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PLASMA RADIATION SHIELDING

R. H. Levy and S. Janes

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HEADQUARTERS
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OFFICE OF ADVANCED RESEARCH AND TECHNOLOGY
Washington, D. C.
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AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
Washington 25, D. C.
under Contract No. AF 49(638) - 1553
Project Task: 9752 - 01

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by

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Everett, Massachusetts

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*Plasma radiation shielding is being studied under Contract NASw-1101. Related physical problems are also being studied under Contract AF 49(638)-1553.

ABSTRACT

The principles of operation of the Plasma Radiation Shield are explained and the current status of research on this project is described. The relationship between this device and others using crossed field electron beams (such as the microwave magnetron) is indicated.

INTRODUCTION

It has been known for some time that for a day or two following some solar flares, large parts of the solar system are filled with energetic protons in sufficient quantity to be hazardous to lightly shielded astronauts. Considerable uncertainty surrounds the exact nature of the hazard, due in part to the unusual (by terrestrial standards) nature of the radiation. Thus the effect of the steep energy dependence of the proton spectrum is to deposit most of the radiation dose near the surface of the body.[1] We cannot go into detail on this problem here, but observe that the problem of radiation shielding in space seems likely to continue to attract the attention of specialists from many fields. With respect to the flares themselves, the flares that actually produce significant numbers of protons occur about once a year, with some apparent tendency to favor solar maximum. (The next solar maximum is in 1970.) While this frequency is not large, flare prediction on time scales of more than a few days is not at present possible. It follows that on trips lasting more than a week or two, an astronaut must be prepared to encounter an important solar flare.

On earth we are protected from these solar protons in the first instance by our magnetic field. This magnetic field not only protects most of the surface of the earth, but also the region of space above it, up to an altitude of perhaps three or four times the radius of the earth. Protection by the earth's magnetic field is, however, not uniform. Solar protons are effectively prohibited from going across magnetic field lines, but a magnetic field offers no resistance to the motion of charged particles along it. Magnetic protection is, therefore, best at the equator but ineffective near the magnetic poles. Up to the present, all astronauts have used orbits of low inclination and have therefore been in no danger from solar flare protons. In the polar regions, the surface of the earth is protected from solar protons only by the atmosphere so that at 75,000 ft over the geomagnetic pole a supersonic transport could be significantly exposed.[2] For the SST this appears to pose no more than a minor operational problem; more serious would be the position of a satellite at an altitude of 100 miles in a polar orbit. Here there is a real question of whether to provide the shielding necessary for an astronaut to stay in orbit, come what may, or whether to provide for an emergency re-entry in the event of a large flare. For short trips into deep space (less than a week or two) one can achieve a reasonable probability of not encountering a large flare, that is, one can "run for it". This procedure is suitable for initial trips to the moon. For all trips into deep space lasting more than a couple of weeks, the problem of shielding against solar flare protons will have to be seriously considered.

There are very few ways of providing shielding against solar flare protons. Of the few that exist, by far the simplest is to place solid material in the path of the protons. However, to stop 30, 100 or 200 MeV protons requires roughly 1, 10 or 30 gms per square centimeter of surface area and these weights can add up very rapidly. A second possible method of shielding - with magnetic fields - [3, 4, 5] is suggested by the discussion of how the earth's magnetic field protects us. This method would involve carrying a large, intense magnetic field generated by superconducting coils into space. Magnetic fields have an inherent tendency to expand and - just like compressed gas - require some structure to hold them together. The stored pV energy provides a rough measure of the weight of a structure for containing a compressed gas. The magnetic energy is the corresponding indicator for a magnetic field. Detailed analysis shows that the mass of the structure required to keep a magnetic radiation shield together is not much less than the mass of a solid radiation shield, except possibly for very large sizes. For a 200 MeV proton energy, the results of a careful calculation of this type are shown in Fig. 1. The lines on this graph represent solid shielding, magnetic shielding, and Plasma Radiation Shielding - the last being the subject of this article. The magnitudes of the weights involved in shielding even relatively modest volumes by conventional means are an obvious encouragement to seek more elegant (and lighter) ways of performing the shielding function.

