RADIATION SHIELDING OF SPACE VEHICLES BY MEANS OF SUPERCONDUCTING COILS

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by

Richard H. Levy

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

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Richard H. Levy
AVCO-Everett Research Laboratory.
Everett, Massachusetts

Abstract

The general problem of shielding the occupants of manned space vehicles from various radiations likely to be encountered in space flight is discussed, and various published papers on the subject are briefly reviewed. The review indicates the importance of the problem and the interest that would attach to a radical solution. One possibility is shielding by the permanent magnetic field of a superconducting coil. A detailed analysis is made of the shielding that could be provided by such a coil and a preliminary estimate of the weight of such a device is made paying particular attention to the weight of the structure required to support the coil. A comparison is made of the weights calculated in this way with the weight of the spherical H$_2$O shield which would give comparable protection.

Introduction

With the advent of manned space vehicles, considerable attention is being devoted to the problem of protecting the occupants of such vehicles from the harmful and dangerous effects of ionizing radiation. This radiation arises from three principal sources: the Van Allen belts surrounding the earth, solar flares which occur from time to time with wide variations in strength, and galactic cosmic radiation. Protection of space travellers from some or all of these sources of radiation has been considered by many authors, and nearly all consider shielding by the straightforward method of interposing solid masses between a shielded region and the exterior world.

The possibility of using magnetic fields for shielding has also been discussed (e. g. (1) and (2)). That magnetic shields can provide effective shielding is clear since the earth's field provides a shielding effect against energetic charged particles (at least in low geomagnetic latitudes), while apparent changes in the level of cosmic radiation are attributed to changes in the shielding effect of the interplanetary
field. (3). Practical magnetic shields have, however, appeared unattractive since the power required to provide the necessary field is so large. On the other hand, Dow (1) points out that superconductors might be used to advantage, and it is the purpose of this paper to show in some detail that this is indeed possible, especially in view of the recent spectacular advances in superconductors achieved at Bell Telephone Laboratories (4).

**Review of Literature**

The literature on the radiation protection problem is very extensive, and it is not the purpose of this paper to provide anything approaching an exhaustive survey. Rather, certain papers have been selected to show in a general way the nature and size of the problem and to collate some results for comparative purposes.

The papers in which we are interested may be divided into three classes. In the first class are those papers in which measurements of the actual quantities of the ionizing radiation are reported. The second class consists of biologically oriented papers in which the effects of radiation are discussed and, in many cases, limits are set for permissible radiation doses. The third class of papers combines the radiation measurements and the permissible dose levels to draw conclusions about shielding weights required in various cases.

Rather complete lists of references to radiation measurements are given in (5), (6), (7) as well as many others. The radiations of interest may be divided into three principal classes: galactic cosmic radiation which changes slightly in accordance with the 11 year solar cycle (3) and consists of extremely energetic primaries in the range from $10^8$ ev up to at least $10^{16}$ ev; geomagnetically trapped radiation in the two Van Allen belts, but principally the lower belt which has a component of protons with energies of the order of $10^8$ ev; and last but by no means least the sporadic emission from the sun of energetic protons associated with solar flares.

Numerous references are available on the biological aspects of these and other radiations; we will refer principally to (8), (9), (10), (11), in outline, the quantities of principal interest are the energy deposited per gram of tissue (which gives the dose in rads) and the "relative biological equivalent" or RBE which is a number depending on the type of radiation (X-rays, gamma rays, protons, neutrons, etc.) and which, when multiplied by the dose in rads, gives the dose in rem. For our purposes it will generally be satisfactory to take the RBE of energetic protons as unity.
As to the question of permissible doses in manned space flight, most authorities ([6], [7], etc.) seem to be in agreement that there should be a "design dose" of approximately 5 rem and an "emergency dose" of 25 rem. The most complete discussion of this question known to the author is given in [6]. Some authors ([5], [12]) recommend higher doses than the above; the reasons given are generally that the shielding problem is insoluble with the doses given above and a compromise must be made at some point. By way of comparison 400 rem will be fatal to approximately 50 per cent of a group of individuals.

