Plasma Radiation Shield: Concept and Applications to Space Vehicles

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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. Other aspects of the plasma radiation shield discussed include selection of the shielding voltage, vehicle configuration possibilities, some aspects of the superconducting coil system, and the vehicle power supply. The effects of the plasma radiation shield on the communications, attitude control, propulsion, and life-support systems of the space vehicle are also considered.

Introduction

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 this 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 a comparatively low weight, provided that certain of its features 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 results sufficiently encouraging to make it worthwhile to consider the broader problems that must be solved if the concept is to be useful in a practical sense. The present paper 1) explains the fundamentals of the plasma radiation shielding concept; 2) outlines the present status of research and the remaining uncertainties on basic aspects of the concept; 3) lists the problem areas likely to arise in integrating the shield with a realistic spacecraft design; and 4) discusses these problem areas in general terms, quantitatively where possible.

The amount of solid shielding required to protect astronauts against solar flare protons has been much studied. A recent study[1] concludes that for a one-year mission at solar minimum, the thickness of aluminum required to keep the skin dose below 200 rem with 99% reliability was 5 g/cm^2; for 99.9% reliability the required thickness was 15 g/cm^2. The corresponding figures at solar maximum were 20 and about 80 g/cm^2. The total weight of a minimum spherical "storm cellar" 1 m in radius shielded by 80 g/cm^2 of aluminum is 26,000 lb, so that very severe weight penalties may be involved in providing adequate shielding for the entire crew of a one- or two-year deep space mission. 80 g/cm^2 of aluminum will stop a 340 Mev proton.

The large weights involved in solid shielding clearly suggest the desirability of finding an unconventional lightweight means of providing the necessary shielding. Two such methods, pure magnetic[2] and pure electrostatic[3] shielding, have previously been discussed in the literature. However, in our opinion, neither of these methods looks attractive; furthermore, the limitations on both methods are of a sufficiently fundamental character that it is unlikely that our conclusion 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 shield," described in Refs. 4 and 5. Briefly, the plasma radiation shield is an electrostatic shield; the shielding voltage is maintained between the space vehicle and a surrounding cloud of free electrons; the cloud of electrons is held in place by a magnetic field. The preliminary estimates of the weight of a plasma radiation shield given in Fig. 1 of Ref. 4 suggest the possibility of constructing a plasma radiation shield to shield a volume of 1000 m^3 against 200 Mev protons for a total weight of about 2000 kg; this compares with 50,000 kg using pure magnetic shielding, and over 100,000 kg using aluminum. Although these figures are subject to several important uncertainties, they still represent the best available estimate of the weight of a plasma radiation shielding system. The present paper is a brief review of the current status of research on the plasma radiation shield.

Electrostatics

The electric field in the plasma radiation shield is established between the space vehicle, which is positively charged, and a cloud of free electrons surrounding it. The outer edge of the electron cloud is at the potential of free space. The charges on the space vehicle and the electron cloud are equal and opposite, so that the arrangement can be considered as a capacitor. The charge Q, the voltage V, and the capacitance C are connected by the usual formula, $Q = CV$. From geometrical considerations, C will be on the order of 10^{-10} or 10^{-9} farads. For a voltage of 10^8 v, the charge is 10^{-2} or 10^{-1} coul, corresponding to a total of 10^{17} or 10^{18} electrons in the cloud. The electrostatic field energy is around 10^6 or 10^7 joules. If the electron cloud around the space vehicle occupies a volume of 10 m^3, a characteristic electron density in the cloud is 10^{10} or 10^{11} electrons/cm^3. Taking a characteristic dimension of the electron cloud as 1 m, a typical electric field is 1 Mv/cm, corresponding to a stress on the surface of the plasma radiation shield of about half an atmosphere. This stress, which represents the force of attraction between the positively charged vehicle and the

Received May 5, 1967; revision received March 4, 1968. This work was supported by the NASA Marshall Space Flight Center, under Contract NAS8-20310. It is a pleasure to acknowledge the assistance of G. S. Janes and J. D. Daugherty in connection with several parts of this paper.

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negative electron cloud, is therefore comparable in magnitude (and similar in direction) to the stress involved in providing a breathable atmosphere inside the pressurized space vehicle.