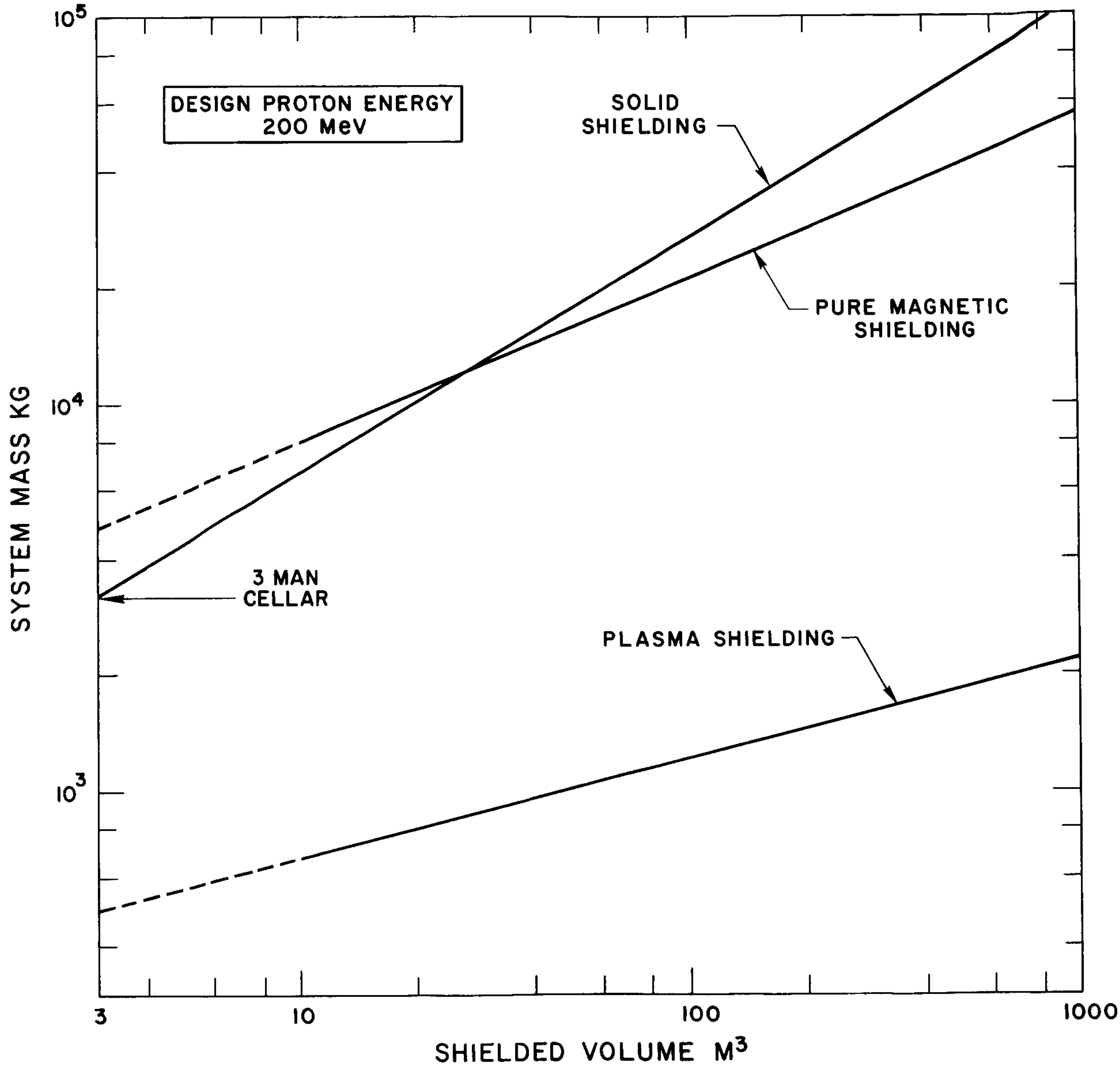

Fig. 1 Comparative weights of solid, pure magnetic, and Plasma Radiation Shields, for 200 MeV design proton energy. Note the large absolute weights of solid and pure magnetic shielding, and that, even in very large volumes, the Plasma Radiation Shield weighs less than a three man storm cellar. Note also that while the storm cellar "works", the Plasma Radiation Shield has not yet been shown to work.

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Electrostatic Shielding

Such a way is at hand - electrostatic shielding.[6] Protons, positively charged particles, can be affected by electric fields as well as by magnetic fields. The force on a charge e in an electric field E is eE; at velocity v in a magnetic field B the force is evB. To stop a given proton requires the application of the same force, by whatever means; the required electric field is therefore given by $E = vB$, where B is the magnetic field required for a pure magnetic radiation shield against protons of velocity v. This formula allows us to compare the energy densities in the two fields, and hence, in a rough way, the weights of the two shielding systems. On an energy basis, electric shielding is cheaper than pure magnetic shielding by the ratio $E^2/c^2B^2 = v^2/c^2$. This ratio is small whenever the proton is non-relativistic (i.e. has an energy less than about one BeV which is almost always the case.) This calculation, of course, has ignored an enormous number of important details, but is suggestive of the potential advantage of electrostatic shielding.

How are these advantages to be realized? An electrostatic potential of 200 million volts is required to stop a proton having 200 MeV kinetic energy. We reject at once all schemes in which this potential is developed between two solid conductors: the largest potentials made on earth are on the order of 10 million volts, and these are made by large and complicated Van de Graaff machines. There seems no reason to think that the Van de Graaff technique would allow the achievement in space of voltages which are far in excess of those achieved on earth.

There remains the possibility of charging the space vehicle positive as a whole to a voltage of 200 million volts "relative to infinity".

