12} mm Hg. An estimate of the electron confinement time at this pressure is 1000 secs.

A7676

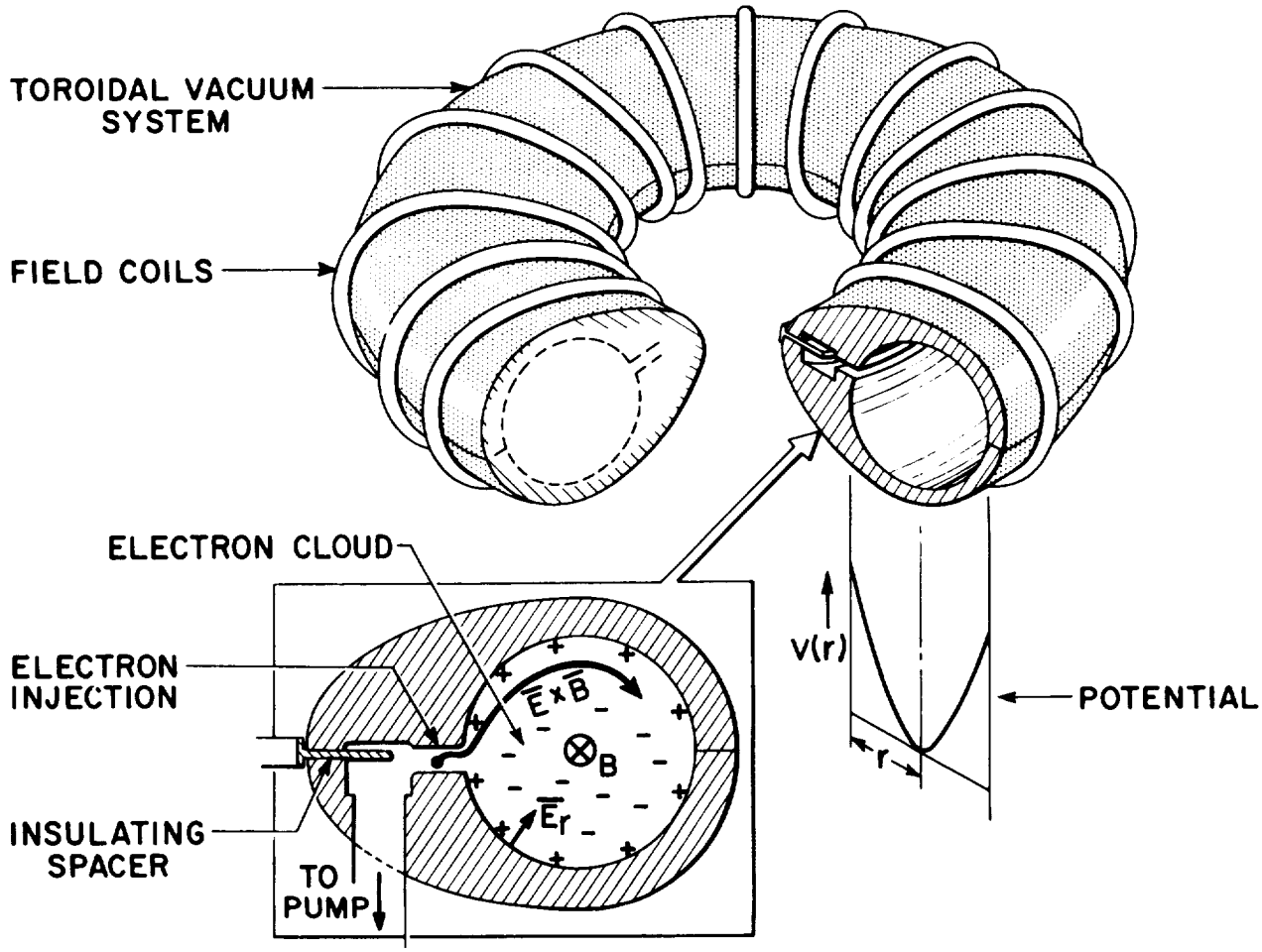


Fig. A. 3 Schematic of toroidal electron plasma experiment. Electrons are introduced into the torus from a filament in the slot, compressed by a rising magnetic field, and create a potential depression along the circular axis of the device.