The Magnetic Field

The force exerted on an electron of charge $-e$ moving with velocity $\mathbf{v}$ in a magnetic field $\mathbf{B}$ is $-e(\mathbf{v} \times \mathbf{B})$. This force has no component parallel to $\mathbf{B}$, 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 a large voltage, 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 outside the space vehicle, and that is, in its simplest form, the magnetic field due to a loop of current. 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 topologically the same as the single loop coil. 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. 1 and 2. A discussion of these and other configurations is given later under the general heading of Vehicle Configuration Possibilities. For the present, we observe that the configuration of Fig. 2 is believed to have important advantages.

A 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 $B = E/v = E/\beta c$, where $\beta = v/c$, 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 $E = 0.5$ Mv/cm and assuming that the electron velocity can be one-half of its maximum value (i.e., $\beta = \frac{1}{2}$), we find a characteristic magnetic field of .33 webers/m^2, or 3.3 kgauss. This magnetic field is far below what would

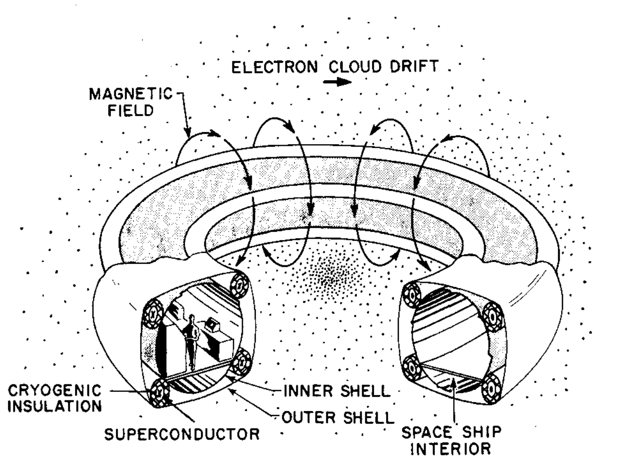

Fig. 1 A possible approach to the design of a space vehicle incorporating a plasma radiation shield. The magnetic field is provided by the 4-term superconducting coil. Note the direction of the drift of the electron cloud.

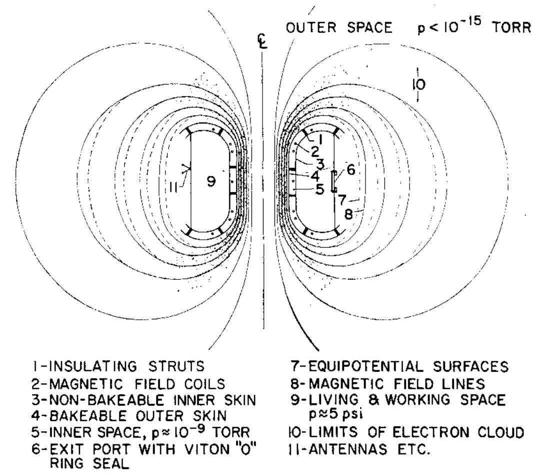

Fig. 2 Possible alternative configuration for a plasma radiation shielded space vehicle. The equipotentials follow magnetic field lines in the interior of the electron cloud, but are distinct outside of the cloud.

be required for a pure magnetic radiation shield. Note, however, that the strength of the magnetic field depends directly on our assumption about the electron velocity. Thus, if β had been chosen to be $\frac{1}{10}$ rather than $\frac{1}{2}$, the magnetic field would have been 5 times more intense than the 3.3 kgauss 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 kgauss. 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 $\beta = \frac{1}{2}$ 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. 2 would probably operate with rather substantial fields (10–30 kgauss) 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.

Containment of the Electron Cloud

We saw in the last section that for the electron cloud to be in equilibrium, the electrons had to be in motion, and, further, that the faster this motion, the smaller the required magnetic field. Thus the equilibrium of the electron cloud in the plasma radiation shield is dynamic rather than static. An indication of typical electron motions is given in Fig. 3. Now, although a dynamic equilibrium of this type is certainly possible, many difficult problems must be solved before it can be stated with assurance that this possibility can actually be realized. The basic problem is that the electron cloud has a