In electrostatic terms, "charged to 200 million volts relative to infinity" means just this: the work necessary to bring a positive elementary charge (i.e. a proton) from infinity to the surface of the vehicle is 200 million electron volts. If this is the kinetic energy of the proton when at infinity, the proton will just "make it" to the surface of the vehicle at which point it has no kinetic energy, but 200 million electron volts of potential energy. It will then be turned around and sent back to "infinity". At "infinity" the proton will once more be the possessor of 200 million electron volts of kinetic energy.

This explanation reveals a basic defect in the scheme: an electron at infinity will possess no (appreciable) kinetic energy, but 200 million electron volts of potential energy; it will be all too willing to trade one for the other and arrive with devastating energy at the space vehicle. Like charges repel, but unlike attract and if the space vehicle is to be positively charged, this difficulty is unavoidable. In addition, space contains enormously more electrons of low kinetic energy than protons of high kinetic energy. The arrival of these electrons means that the space vehicle's net positive charge is reduced. To maintain this charge electrons must be ejected from the vehicle at the same rate at which they are attracted. Furthermore, to make sure that ejected electrons stay ejected, each must have a kinetic energy in excess of 200 MeV. The product of the rate of ejection of electrons and the voltage through which they must be accelerated before ejection represents the power necessary to maintain the initial positive charge. This power has been conservatively estimated at 10,000 megawatts, and would require a massive power station. Even if one never turned the whole thing on, the power station would be an excellent protection against the solar flare protons by virtue of its mass alone!

Plasma Radiation Shielding

Plasma Radiation Shielding is an attempt to make electrostatic shielding possible, in spite of the unpromising situation outlined above. It consists of the basic electrostatic shielding scheme as discussed - plus an agent designed to control the resulting flow of electrons. This agent is a magnetic field arranged in such a way that an electron cannot get to the space vehicle. In particular, there must be no magnetic "holes" like the poles of the earth. This leads us to the toroidal space station illustrated in Figs. 2 and 3. The essential point of the Plasma Radiation Shield is this: to control electrons of modest energy requires a magnetic field much less intense than that required to control energetic protons. The Plasma Radiation Shield therefore makes use of the basic asymmetry between electrons and protons, an asymmetry not unconnected with the fact that solar flare radiation is exclusively protons. If the Plasma Radiation Shield works - and this is by no means certain - it will be light. Estimated weights are shown in Fig. 1 for 200 MeV design proton energy. In all sizes it is twenty times lighter than solid shielding, and even in very large sizes it is lighter than a three-man solid "storm cellar." On the basis of this promising estimate, Plasma