The conclusions that may be drawn in a general way from the published literature are as follows:

1. The dosage rates from primary galactic cosmic radiation are on the order of 5 - 12 rem/yr. This figure assumes firstly that no exceptional and highly localized damage is to be expected from individual energetic heavy primaries. This is a very uncertain point and is discussed, for instance in [9]. Secondly, the multiplying effects which may be introduced by the passage of the primary particles through the shielding provided are ignored. If these assumptions are granted, it is clear that cosmic radiation implies no unacceptable hazard for trips lasting up to about a year. It will be shown in the course of this paper that for trips approaching this length shielding against particles with energies up to 1 Bev or so will be required; such shielding would certainly reduce the cosmic ray dose so that ultimately we may conclude that cosmic rays will not imply a limiting design criterion. This statement is subject to the reservations implied by the above assumptions both of which require much more attention.

2. The dosage rates that would result from unprotected exposure to the inner and outer Van Allen belts are estimated at 24 rem/hr and 200 rem/hr respectively ([3]). However, the outer belt dosage is delivered chiefly by energetic electrons which are relatively easy to stop, while the inner belt dosage comes from energetic protons which have a much higher penetrating power. Thus, in order to reduce the dose from 24 rem/hr to 0.5 rem/hr it is indicated that 800 kg/m² of shielding would be required.

In considering dose rates in the Van Allen belts it is clearly essential to discuss the particular mission involved. For the total dose delivered will depend strongly on the time which it is planned to spend in these belts. These considerations have their greatest effect on the so-called "low-thrust spiral escape trajectories" as considered in ([4]). In this paper it is estimated that adequate shielding for a spiral escape maneuver at 10⁻³ g's would be nearly 1000 kg/m². At the opposite extreme is the work reported in ([5]) where it is proposed to depart from the earth over the north pole in
order to avoid the worst parts of the radiation belts. This approach is interesting, but tends to impose difficult restraints on the astrodynamical problems of the trip. Also, in this approach as in all others, the problem of the abort trajectories might prove to be the limiting factor.

3. Mention was made in the previous paragraph of surface densities of shielding material required for this or that purpose. Several points must be made in this connection. In the first place, the stopping by electronic collision of an energetic proton in matter is well understood. Curves can be drawn showing the range (in kg/m²) of a proton of a given energy in any particular material. Such curves are drawn, e.g., in (16), (17), and (23). It appears that on a stopping power per unit weight basis, hydrogen is uniquely powerful. However, it is unsuitable for shielding purposes owing to its great bulk even in liquid form. In consequence, it is nearly always proposed that proton shields be made either of carbon, or of water. The stopping power of these materials is similar; range-energy curves for either show that a 100 Mev proton will penetrate about 76 kg/m² of water or 85 kg/m² of carbon and a 1 Bev proton will penetrate 3215 kg/m² of water or 3579 kg/m² of carbon. It must now be emphasized that these ranges neglect nuclear interactions. These interactions become increasingly likely at high energies; the ones of interest are chiefly of the type (p, n) and (p, pn). By means of such reactions it is certainly possible to generate secondary particles to the extent that they will figure importantly in calculating the radiation dose. Most of the secondary particles will be neutrons which will travel considerable distances through any shielding material.

The treatment of these secondary radiations in the literature is very uneven. The reasons for this appear to be (among others), shortage of accurate nuclear cross sections for these reactions at the energy levels considered and the strong dependence on the particular material used. In this regard, it is interesting to note that hydrogen (which cannot produce neutrons in this manner) would again be a logical choice for shielding; however, the arguments given above are still sufficient to make its use nevertheless undesirable.

Possibly the most comprehensive treatment in the literature of this problem is given in (16). In this paper a careful estimate of the neutron yield is made; the number of neutrons produced (in copper) per proton as a function of the incident proton energy is given as $E^2/9 \times 10^4$ in the range 10 - 1000 Mev. Now in the Van Allen belts, and in solar flares, the spectrum of energetic protons is typically of the form $E^{-a}$, where a is some number generally greater than 2 and frequently as high as 5. This leads to the unexpected conclusion that more neutrons are produced by the low energy.
incident protons than by the high energy protons. This implies that for the calculation of the secondary dose it is essential to know accurately the spectrum of the incident radiation down to slightly above the threshold energy to produce neutrons. From this point of view, carbon is an ideal shielding material since the threshold energy in question is about 18 Mev. This is definitely below the present level of accurate measurements in space, and indicates an important field for investigation in connection with the use of solid shielding.