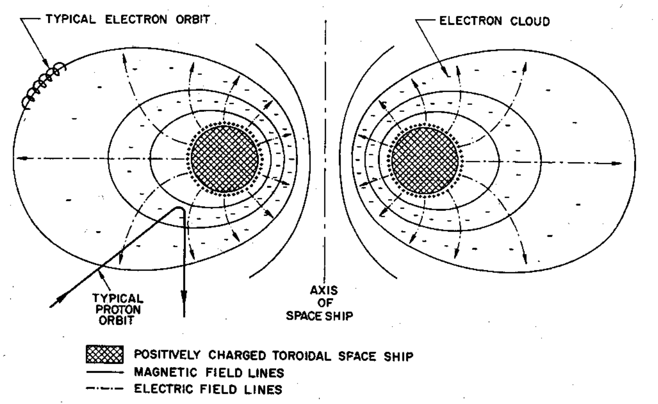

Fig. 3 Electric and magnetic field lines around a typical shield. The principal electron motion is an azimuthal drift around the axis of symmetry. The electrons may also have lesser motions along the magnetic field lines and around them in the manner shown.

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 ways of giving up free energy available to the electron cloud 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 $\approx 2 \times 10^5$ sec, and take the total charge in the cloud to be 0.02 coul, the loss current due to all losses should be substantially less than 0.1 μamp. A current of this magnitude crossing a voltage of 5×10^7 v yields a maximum acceptable loss power of 5.5 w. Put somewhat differently, at a speed of 0.5 c, an electron will drift around the plasma radiation shield in a time of about 0.1 μsec. Thus the mean direction of drift must be perpendicular to the electric field to an accuracy of roughly 1 part in 10^{12} (10^5 sec/0.1 μsec). Although the difficulties suggested by this very large nondimensional number are considerable, prolonged study has not brought to light any reason of a fundamental character why it should not be attained. Furthermore, pending full-scale demonstration of this degree of containment in the plasma radiation shield geometry, this double negative is the best that can be hoped for.

Briefly, the argument in favor of the possibility of attaining this degree of containment falls into two distinct parts. First of all, there is the possibility that the dynamic equilibrium in question is grossly 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., 0.1 μsec), 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 Refs. 6–11; 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)[12] 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.

If it is accepted that the equilibrium of the electron cloud is (or can be made) stable, the question of long-term containment reduces to keeping the various forms of classical diffusion to sufficiently small values. These forms involve collisions between electrons of the cloud and 1) other electrons, 2) positive ions, 3) neutral atoms leaked or outgassed from the space vehicle, and 4) particulate material such as micrometeorites or interplanetary dust. Of these mechanisms, only the third seems to pose a serious problem, and will require a greater degree of control over outgassing and leaks than is normally contemplated for space vehicles. The reason for the stringent requirements in this area arises as follows: a neutral atom leaving the space vehicle and struck by an electron of the cloud will usually be ionized; on account of its mass the positive ion thus formed is not restrained by the magnetic field but is accelerated away from the space vehicle by the electric field. If the event takes place at a potential of 50 Mv above the potential of free space (i.e., near the surface of the space vehicle), the ion will acquire, and the electron cloud will lose, an energy of 50 Mev. Thus a leak rate of only 10^{12} atoms/sec could cause a loss current equal to the maximum permissible value of 0.1 μamp. This rate corresponds to the loss of gas on the order of 1 μg/day from the whole vehicle.

This calculation is extreme in many respects but does indicate clearly that control of leaks and outgassing will be a serious problem in the design of a plasma radiation shield. We cannot here go into the various means of alleviating the problem,[5] but it appears that with a good configuration (perhaps that of Fig. 2) and careful attention to detail the requirements in this area can be met.

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 that 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. 13 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. 14, 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. 13 shows that the maximum surface dose behind 10 g/cm² 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 g/cm^2 of aluminum. Reference to range-energy tables 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 g/cm^2 aluminum. Suppose, for example, that it is required to stop 100 Mev protons. If the skin thickness is 2 g/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 v 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 g/cm^2 of skin. If the skin thickness is 4 g/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 g/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. 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 g/cm^2, with plasma radiation shield voltages of 60 and 40 million v, respectively. Another way to look at Fig. 4 is to consider the relative effectiveness of, say, a 40 million v plasma radiation shield against protons of various energies. For example, to stop a 100 Mev proton requires 10 g/cm^2 of solid shielding. But we saw previously that 40 Mv plasma radiation shielding ahead of 4 g/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 g/cm^2 of solid shielding. Again, to stop a 150 Mev proton requires 19 g/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 g/cm^2. At this level, the 40 Mv plasma radiation shield is the equivalent of 7 g/cm^2 of solid shielding.