A5292

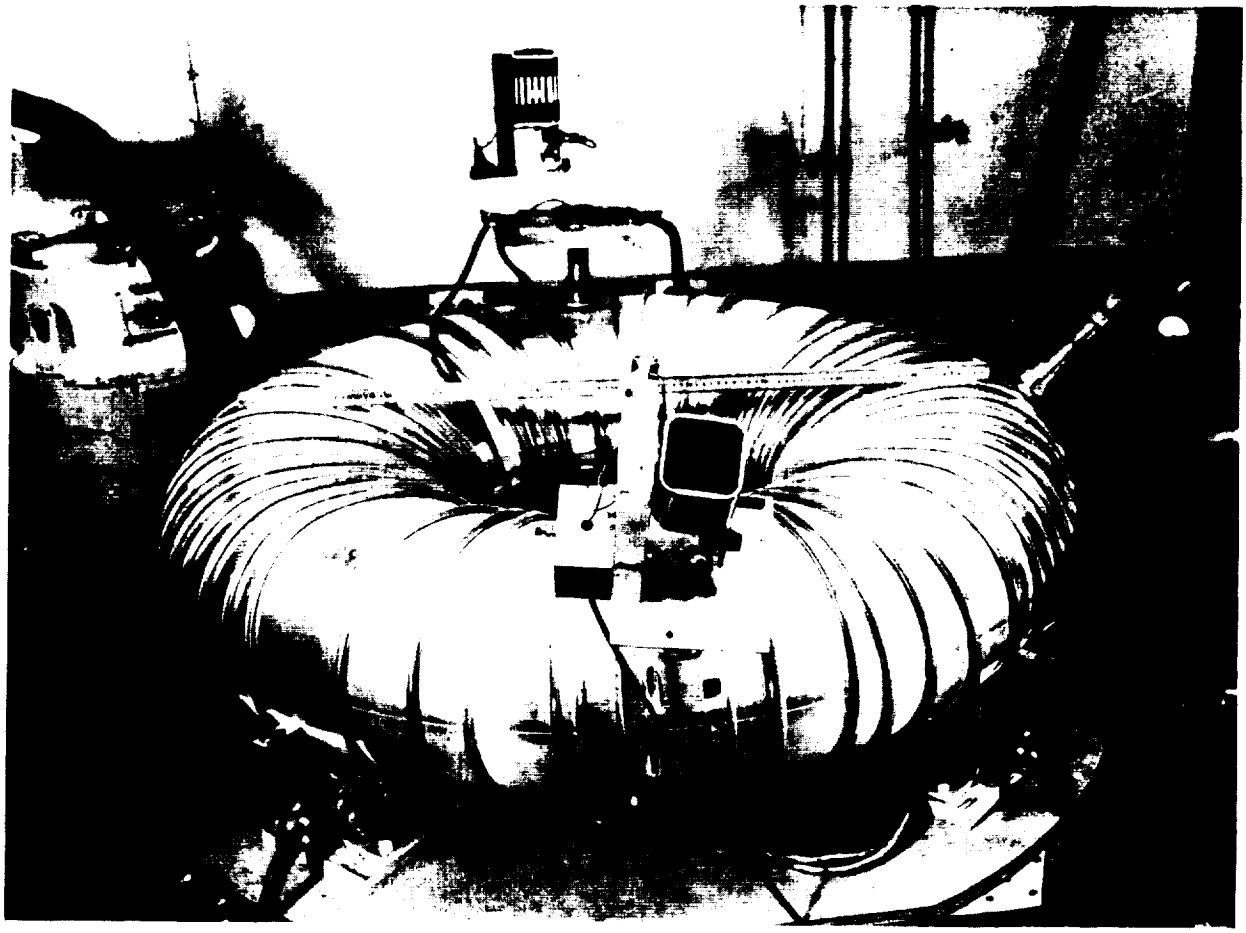


Fig. A.4 Photograph of the apparatus shown in Fig. A.3. Note the meter rule across the device.