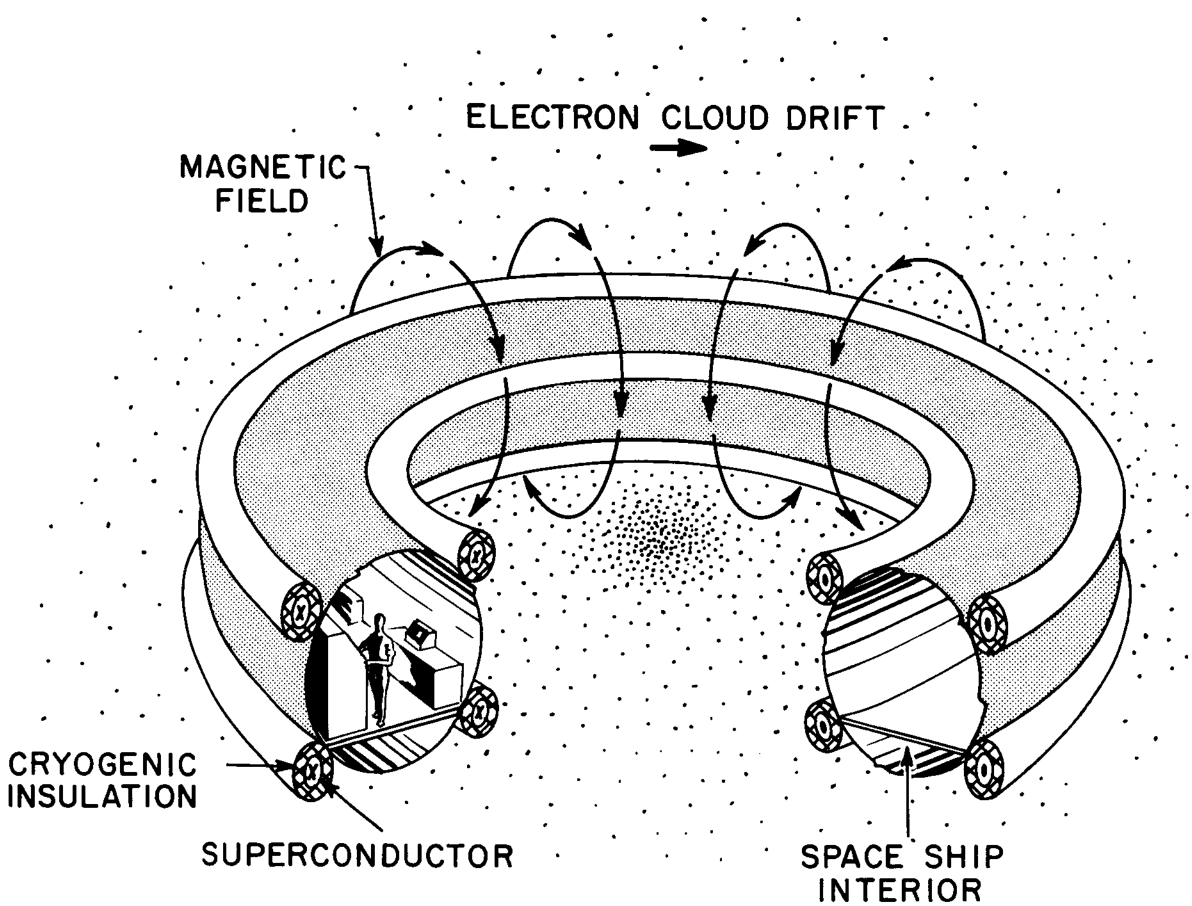

Fig. 2 The Plasma Radiation Shield. The four coil arrangement of the superconductor is more of a suggestion than a definite design. The electron cloud carries a negative charge equal and opposite to the positive charge on the space vehicle. Solar protons are reflected by the electric field between these charges, and are virtually unaffected by the magnetic field. The electron cloud drifts around the vehicle in the direction shown; the existence of this drift (see Fig. 4) makes the Plasma Radiation Shield a cousin of the crossed-field microwave magnetron.

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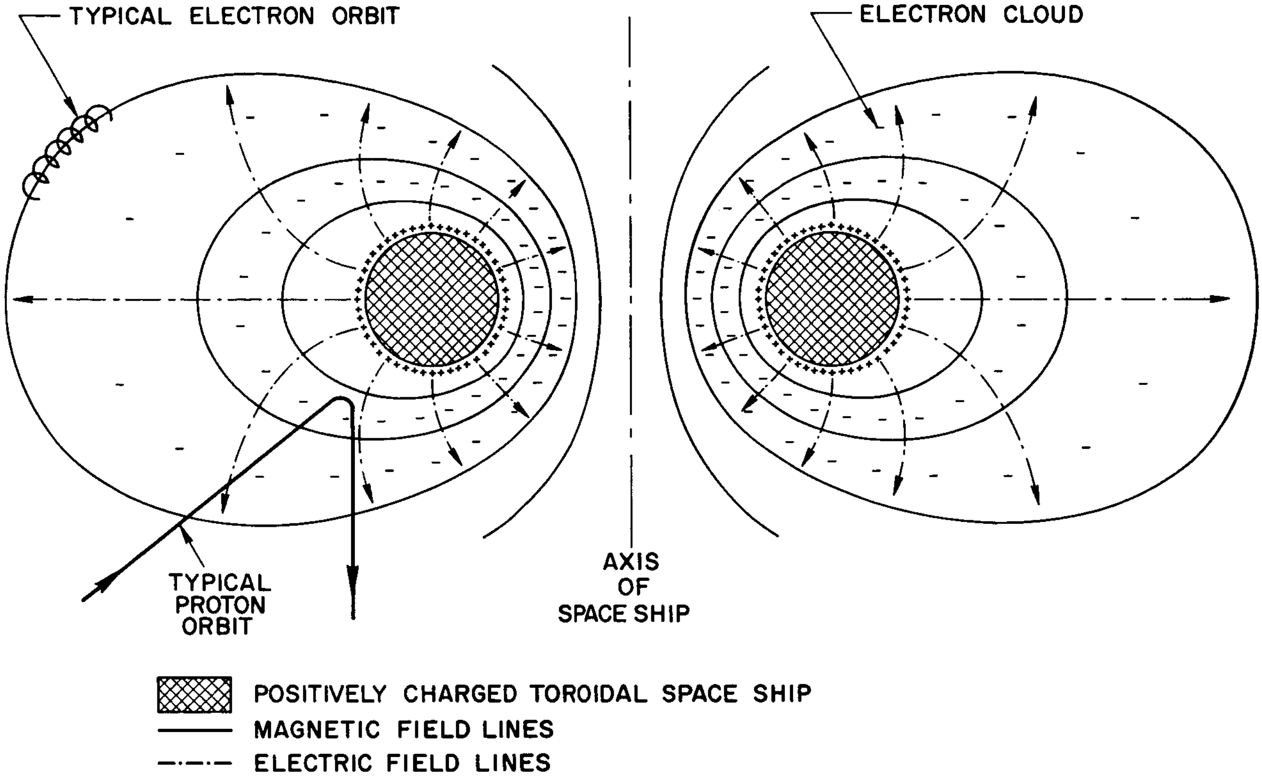

Fig. 3 In this section view of the Plasma Radiation Shield the electric and magnetic field lines can be seen to be mutually perpendicular. All the electric field lines start on the surface of the vehicle and end on electrons in the cloud; this effect guarantees that the charge on the vehicle and the cloud will be equal and opposite. The whole arrangement is something like a capacitor; the electric field is important only between the "plates". The "plates" attract each other, but are kept apart by the magnetic field.