Many other papers (e.g. (12)) refer to the problem of the secondaries, but none of these seem to be as detailed as the one just cited. On the other hand, a remarkable statement concerning these effects appears without support in (18). This is to the effect that in a really large flare (such as that of February 23, 1956), the neutrons produced in shielding material are so numerous that the effect of the first 1000 kg/m² of shielding is to make the net dose worse rather than better! The implications of this situation will be dealt with in the next section.

4. We have now dealt with the literature on radiation shielding in the contexts of cosmic radiation, the Van Allen belts, and the production of secondary energetic particles in a radiation shield; it is now time to turn to what is apparently the most serious of all the problems in this field, namely that posed by the eruption from time to time of violent solar flares which fling out huge quantities of highly energetic protons. Most of the more recent literature on radiation shielding concentrates strongly on these events; noteworthy in this respect are (12) and (16).

From the shielding point of view the most important aspects of solar flares are that they occur from time to time with enormous variations in intensity (although they are considerably more frequent at times of sunspot maximum); that they send out beams which consist almost entirely of protons having a steep energy spectrum; that they start very rapidly (a few minutes) and decline slowly, over a period of 6 - 24 hours, the total intensity usually decaying like the square of the time.

The shielding problems posed by these flares is immense; the largest event known might have required 5800 kg/m² of shielding (without considering the secondaries) (16) although subsequent estimates (again omitting secondary effects) are somewhat lower (12). The current treatment of the shielding problem appears to run along the following lines: it is thought that an improved understanding of the solar mechanisms involved may lead to a method of forecasting the occurrence of large flares; missions would be undertaken when the forecast was favorable. At present, it is hoped (18), (25) to be able to predict flares four days ahead, and this might
conceivably be extended to times of the order of a week. As a week is about the time of formation of an active sunspot group it is unlikely that prediction schemes could work for longer periods than this. A successful prediction scheme of this type would permit missions of the order of one or two weeks to be undertaken with reasonable probabilities of success. It must be emphasised, however, that it really is a question of probabilities, since the processes involved are extremely complex and quite poorly understood. In many ways, solar flare prediction is analogous to weather prediction. Again, it must be recognised that solar flares are so frequent at solar maximum that a large fraction of the days in the neighborhood of solar maximum may yield unfavorable predictions.

On the other hand, as the mission grows longer we find two effects growing increasingly important; first, as the quality of the prediction deteriorates, the risk of encountering a large flare will grow. Secondly, a sufficiently long term prediction will ultimately be indistinguishable from a purely random calculation based solely on knowledge of the overall frequencies of occurrence. Thus, a point will be reached where a forecast will at all times state with some confidence that during the next interval of such and such a length one or more large flares will certainly occur. It is of some interest to estimate roughly the length of time during which a large flare will almost always occur.

Since observations of flares have been maintained, only seven flares of the largest class (Class 4) have been observed. It is significant that these seven flares do not show a very strong correlation with the sunspot number. Furthermore, since the frequency of occurrence is of the order of 0.4 per year, it will be many years before a good statistical analysis can be made. Since we could hardly contemplate leaving on a mission with less than a 90 per cent chance of avoiding such a flare, it is clear that for mission times over about three months shielding adequate for protection in the largest flares known will have to be carried. Such shielding will probably have to be capable of stopping protons with energies of the order of 1 Bev. Three months is certainly less than the time required for round trips even to the nearest planets. As a result we may confidently predict that before manned voyages to the planets can be made, a solution will have to be found to the problem of radiation protection against the most violent flares known. The dosage behind such shielding will have to be calculated on the basis of the possibility of the occurrence of at least one Class 4 flare as well as a wide variety of smaller flares; each individual flare will have to deliver much less than the allowable total dose.
5. The shielding problem, as it has been reviewed, is clearly a problem of the first magnitude, and it is obviously worthwhile to try to solve the problem in a radical manner. Two such methods have been discussed, namely, electrostatic and magnetic shielding (1), (2). The former appears to be quite impractical since in order to shield against a proton having an energy of 1 Bev it is necessary to maintain the shield at a potential of $10^9$ volts. This far exceeds the capacity of the heaviest ground based generators so far constructed (although it is possible that conditions in space might make the leakage problem slightly more tractable). In addition, it appears to have the serious disadvantage that electrons will strike the shield with the same energy, namely 1 Bev, and this will itself pose a considerable shielding problem, especially in view of the X-rays likely to be produced by such a process. Finally, unlike the magnetic shield to be discussed, it will have a definite power consumption.