A5294

short times ($\sim$1 msec.), and the achievement of high voltages by compressing the electron cloud with a rising magnetic field. Containment times longer than 1 msec. cannot be achieved with this apparatus since a) the magnetic field is aligned by image currents in the aluminum torus; these currents decay after about 1 msec., and b) the apparatus cannot be pumped down below pressures of a few x 10^{-8} mm Hg. The residual gas at this pressure will discharge the electron cloud in approximately 1 msec.

Electrons are injected into the apparatus from the heated circular filament shown in Fig. A. 3. The rising magnetic field then carries these electrons in towards the middle of the device, where they generate a potential depression or well. The depth of the well is measured by electrostatic probes. When the magnetic field reaches its peak value, it is "crowbarred," and decays in about 1 msec.

The experiment has a minor radius of 10 cm and a major radius of 50 cm. Approximately .02 webers of magnetic flux are introduced in a rise time of about 20μ sec, giving an induced voltage of about 1 kV. This voltage appears across the slot where the filament is located. The peak magnetic field is about 5 k gauss.

An experimental oscillogram is shown in Fig. A. 5, and data from several runs is plotted in Fig. A. 6. Peak well depths in excess of 80,000 volts have been observed, and our ability to generate higher voltages is limited at present by lack of means to measure them, since the electrostatic probes cannot be operated much beyond this figure.

The well depth generated appears to scale roughly with the voltage induced across the gap by the rising magnetic field, the amplification factor (or gain), being in the range 50-100.

So far as they go, these experiments may be regarded as satisfactory. Current work is directed at improving the gain to a number on the order of several hundred; it is hoped that this can be done through better control of the details of the injection process. Another objective is the development of diagnostic techniques capable of recording voltages above 100 kV. When these techniques become available, it should be possible to operate the experiment at generally higher levels of power, voltage, etc.