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Radiation Shielding is currently the object of an intensive study. As we shall see, it is not yet known if the scheme will work, but the outlook at present is distinctly favorable.

In the general vicinity of the Plasma Radiation Shield, there will be a cloud of free electrons; this cloud will carry a negative charge exactly equal in magnitude to the positive charge carried by the space vehicle. This arrangement gives a gross electrical neutrality to the whole device. This large scale neutrality is necessary, because, outside some radius, representing the effective limit of the magnetic field, the electric field must be zero. Thus, from Gauss' law, there is no net charge inside this radius and the electron cloud is in the general vicinity (i.e. in the magnetic field of) the Plasma Radiation Shield. A magnetic field, as we have seen, exerts a highly directive force on a charged particle. In particular, no force is exerted in the direction of the magnetic field to the flow of electrons along itself. It follows that after some very short initial period, the electrons will so distribute themselves along the magnetic field as to make the magnetic field lines equipotentials. This means that the electric and magnetic fields are mutually perpendicular, and from this follows the observation that the Plasma Radiation Shield is essentially a new type of crossed-field electron beam device, a close cousin to such devices as the microwave magnetron, the Philips Ionization Gauge and a string of others well-known to the electronic engineer. We cannot here go into this whole family of devices, but merely observe (see Fig. 4) that in crossed fields tend to "drift" in a direction perpendicular to both the electric and

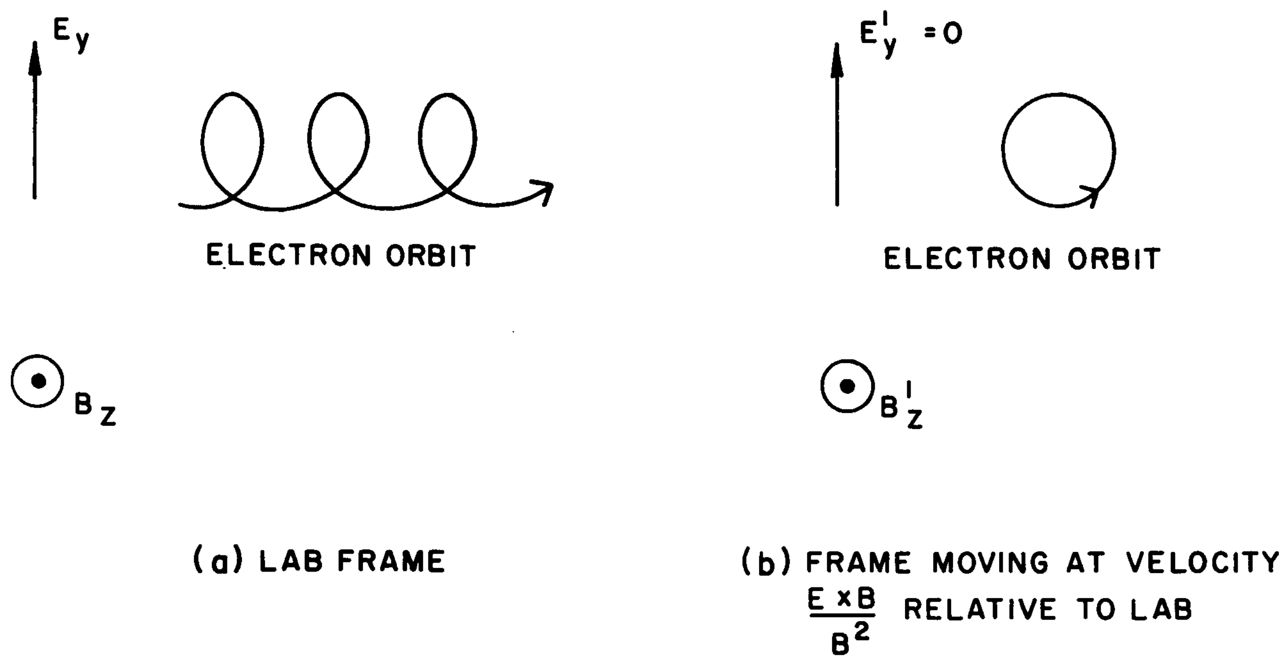

Fig. 4 Illustrates the characteristic motion of an electron in crossed electric and magnetic fields. Figure 4a shows how an electron has a net "drift" to the right; the velocity of this drift is $\underline{E} \times \underline{B}/\underline{B}^2$. Figure 4b shows the electron motion in a frame moving with the average drift velocity of the electron. In this frame the electric field vanishes and the electron merely circles the magnetic field. The superposition of the circling and drift motions yields the cycloidal path shown in Fig. 4a.