The conclusion to be drawn from Fig. 4 is therefore that the total voltage of the plasma radiation shield can be reduced considerably by considering the effect of the vehicle skin. More generally, Fig. 4 suggests that an optimization could be performed to divide the total shielding between electrostatic and solid in such a way as to minimize the total weight. Sufficient data are not yet at hand to perform this minimization with confidence.

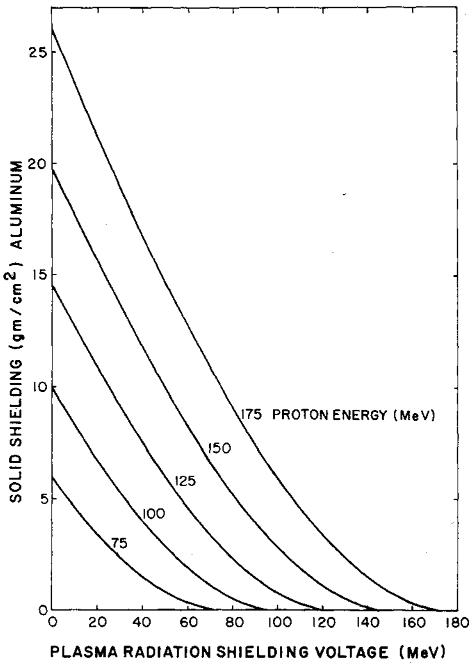

Fig. 4 Tradeoff curves appropriate to a combination of electrostatic and solid shielding.

Vehicle Configuration Possibilities

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. 5a to 5f 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. Figure 5a 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 ft 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 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. 5b, which shows a larger space vehicle constructed from two rigid toroidal modules. The modules could be stacked up, for instance, on a 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. 5a, 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. 5c 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. 5c 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 ve-