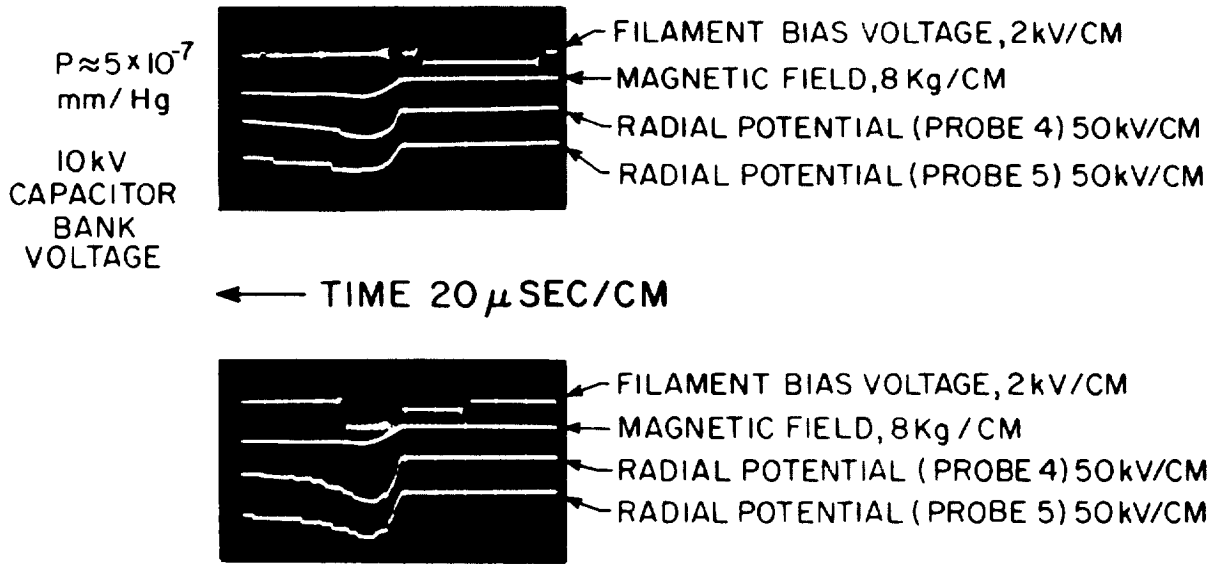


Fig. A.5 Data obtained with the apparatus of Figs. A.3 and A.4. Note the favorable effect of biasing the filament in the second oscillogram. The peak potential is 80,000 volts, when the magnetic field is about 5 k gauss.