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magnetic fields, at a speed E/B. This drift is shown in Fig. 2; in Fig. 3 it would be around the major axis.

There are four important questions to be answered before it can be known whether the Plasma Radiation Shield will work. First, will losses due to such causes as collisions between electrons of the cloud and atoms outgassed from the space vehicle be acceptable or unacceptable? Roughly such losses would be acceptable if each electron were to drift around the space ship something like 10^{12} (a million million) times before crossing the magnetic field to reach the space vehicle. Calculations indicate that this figure may be attainable in the ultrahigh vacuum of space. The second question is whether we expect to be able to achieve with the Plasma Radiation Shield voltages ten to twenty times bigger than any hitherto achieved. Here there is considerable uncertainty, but also reason for optimism. High voltage breakdown is not fully understood; however, the necessity for extracting electrons from a material cathode by field emission or photoelectric effect is fundamental to most theories on the subject. In the Plasma Radiation Shield we have eliminated the material cathode and substituted (see Fig. 2 and 3) an electron cloud as a virtual cathode. There may indeed be difficulties associated with such a virtual cathode; however, such difficulties would more properly be described as instabilities. There appears to be little danger of extracting ions from the anode (space vehicle) at the electric fields contemplated. Thus there is real hope that extremely high voltages can be attained.

The third question relates to the existence of serious instability mechanisms in the electron cloud. We cannot, in this paper give a thorough discussion of this point, but will confine ourselves to the following observations: firstly, the microwave magnetron works by virtue of an instability having a growth rate on the order of the frequency of the emitted wave, that is, on the order of 10^{10} cps. This establishes the potential importance of instabilities. Second, there is experimental[8] and theoretical[9, 10, 11, 12] evidence to the effect that there need be no instabilities if the ratio of electron density to magnetic field strength is sufficiently low. Further discussion of this point can be found elsewhere. The fourth and last question is: can the device be started? Here the answer seems to be unequivocally "yes." An ingenious scheme, called "Inductive Charge Ejection," in which a time varying magnetic field is made to take over the function of the belt in a Van de Graaff, has been tested in the laboratory (at low voltage) and found to work[8, 11] essentially as anticipated.

We have seen that, although a final answer is not yet at hand, the Plasma Radiation Shield may prove to be a workable invention. If it works, what are the basic design parameters, and how much will it weigh? Table I gives, for a typical design, the basic parameters assumed and derived. Basically, we assume the size (here 5 meters, big enough for a few men) and the voltage (200 million volts). Using elementary physical principles of electrostatics, these two numbers allow immediate estimation of the derived quantities under the heading " Electrostatic Quantities." We need next to specify the magnetic field strength. We would like to use as weak a magnetic field as possible; however, we cannot reduce it below the level of stability. The value of B chosen in

TABLE I

TYPICAL DESIGN OF A PLASMA RADIATION SHIELD

Assumed Quantities		
Overall Voltage	V_o	200×10^6 volts
Size	R	5 meters
Electrostatic Quantities		
Electric Field	E	40×10^6 volts/meter
Total Charge	Q	.3 coulombs
Number of electrons	N_E	2×10^{18}
Electron density	n_e	2×10^9 cm^{-3}
Electric Field Energy	U_E	30×10^6 joules
Magnetic Quantities		
Magnetic Field	B	2660 gauss
Magnetic Field Energy	U_B	120×10^6 joules
Electromagnetic Quantities		
Electron Drift Velocity	v_e	150×10^6 m/sec
Power required to charge both fields in 5000 secs.		30 kw
Superconducting Coil Quantities		
Magnet Current	I_{magnet}	2×10^6 amps
Mass of Superconductor	$M_{s.c.}$	550 kg
Cryogenic Area	A_{cry}	$10m^2$
Cryogenic Mass	M_{cry}	180 kg
Cryogenic Power	P_{cry}	6 kw

Table I is 2660 gauss. On the basis of our present knowledge of the stability problem, this value should be quite conservative. Note that the drift speed of the electrons, E/B, comes out with this value of B at just one-half the speed of light. Note also that the effect of a 2660 gauss magnetic field spread over 5 meters on a 200 MeV solar proton is almost entirely negligible - we don't even begin to have a magnetic radiation shield.

Given the magnetic field, B, all the remaining parameters of the Plasma Radiation Shield can now be calculated. The parameters fall under the headings of magnetic, electromagnetic, and superconducting coil quantities. The latter determine the weight of the Plasma Radiation Shield as follows: the magnetic field and the size determine the current that must circulate in the field coils. We take 10^5 amps/cm^2 for the current-carrying capacity of superconductor (a figure that should not be too far in the future) and we can then find the mass of superconductor required. For the field strength chosen, the superconductor should be self-supporting and need no external supporting structure. As estimate of the weight of other components of the superconducting system is also given. Additional calculations have been made for other vehicle sizes and the results are shown in Fig. 1.