The remaining possibility is a magnetic shield; the chief problem in this context is the huge power required to provide the necessary field and and remove the dissipated heat. However, in (1), the possibility of using superconductors, in which no power at all would be dissipated, is mentioned. The recent spectacular advances in superconductors (4) have brought this idea to the verge of possibility, and it is the purpose of this paper to show in a general way how such a shield might operate.

**Analysis**

We now turn to the analysis of the shielding effects of magnetic fields. There are many references to such calculations, mostly having reference to cosmic radiation in the earth’s field (e. g. (19)), but it will be suitable here to give a brief review of the principal features of this work.

The equation of motion of a proton moving under the influence of an axially symmetric magnetic field only is:

$$\frac{d}{dt} \left\{ \frac{m_p v}{\sqrt{1 - v^2/c^2}} \right\} = e \frac{v \times B}{c^2}$$

(1)

Since the force is perpendicular to the velocity vector, we conclude at once that the speed $v$ is a constant of the motion. Since the field is supposed to have axial symmetry, the vector potential $A$ has only one component $A_\phi$, say, where $r$, $\theta$, $\phi$ are spherical polar coordinates. The equation of motion in the $\phi$ direction can now be written
\[ \frac{m_p}{\sqrt{1 - \nu^2/c^2}} \frac{d}{dt} (\gamma \sin^2 \theta \phi) = -e \frac{d}{dt} (\gamma \sin \theta A_\phi) \]  

and this can be integrated to yield

\[ Q = -\frac{\gamma \sin \theta \phi}{\nu} = \frac{e A_\phi}{\nu} + \frac{2 \gamma m_p}{\nu \gamma \sin \theta} \]  

where \( \gamma \) is a constant of integration. Since, for a finite distribution of currents \( A_\phi \to r^{-2} \) as \( r \to \infty \), \( \gamma \) can be seen to be proportional to the angular momentum about the polar axis when the particle is at infinity.

We next introduce the Stormer radius \( c^2 = em/4\pi p \) which is a length scale for motion of a particle of momentum \( p \) and charge \( e \) in the field of a dipole of magnetic moment \( m \). A clearer idea of this quantity is obtained if it is noticed that the Larmor radius of a proton of momentum \( p \) moving in the equatorial plane of a dipole of magnetic moment \( m \) at a distance \( c \) from the dipole is just the Stormer radius \( c \). This implies that there exists a circular equatorial orbit of radius \( c \) with center at the dipole.

Introducing the non-dimensional quantities \( A_\phi = 4\pi a^2 \frac{A_\phi}{m} \), \( \rho = r/c \), \( \nu = \gamma m_p/pc \), \( \lambda = a/c \) where, for the moment, \( a \) may be taken to represent an arbitrary length. Eq. (3) becomes

\[ Q = \sqrt{\frac{\gamma}{\nu}} \lambda^2 + 2 \frac{\nu}{\gamma} \sin \theta \]  

Finally we note that since \( r \sin \theta \phi \) is one component of the velocity \( \nu \), we have

\[ |Q| = \left| \frac{\gamma \sin \theta \phi}{\nu} \right| \leq 1 \]  

Now for a dipole field, \( A_\phi = (a/r)^2 \sin \theta \), and Eq. (4)
becomes

\[ Q = \frac{\sin \theta}{\rho^2} + \frac{2\gamma}{\rho \sin \theta} \]