A7017

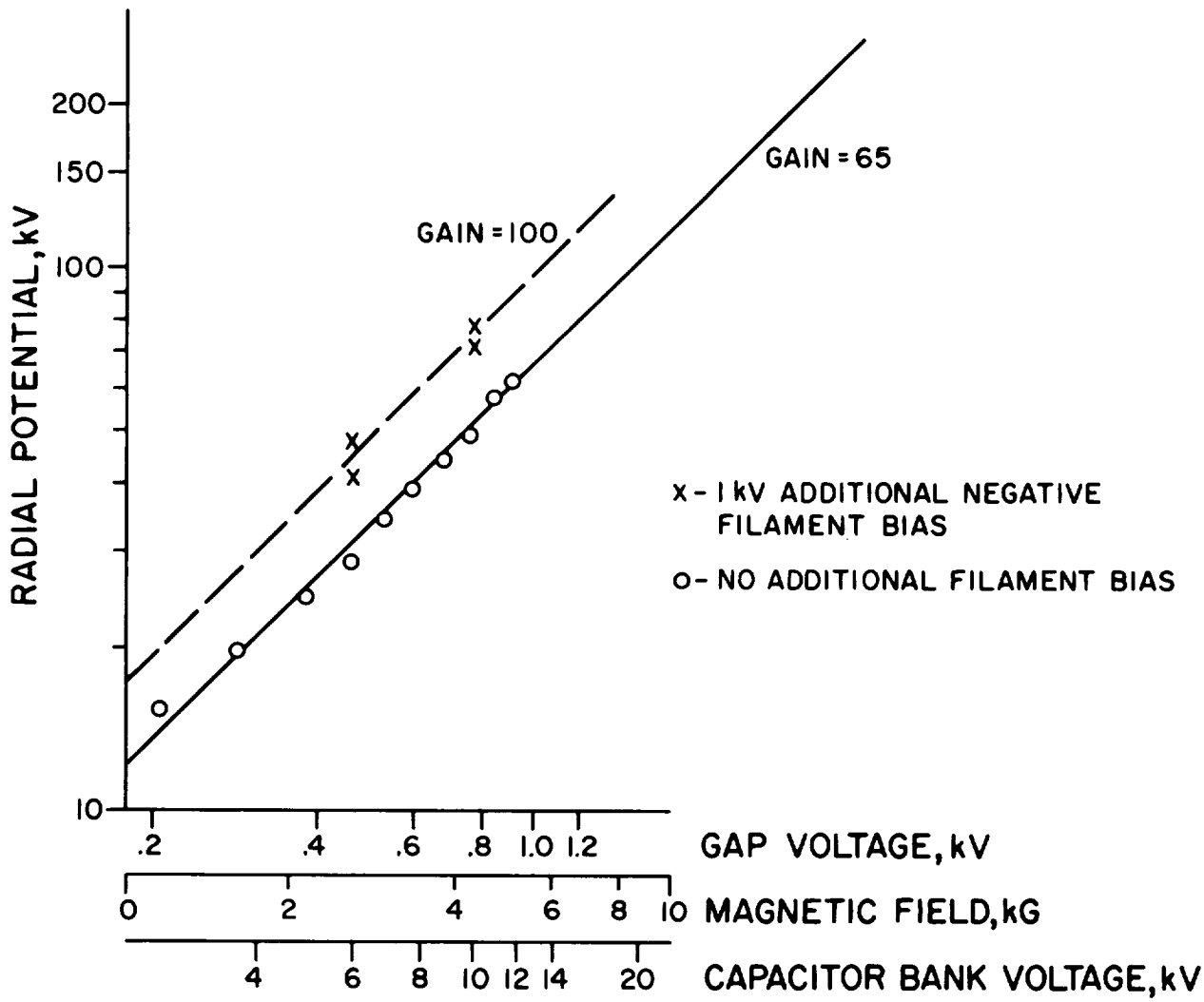


Fig. A.6 Cross plot of data from the apparatus of Figs. A.3 and A.4. Note the linear relationship between the depth of the potential well and the gap voltage.

A7018

Under consideration is a new experiment designed to extend our capabilities in the direction of longer containment times. In this area, the primary requirement is the use of superior vacuum techniques.

A.5. Summary

Experimental and theoretical work on a wide front has failed to produce any fundamental obstacle to the realization of the Plasma Radiation Shield; on the other hand, the highest voltage exhibited falls short of that required for the Plasma Radiation Shield by a factor of several hundred, and containment times at these voltages fall short of the Plasma Radiation Shield requirements by a factor of 10^8.

With regard to the absolute voltage level, however, for a given electron number density this scales with the square of a suitable linear dimension. As a full scale device would certainly be ten times the size of the existing experiment, the short fall in voltage level appears quite reasonable. As regards the containment time, the Vac-Ion Pump shows that in devices of this kind very long containment times are possible, and that these times depend only on the pressure of the residual gas. Thus, while further experimental and theoretical work is obviously required, it is reasonable to interpret optimistically the data obtained so far.

REFERENCES

1. Second Symposium on Protection Against Radiations in Space, NASA SP-71, Gatlinburg, Tennessee, October 1964.

2. Burrell, M. O., Wright, J. J. and Watts, J. W., "A Preliminary Report on Energetic Space Radiation and Dose Rate Analysis," NASA Technical Memorandum X-53531, October 31, 1966.

3. Hilberg, R. H., "Solar Cosmic Ray Events," Bellcomm, Inc., Report No. TR-65-340-1, November 1, 1965.

4. Hilberg, R. H., "Radiation Shielding Needed for Extended Interplanetary Missions – Case 103-2," Bellcomm, Inc., August 11, 1966.

5. Burrell, M. O., "Space Radiation Doses During Planetary Missions," NASA Technical Memorandum X-53190, January 20, 1965.

6. Anderson, K. A., "Preliminary Study of Prediction Aspects of Solar Cosmic Ray Events," NASA TN D-700, April 1961.

7. French, F. W. and Hansen, K. F., "Radiation Shielding Requirements for Manned Satellites," J. Spacecraft and Rockets 2, 931 (1965).

8. Keller, J. W., "Long-Range NASA Shielding Requirements," Symposium on the Protection Against Radiation Hazards in Space, Gatlinburg, Tennessee, November 1962.

9. Abel, J., "Radiation Considerations for Lunar Missions," AAS Preprint 62-37, January 1962.

10. Bailey, D. K., "Time Variations of the Energy Spectrum of Solar Cosmic Rays in Relation to the Radiation Hazard in Space," J. Geophys. Res. 67, 391-396 (January 1962).

11. Ehricke, K. A., "A Study of Early Manned Interplanetary Missions (Empire Follow-On)," General Dynamics/Astronautics, GD/A-AOK 64-002, January 1964.

12. "Manned Mars Exploration in the Unfavorable (1975-1985) Time Period," Vol. II, Summary, Douglas Report SM-45576, January 1964.

13. Sanders, H. C., "The Effects of Man on the Weight of a Manned Space Vehicle," AAS Preprint 62-12, January 1962.

14. "Manned Interplanetary Missions," Lockheed Missiles and Space Company, Vol. I, Summary, 8-32-63-4. January 1964.