Experimental Problems

To sum up the foregoing, while many questions remain to be answered, the outlook for the Plasma Radiation Shield is decidedly interesting. Further progress will require more analytical work, however, only experiments can provide a decisive answer to questions such as stability. Experimentally we encounter a curious and somewhat surprising situation.

Figure 5 shows a small-scale Plasma Radiation Shield ready for testing in a vacuum tank. The important point to observe is the strut attached to the model - obviously a necessity for support during the experiment. The problem is this: reference to Fig. 2 will show that the strut intercepts the orbits of the electrons drifting around the Plasma Radiation Shield. But the strut also provides a path for electrons to cross the magnetic field. It may be possible to make certain tests at low voltage in this type of apparatus, however, it is quite certain that very high voltages could never be attained. And yet, high voltage tests are obviously necessary.

There are several ways out of this dilemma: it may, for example, be possible (though difficult) to perform an experiment on a torus without a strut by dropping it through a vacuum tank. For tanks of reasonable size the whole experiment must be performed in a few milliseconds. Experiments of this kind have been done before, but are quite tricky. In our case, the energy source for the magnetic field and most of the diagnostics would have to be internal to the dropped torus. Despite these problems, the dropped experiment is probably easier than a scaled-down experiment in space. Such a space experiment would, however, be a necessary intermediate stage between a "dropped" laboratory experiment and operational use of a Plasma Radiation Shield. It would, in many respects, be an interesting and valuable experiment to perform in space; however, for best results the supervision of a scientist-astronaut would be desirable. The duration of the experiment would be essentially unlimited. The Plasma Radiation Shield is so much a product of outer spatial considerations,