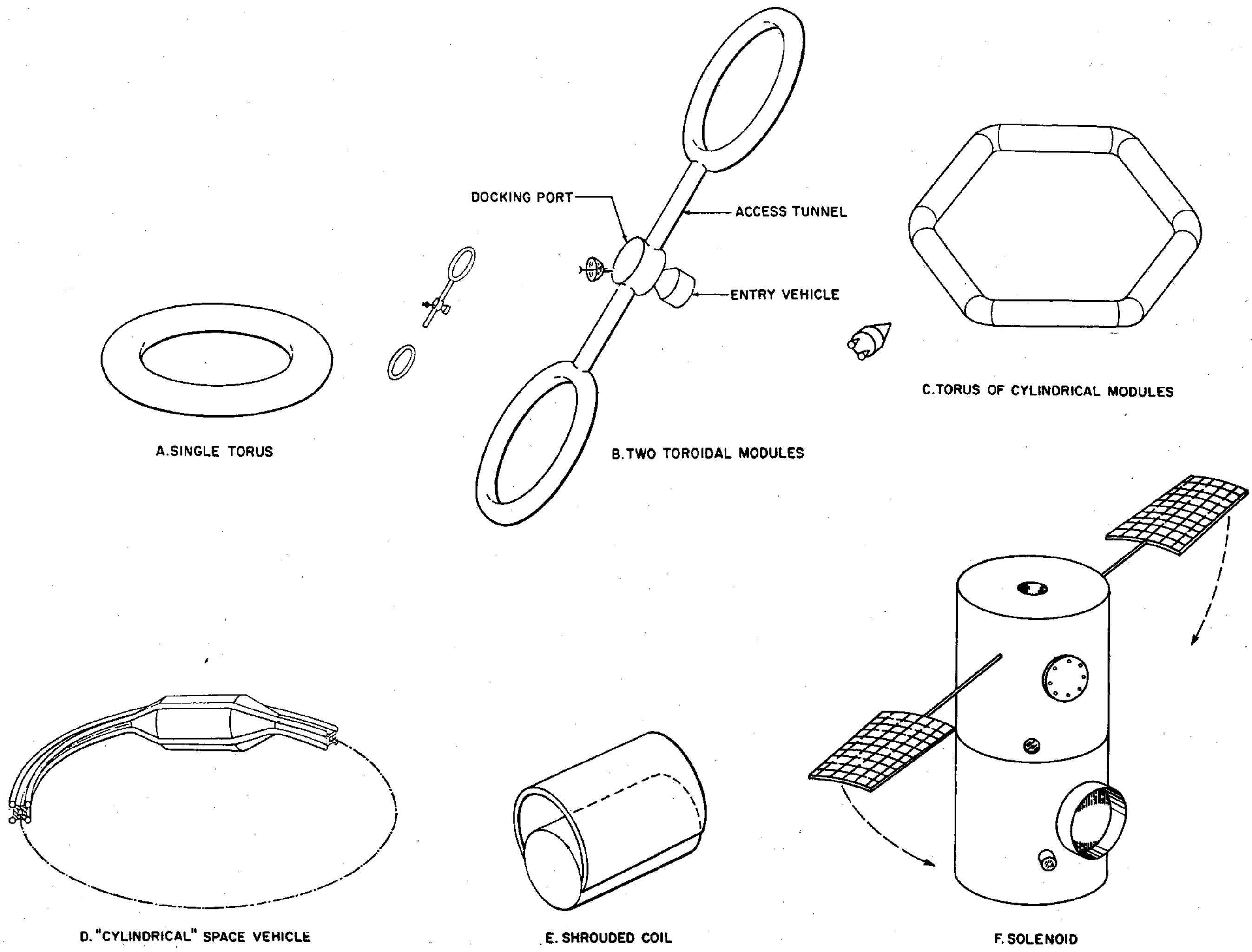

Fig. 5 Some possible configurations of spacecraft that utilize the plasma radiation shield concept.

hicle shown in Fig. 5c 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. 5d, 5e, and 5f. In Fig. 5d 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. 5e is a variation of that shown in Fig. 5d, 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. 5f where the vehicle has many of the characteristics of a solenoid (see also Fig. 2). 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. 5f, 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 previously that the outer surfaces of the vehicles (with the possible exception of that shown in Fig. 5f) 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.

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°K (boiling point of liquid helium). But the plasma radiation shield may be operated with relatively small fields over the relatively large volumes. In this case it might be adequate to operate around 13°K†

† For example, Niobium-Tin has a critical temperature of over 18°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°K and room temperature is three times greater than the efficiency of a cycle operating from 4.2°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. 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 ER. Thus

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

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 $V = 50 \times 10^6$ v and $\beta = \frac{1}{2}$, the preceding relation yields a current of 3×10^5 amp, 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 amp turns as a typical value, allowing a factor of 10 for the various uncertainties in the preceding equation.

Present-day superconductors are characterized by maximum current densities of about 10^4 amp/cm², 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/cm² will be available, then the cross-sectional area of superconductor required, $A_{s.c.}$, will be $10^{-5}I$ cm². If $I = 3 \times 10^6$ amp, $A_{s.c.} = 30$ cm². The associated mass of superconductor, $M_{s.c.}$, is then

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

$\rho_{s.c.}$ is the density of the superconducting material, and may be taken as 10 g/cm³. The value of R depends on the coil configuration but will probably be in the neighborhood of 5 m. 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, the area of the cryogenic surface is

$$A_{cry} = 0.7R(I/10^6)^{1/2} \text{ m}^2$$

For $I = 3 \times 10^6$ amps, $R = 5$m. This is 6.6 m², and is less sensitive to the uncertainty in I than $M_{s.c.}$. The four-coil arrangement of Fig. 1, having one-quarter the current in each of four coils, would have twice the cryogenic area, about 13.2 m². If the configuration of Fig. 2 used a winding distributed along the length of the solenoid, A_{cry} might be as much as 50 m². 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 (based on Ref. 2). From this figure it is seen that if $A_{cry} = 50$ m², 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.