15. Langham, W. H., "Some Radiation Problems of Space Conquest," Astron. Sci. Rev. 2, 9 (October-December 1960).

16. Proceedings of Conference on Radiation Problems in Manned Space Flight, NASA TN D-588, June 1960.

17. Barnes, T. G., Finkelman, E. M. and Barazotti, A. L., "Radiation Shielding of Lunar Spacecraft," Astron. Sci. Rev. 3, 11 (January-March 1961).

18. Tobias, C. A., "Radiation Hazards in Space Flight," University of California RAD Laboratory Report UCRL 8115, January 1958.

19. Schaefer, H. J., "Radiation Danger in Space," Astron. 5, 36 (1960).

20. Schaefer, H. J., "Proton Radiation Hazards in Space," Astron. 6, 39 (1961).

21. Foelsche, T., "Protection Against Solar Flare Protons," 7th Annual Meeting, American Astronautical Society, Dallas, Texas, January 1961.

22. Babinsky, A. D., Del Duca, M. G. and Bond, A. F., "The Radiation Problem in Low Thrust Space Travel," presented at the ARS 14th Annual Meeting, Washington, D. C., November 16-20, 1959, ARS Report 989-59.

23. Robey, D. H., "Radiation Shield Requirements for Two Large Solar Flares," Astronautica Acta 6, 206 (1960).

24. Barbieri, L. J. and Lampert, S., "The Interdependence of Manned Spacecraft Design and Radiation Shielding," Aerospace Eng. 20, 14 (1961).

25. Anderson, K. A. and Fichtel, C. E., "Discussions of Solar Proton Events and Manned Space Flight," NASA TN D-671, March 1961.

26. Savin, R. C., Deerwester, J. M., and Mascy, A. C., "Sensitivity of Manned Planetary Spacecraft Design to Radiation Uncertainties," J. Spacecraft 4, 249 (1967).

27. French, F. W., "Radiation Shielding of Manned Mars Vehicles," presented at AIAA "Stepping Stones to Mars Meeting" at Baltimore, Maryland, March 1966.

28. Saylor, W. P., Winter, D. E., Eiwen, C. J. and Coriker, A. W., "Space Radiation Guide," Aerospace Medical Div. Report AMRL-TDR-62-86, p. 25, 1962.

29. Webber, W. R., "An Evaluation of the Radiation Hazard Due to Solar-Particle Events," Boeing Company Report D2-90469, December 1963.

30. "Radiation Biology and Space Environmental Parameters in Manned Spacecraft Design and Operations," Aerospace Medicine 36 (February 1965).

31. Private communication, A. Reetz.

32. Cosmic Rays, Handbuch d. Phys. 46 (1961).

33. Levy, R. H., "Radiation Shielding of Space Vehicles by Means of Superconducting Coils," ARS J. 31, 1568 (1961).

34. Brown, G., "Magnetic Radiation Shielding," Proceedings of the International Conference on High Magnetic Fields, M.I.T., November 1961; also Wiley, 1962, pp. 370-378.

35. Dow, N. F., "Structural Implications of the Ionizing Radiation in Space," Proceedings of the Manned Space Stations Symposium, Los Angeles, California, April, 1960.

36. Bernert, R. E. and Stekly, Z. J. J., "Magnetic Radiation Shielding Systems Analysis," Avco Everett Research Laboratory Report AMP 134, July 1964.

37. Levy, R. H., "Prospects of Active Shielding," presented at Symposium on the Protection Against Radiation Hazards in Space, Gatlinburg, Tennessee, November 1962.

38. Tooper, R. F. and Davies, W. O., "Electromagnetic Shielding of Space Vehicles," IAS Paper No. 62-156, June 1962.

39. Tooper, R. F., "Electromagnetic Shielding Feasibility Study," Armour Research Foundation Technical Documentary Report No. ASD-TDR-63-194, May 1963.