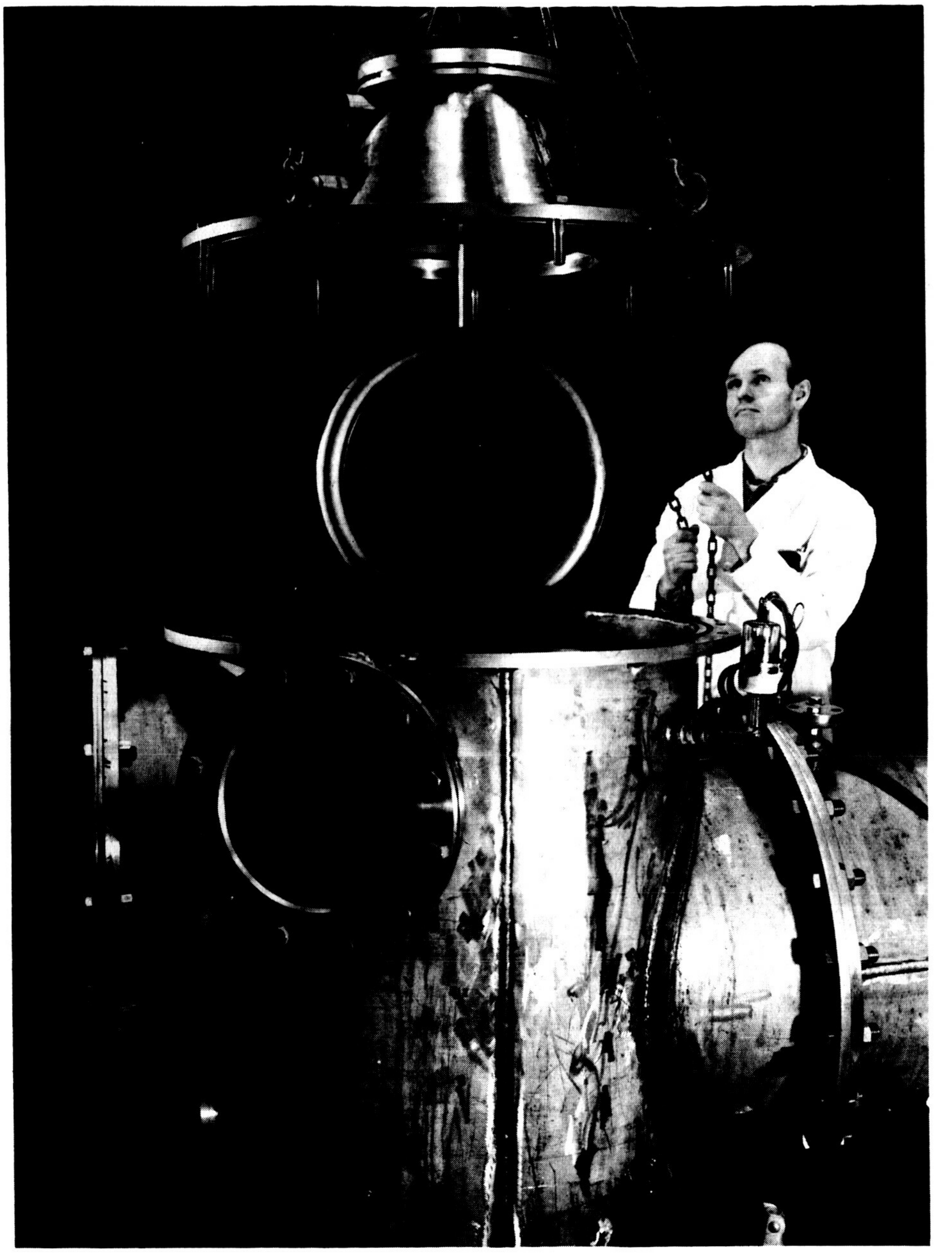

Fig. 5 The trouble with this experiment on a model Plasma Radiation Shield is the strut. This strut, an obvious necessity for an experiment in a vacuum tank, can be seen from Fig. 2 to represent a serious impediment to the electron drift motion. This defect guarantees that really high voltages can never be reached in strut-supported experiments of this kind.

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that space seems to be the only place where even a scaled-down test can be performed.

An alternative possibility is to make an invention which would allow laboratory study of at least some of the physical uncertainties to be made in a device having the same general principles of operation as the Plasma Radiation Shield, but a different geometrical configuration. Such an invention has been made - and it appears that the significance of this invention may go far beyond the mere simulation of parts of the Plasma Radiation Shield. It may conceivably open entirely new vistas in certain areas of nuclear physics. This device is illustrated in Fig. 6. It consists, like the Plasma Radiation Shield, of a torus, but now the electron cloud and magnetic field are on the inside - an arrangement obviously more suitable for laboratory study. Details of this device are given elsewhere,[13] but we note here that intrinsically it is as capable as the Plasma Radiation Shield of reaching voltages in the hundreds of millions, and that whereas, for the Plasma Radiation Shield, energetic protons can be described as being trapped at "infinity" in the lab device energetic protons can be "trapped" on the inside of the device. It is this property that opens vistas in nuclear physics. We shall not go into this subject here, but will merely point out that a tool of considerable interest to nuclear physicists may very well turn out to be descended - intellectually at least - from research on a serious and pressing problem associated with manned flights in deep space.

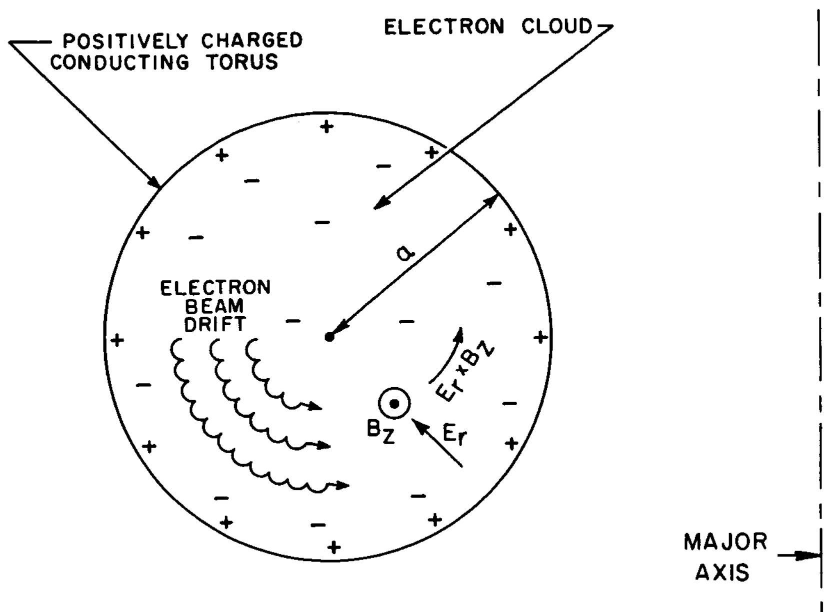

Fig. 6 This device, developed for the purpose of avoiding the difficulty illustrated in Fig. 5, may have interesting applications in the area of nuclear physics. In geometry it is a Plasma Radiation Shield turned inside out, but it operates on just the same principles. The large voltage now appears between the circular axis and the wall of the device. Any attempt to connect to this voltage would interrupt the electron drift motion — a situation analogous to that shown in Fig. 5 for the strut-supported Plasma Radiation Shield.

Conclusions

We conclude by observing that although Plasma Radiation Shielding has come a long way since its conception in November 1963, it is still surrounded on all sides by uncertainties. A vigorous program of research and development is under way which has already yielded many interesting results, as well as a potentially very exciting item of technological fall-out. Grounds exist for hope that the danger of solar flare proton radiation can be controlled in an elegant manner at a cost in weight which is a mere fraction of that required to do the same job by other means.

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14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional

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