Clearly as \( \rho \to 0 \), \( Q \to \infty \) provided \( \sin \theta \) and \( \gamma \) do not both vanish. Thus, there is a "forbidden region" near the dipole into which particles cannot penetrate, and which is given by the condition \( Q > 1 \), or

\[ \rho < \left[ \frac{\gamma}{\sqrt{\gamma^2 + \sin^2 \theta}} \right] \frac{1}{\sin \theta} \]

(6)

It can be seen (e.g., by differentiation) that this function increases steadily with \( \gamma \), but vanishes as \( \gamma \to -\infty \). However, for large negative values of \( \gamma \) there is an additional forbidden region defined by

\[ \frac{-\sqrt{\gamma^2 - \sin^3 \theta}}{\sin \theta} \leq \rho \leq \frac{-\sqrt{\gamma^2 - \sin^3 \theta}}{\sin \theta} \]

(7)

The existence of this region implies that only periodic orbits can exist in the neighborhood of the inner forbidden region. Since this excludes normal radiation which comes from infinity, it puts the effective boundary of the forbidden region at the upper limit of Eq. (7) as long as the interval defined by Eq. (7) is finite. This ceases to be the case when \( \gamma = -1 \), \( \sin \theta = 1 \), so the final radiation-free region is given by letting \( \gamma = -1 \) in Eq. (6):

\[ \rho = \frac{\sqrt{1 + \sin^3 \theta} - 1}{\sin \theta} \]

(8)

Sketches of the various forbidden and permitted zones are displayed in Fig. 1 for various values of \( \gamma \), and the plot of Eq. (8) is given in Fig. 2. Among the interesting deductions
Fig. 1 Radiation Free Zones for Dipole Field.
Fig. 2 Shielded Zones for Dipole Field.
from this analysis are the following:

1. It is not necessary to orient the field with respect to the incident radiation, since all incident directions are included in this analysis. A singular case is radiation approaching directly along the axis, but it will be shown that even this case is included when we consider a coil rather than an imaginary dipole.

2. A space vehicle of the shape defined in Fig. 2 and carrying a magnetic dipole at its center would be completely shielded against radiation of energy less than that implied by the design. However, we note that the equatorial dimension of this shape is \( r = (\sqrt{2} - 1) c \approx 0.41 c \). The factor of 0.41 is missing in (1), so that the figures given there are about two and one-half times too large. Correct values are shown in Fig. 3.

The origin of the factor 0.41 can be seen from a study of the particle orbits in the equatorial plane. These orbits (which can be integrated explicitly) are shown in Fig. 4; the shape of the critical orbit for which \( \gamma \) is just greater than -1 is particularly interesting.

The analysis above was originally due to Stormer and may be found in many places (e.g. (19)).

We now turn to the analogous calculation for the case of a single turn circular coil. This shape seems to be appropriate for consideration at this stage in view of its relative simplicity; however, it is not at all certain that it is the optimum shape for a shielding device.

If the coil has radius \( a \) and carries a current \( I \), the non-dimensionalized vector potential may be written:

\[
\overline{A}_\phi = \frac{4 \frac{I}{k}}{\pi \left( \frac{r}{a} \right)^2 + 1 + \frac{2r}{a} \sin \theta}
\]

(9)

where

\[
k^2 = \frac{4 \frac{r}{a} \sin \theta}{\left( \frac{r}{a} \right)^2 + 1 + \frac{2r}{a} \sin \theta}
\]

(10)
Fig. 3 Dipole Shielding Distances.
and where \( C(k^2) \) is a complete elliptic integral. (For definitions and formulae on elliptic integrals used in this paper see (20) and (21)).

We also note that \( \lambda \), which is now defined as the ratio of the two characteristic lengths of the problem (namely the coil radius and the Stormer radius), is a free parameter; the determination of \( \lambda \) will be made in the course of an optimization procedure described in the next section. For the moment, it is sufficient to remark that \( \lambda \to 0 \) will give the dipole results, where the dipole is regarded as an infinitesimal circular coil, carrying infinite current.