40. Kash, S. W., "Magnetic Space Shields," AIAA Paper No. 65-629, August 1965.

41. Levine, S. H., Bhattacharjie, A. and Lepper, R., "Forbidden Regions Produced by Two Parallel Dipoles," AIAA J. 4, 654 (1966).

42. Prescott, Urban and Shelton, "The Application of the Liouville Theorem to Partially Shielded Regions," Paper presented at Second Symposium on Protection Against Radiation Hazards in Space, Gatlinburg, Tennessee, October, 1964.

43. Bhattacharjie, A. and Michael, I., "Mass and Magnetic Dipole Shielding Against Electrons of the Artificial Radiation Belt," AIAA J. 2, 2198 (1964).

44. Levy, R. H., Comment on "Mass and Magnetic Dipole Shielding Against Electrons on the Artificial Radiation Belt," AIAA J. 3, 988 (1965).

45. Felten, J. E., "Feasibility of Electrostatic Systems for Space Vehicle Radiation Shielding," J. Astronautical Sci. 11, 16 (1964).

46. Levy, R. H. and Janes, G. S., "Plasma Radiation Shielding," AIAA J. 2, 1835 (1964).

47. Levy, R. H. and Janes, G. S., "Plasma Radiation Shielding," Space/Aeronautics 45, 106 (1966).

48. Levy, R. H., "The Diocotron Instability in a Cylindrical Geometry," Phys. Fluids 8, 1288 (1965).

49. Levy, R. H., "The Effect of Coherent Radiation on the Stability of a Crossed-Field Electron Beam," J. Appl. Phys. 37, 119 (1966).

50. Levy, R. H. and Janes, G. S., "The Electron Plasma: Experiment, Theory and Applications," AIAA Paper No. 65-538 (1965).

51. Janes, G. S., "Experiments on Magnetically Produced and Confined Electron Clouds," Phys. Rev. Letters 15, 135 (1965).

52. Levy, R. H. and Callen, J. D., "The Diocotron Instability in a Quasi-Toroidal Geometry," Phys. Fluids 8, 2298 (1965).

53. Buneman, O., Levy, R. H. and Linson, L., "The Stability of Crossed-Field Electron Beams," J. Appl. Phys. 37, 3203 (1966).

54. Helmer, J. C. and Jepsen, R. L., "Electrical Characteristics of a Penning Discharge," Proc. IRE 49, 1920 (1961).

55. Alexander, W. M., "Cosmic Dust," Science 138, 1098 (1962).

56. Alpert, D., Lee, D. A., Lyman, E. M. and Tomaschke, H. E., "Initiation of Electrical Breakdown in Ultrahigh Vacuum," J. of Vacuum Science & Technology 1, November/December 1964.

57. Dyke, W. P. and Trolan, J. K., "Field Emission: Large Current Densities, Space Charge and the Vacuum Arc," Phys. Rev. 89, 799 (1953).

58. Dyke, W. P., Trolan, J. K., Martin, E. E. and Barbour, J. P., "The Field Emission Initiated Vacuum Arc. I. Experiments on Arc Initiation," Phys. Rev. 91, 1043 (1953).

59. Dolan, W. W., Dyke, W. P. and Trolan, J. K., "The Field Emission Initiated Vacuum Arc. II. The Resistively Heated Emitter," Phys. Rev. 91, 1054 (1953).

60. Fowler, R. H. and Nordheim, L., "Electron Emission in Intense Electric Fields," Proc. Roy. Soc. (London) A119, 173 (1928).

61. Van Atta, L. C., Van De Graaff, R. J. and Barton, H. A., "A New Design for a High-Voltage Discharge Tube," Phys. Rev. 43, 158 (1933).

62. Cranberg, L., "Initiation of Electrical Breakdown in Vacuum," J. Appl. Phys. 23, 518 (1952).

63. Bennett, W. H., "Magnetically Self-Focusing Streams," Phys. Rev. 45, 890 (1934).

64. Boyle, W. S., Kisliuk, P. and Germer, L. H., "Electrical Breakdown in High Vacuum," J. Appl. Phys. 26, 720 (1955).

65. Muller, E. W., "Field Ionization and Field Ion Microscopy," Advances in Electronics and Electron Physics, Vol. XIII (1960).