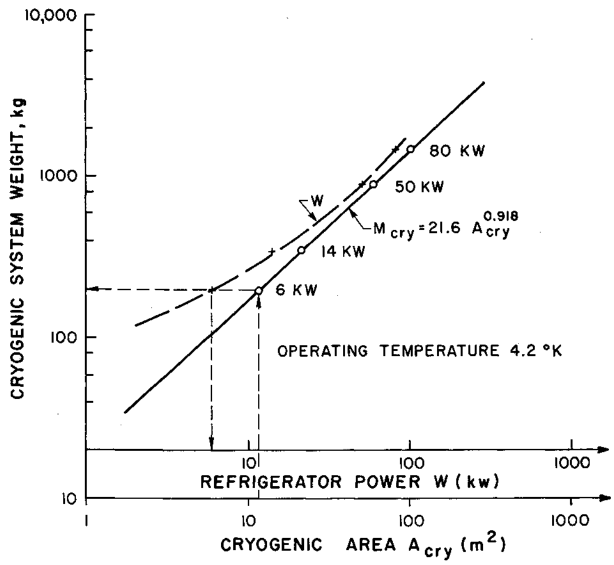

Fig. 6 Mass and required power for a cryogenic system comprising insulation, refrigerator, power supply, and waste heat radiator. The weight of the last two was estimated using a conversion figure of about 10 kg/kw. The graph is for an operating temperature of 4.2°K. At 13°K, all powers and weights would be reduced by a factor of about 3.

The 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.[2] 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. 1 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 associated with the configuration of Fig. 2 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. 1 or the solenoid of Fig. 2. Such designs, however, would entail a penalty in surface area (and hence refrigeration).

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.

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 v 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 10, 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 $1\frac{1}{2}$ hr, the power that must be supplied during this time is about 10 kw for a 50 Mv 50 Mjoule 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. 2) 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 byproduct 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.[15] 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

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

Including the tankage, the total weight of the power supply using hydrogen-oxygen fuel cells should be around 1500 lb 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 $1\frac{1}{2}$ hr is about 200 w-hr/lb.[16,17] Using 10 of these units for the mission would result in a total power supply system weight of about

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

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 lb. 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.

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. 2, 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 $n_e = (2.1 \times 10^8)/\text{cm}^3$, the plasma frequency is 130 MHz. 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.

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.

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. Although 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.[9] 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.

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.

Turning the Plasma Radiation Shield On and Off

It is intended to turn the plasma radiation shield on by a scheme called "inductive charge ejection."[5] In this scheme, which has worked well in scale experiments, the electrons are ejected from the vehicle while the magnetic field is being built up. Basically the electrons are placed on magnetic flux surfaces near the vehicle, and then these surfaces are carried away by the increasing magnetic field. In this way the power supply energizing the magnet also energizes the electrostatic field; the process is analogous to the charging of a Van de Graaff machine, with the magnetic flux surfaces playing the role of the moving belt. This charging process is reversible; reducing the magnetic field corresponds to reversing the belt and has the effect of carrying charge "downhill." This seems to be the obvious way of turning off the plasma radiation shield, though not the only one.

The Inductive Charge Ejection scheme is only reversible with reference to the electrostatic field energy; it cannot supply the kinetic energy of the electrons, and this energy must be dissipated if the scheme is used in reverse for turnoff. However, although the potential energy of each electron may be tens or hundreds of Mev, the kinetic energy is fixed by the electron speed. For $\beta = \frac{1}{2}$ this energy is 80 kev/electron, and if the cloud contains a total of 10^{18} electrons, the total kinetic energy is 13 kjoule. During turnoff, or as a result of leakage in regular operation, this energy could conceivably be an x-ray radiation hazard.

Radiation Hazard of the Electron Cloud

As explained previously the electron kinetic energy may ultimately be dissipated on the vehicle. For comparison, a single typical x-ray photograph may involve 10^{16} electrons of 100 kev each. The worst possible case would then correspond to about 100 x-ray photographs. However, whether in turn off, or by simple leakage, the electrons approach the vehicle in a very tight spiral, so that it should be easily possible to control their point of impact by extending a target a very small distance into the electron cloud. This would concentrate the source of x-rays in a small region. Furthermore, by using a low Z target, the yield of x-rays could be reduced from the yield on a tungsten ($Z = 74$) target as used in medical practice by about 100. This gives a final flux about equal to that used in a single medical x-ray, but even then the source could be shielded by, say, $\frac{1}{8}$ in. of lead and placed at a distance of some meters from the astronauts. For these reasons, x-rays produced by the electron cloud would not seem to constitute a hazard.

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 over-all 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 over-all configuration, and control of leaks.

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.

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