Now as \( r \to \infty \), \( A_\phi \to (4\pi)^2 \sin \theta \), the dipole value, as expected. As \( r \to 0 \), \( A_\phi \to \frac{1}{4} \sin \theta \). We can write Eq. (3) as

\[
Q = \frac{4\pi^2 C(k^2)}{11 \lambda \sqrt{\rho^2 + \lambda^2 + 2\rho \lambda \sin \theta}} + \frac{2\bar{\gamma}}{\rho \sin \theta}
\]

(11)

where

\[
k^2 = \frac{4\lambda \rho}{\rho^2 + \lambda^2 + 2\rho \lambda \sin \theta}
\]

(12)

Now for any non-zero \( \bar{\gamma} \), as \( \rho \to 0 \) or as \( \rho \to \infty \) the second term in Eq. (11) dominates. Thus, there is always a forbidden region \(|Q| > 1\) near the axis and a permitted region \(|Q| \leq 1\) far from the coil. When \( \rho = \lambda \), \( \theta = \pi/2 \), at the coil, the first term tends logarithmically to plus infinity. Thus, there is also a forbidden region around the coil whose boundary is given by \( Q = 1 \). Next, when \( \theta = \pi/2 \), \( \bar{\gamma} \to -\infty \), \( Q \) has a negative minimum value for some \( \rho > \lambda \). If this minimum is less than \(-1\) there will be a forbidden region cutting the equatorial plane at the two points for which \( \rho > \lambda \) and \( Q = -1 \). This region is analogous to that defined by Eq. (7) for the dipole case, and, as in that case, we will be interested in that negative value of \( \bar{\gamma} \) for which the region just vanishes; that is to say the value of \( \bar{\gamma} \) for which the
minimum value of Q is just -1. These statements depend on
the reasonable assumptions (justified by the smoothness of
the functions involved) that the forbidden region which exists
beyond the coil (for sufficiently large negative \( \gamma \)) is connected
with the forbidden region at the axis and completely surrounds
the permitted region whose inner boundary is the outer bound-
ary of the forbidden region surrounding the coil. If this is
the case, we have a situation analogous to that obtaining in
the case of a dipole field, namely one in which orbits origi-
nating at infinity cannot reach an inner permitted region which,
in consequence, can only contain periodic orbits. The sepa-
ration between the inner and outer permitted regions may be
expected to vanish first in the equatorial plane and will be
determined, as indicated above, by the condition that the
minimum value of Q is just -1. The critical value of \( \gamma \) for
which this condition is satisfied will be called \( \gamma_c \). A final
assumption is that the forbidden region around the coil grows
continuously with \( \gamma \) (as in Eq. (6)), so that the inner forbidden
region determined for \( \gamma = \gamma_c \) is the final radiation free zone.
All these statements are illustrated and heuristically justified
in Fig. 5 where the various forbidden and permitted regions
are shown for different values of \( \gamma \) and for \( \lambda = 0.36 \).

The next problem is the numerical determination of
\( \gamma_c \) as a function of \( \lambda \); this is achieved as follows: introducing
the non-dimensional distance \( s = r/a = \rho/\lambda \), and setting
\( \sin \theta = 1 \) in Eq. (11) gives

\[
Q = \frac{4k^2 C(k^2)}{\pi \lambda^2 (\lambda^2 + 1)} - \frac{2\gamma}{\lambda^2}
\]  

(13)

where

\[
k^2 = 4\lambda (\lambda^2 + 1)^{-2}
\]  

(14)

Differentiating, and setting the result equal to zero, we find (by Landen's transformation)

\[
-\frac{\gamma_c}{\lambda} = \frac{2\lambda}{\pi (\lambda^2 + 1)^2} \frac{E(\frac{1}{\lambda^2})}{\lambda^2}
\]  

(15)
Fig. 5 Radiation Free Zones for Coil Field.
since \( \bar{s} \) (the value of \( s \) at the minimum) is greater than unity. With \( \overline{\gamma} \) given by Eq. (15), we can substitute in Eq. (13), and after setting \( Q = -1 \), obtain

\[
\lambda^2 = \frac{4}{\ln(\overline{\Lambda}^2 - 1)} \mathcal{B}\left(\frac{1}{\overline{\Lambda}^2}\right)
\]

(16)

Eqs. (15) and (16) are now simultaneous equations giving \( \overline{\gamma}_C \) as a function of \( \lambda \). These equations have been solved for a wide range of values of \( \lambda \), and the results are presented in Fig. 6. We note that as \( \lambda \to 0 \), \( \overline{\gamma}_C \to -1 \), while \( s \to \infty \) in such a way that \( \rho = \lambda s \to 1 \), corresponding to the dipole situation.