66. Rich, M. and Madey, R., "Range-Energy Tables," University of California Radiation Laboratory Report No. 2301, March 1954.

67. "Environmental Control Systems and Selection for Manned Space Vehicles," ASD-TDR-61-240, Part I, December 1961.

68. Lin, H., "Structures and Materials in the Long-Duration Manned Spacecraft," Astron. and Aeron. 4, 37 (March 1966).

69. Thomas, R. S., "Choice of an Atmosphere for an Extended Space Mission," Proceedings of the First Space Vehicle Thermal and Atmospheric Control Symposium, ASD-TDR-63-260, April 1963, pp. 735-759.

70. Hibben, R. D., "Allis-Chalmers Pushes Fuel Cell Efforts," Aviat. Wk. 86, 65 (1967).

71. "First Quarterly Technical Progress Report, Thermal Battery, 1 July - 30 September 1966," Contract AF33(615)-5343, Allison Division of General Motors, October 1966.

72. Hietbrink, E. H., Private communication, Allison Division of General Motors, Indianapolis, Indiana, 1967.

73. Beischer, D. E., "Human Tolerance to Magnetic Fields," Astron. 7, 24-25, 46-48 (1962).

74. Quarterly Progress Report, Contract NAS8-20310, National Aeronautics and Space Administration, Office of Advanced Research and Technology, December 1966.

75. Vac-Ion Pump 140, 270, 500 and 1000 L/S Data Study, Varian Vacuum Division, Palo Alto, California.

Avco Everett Research Laboratory, Everett, Massachusetts
THE PLASMA RADIATION SHIELD: CONCEPT, AND APPLICATIONS TO SPACE VEHICLES, by Richard H. Levy and Francis W. French. April 1967. 96 p. incl. illus.
(Avco Everett Research Report 258)
(Contract NAS 8 - 20310)

Unclassified report

The Plasma Radiation Shield is an active device using free electrons, electric and magnetic fields for the purpose of shielding astronauts from energetic solar flare-produced protons. The concept of Plasma Radiation Shielding is reviewed in the light of current studies. The available evidence indicates that the concept is physically sound, but important practical questions remain in at least two areas: these have to do with establishment and control of the extremely high voltages required, and with integration of the concept into a realistic vehicle design.

(over)

UNCLASSIFIED

1. Space Radiation Shielding.
2. Plasma Radiation Shielding.
I Title
II Levy, Richard H.
III French, Francis W.
IV Avco Everett Research Report 258
V Contract NAS 8 - 20310.

UNCLASSIFIED

Avco Everett Research Laboratory, Everett, Massachusetts
THE PLASMA RADIATION SHIELD: CONCEPT, AND APPLICATIONS TO SPACE VEHICLES, by Richard H. Levy and Francis W. French. April 1967. 96 p. incl. illus.
(Avco Everett Research Report 258)
(Contract NAS 8 - 20310)

Unclassified report

The Plasma Radiation Shield is an active device using free electrons, electric and magnetic fields for the purpose of shielding astronauts from energetic solar flare-produced protons. The concept of Plasma Radiation Shielding is reviewed in the light of current studies. The available evidence indicates that the concept is physically sound, but important practical questions remain in at least two areas: these have to do with establishment and control of the extremely high voltages required, and with integration of the concept into a realistic vehicle design.

(over)

UNCLASSIFIED

1. Space Radiation Shielding.
2. Plasma Radiation Shielding.
I Title
II Levy, Richard H.
III French, Francis W.
IV Avco Everett Research Report 258.
V Contract NAS 8 - 20310.

UNCLASSIFIED

UNCLASSIFIED

UNCLASSIFIED

UNCLASSIFIED

UNCLASSIFIED