Having obtained these values of \( \overline{\gamma}_C \) as a function of \( \lambda \), the radiation free region around the coil could now be found for any \( \lambda \) by setting \( Q = 1 \) and \( \overline{\gamma} = \overline{\gamma}_C \) in Eq. (11) and solving for \( s \) as a function of \( \theta \). However, further information may be gained in a simple manner by continuing to use Eq. (13) and finding the boundaries of the protected region where \( \theta = \pi/2 \). To accomplish this we set \( Q = 1 \), \( \overline{\gamma} = \overline{\gamma}_C \) in Eq. (13) and find the two roots of the resulting equation in \( s \). These two roots, of which one is greater and one is less than unity, we denote by \( s_0 \) and \( s_1 \); these numbers and their differences \( \Delta s = s_0 - s_1 \) are shown (as function of \( \lambda \)) in Fig. 7. It is important to notice particularly the rapid decline in \( \Delta s \) as \( \lambda \) increases; this means that if the coil radius becomes much greater than the Stormer radius based on the magnetic moment of the coil, the shielded region suffers a drastic decline. An asymptotic value of \( \Delta s \), valid for large \( \lambda \), is:

\[
\Delta s = \frac{16}{\pi} \exp\left\{-2 - \frac{\ln(\lambda)}{2} (\lambda - 2 \overline{\gamma}_C)\right\}
\]

(17)

This formula is surprisingly accurate even when \( \lambda = 0.75 \), say; in this case Eq. (17) gives \( \Delta s = 0.068 \) compared to the correct value of 0.069.

To illustrate the calculations described here, the radiation free zones for \( \lambda = 0.36 \) and various values of \( \overline{\gamma} \) are shown in Fig. 5 while the protected region for all \( \overline{\gamma} \) (the small zone when \( \overline{\gamma} = \overline{\gamma}_C \)) is shown in Fig. 8. It can be seen that this zone is roughly circular, with diameter \( \Delta s \) (in this case 0.64), a fact which will justify our calculation of the shielded volume as \( \frac{1}{2} \pi^2 a^3 (\Delta s)^2 \). Before turning to the
Fig. 6 Critical Values of $\bar{\gamma}$ vs. $\lambda = a/c$. 
Fig. 7 Limits of Radiation Free Zones in Equatorial Plane.
Fig. 8 Shielded Zone for Coil Field.
application of these results it is necessary first to consider in a general manner the characteristics of a superconducting coil such as might be used for radiation shielding.

**Coil Design Considerations**

In spite of the fact that no really large superconducting coils have ever been built, it is quite possible to discuss some of the characteristics of such a coil in a general way. In calculating these characteristics we shall consider a material having the general properties of the Niobium-Tin compound reported in (4). However, it should be noted that there seems every reason to suppose that materials having still better performance will be developed. A highly schematic diagram of the type of coil considered is shown in Fig. 14.

We commence with a consideration of the structure of the coil since it appears that the structure of a coil designed for the purpose of radiation shielding will, in general, be much heavier than the actual current carrying superconductor.

Now the magnetic field energy stored by the coil is given approximately by:

$$E = \frac{1}{2} \mu_0 I^2 \alpha \ln \frac{a}{\gamma_e}$$

so that the structure required to balance the hoop stress in the coil must have a cross-section given by:

$$2\pi A_s \sigma_w = \frac{\partial E}{\partial \alpha} = \frac{1}{2} \mu_0 I^2 \left[1 + \ln \frac{a}{\gamma_e}\right]$$

and the structural mass is:

$$M_s = \frac{\mu_0 \rho_s \sigma_w}{2} I^2 \alpha \left[1 + \ln \frac{a}{\gamma_e}\right]$$

To determine $r_e$ we note first that $r_e < a$. Secondly, we must also have $r_e \leq \frac{1}{4} a \Delta s$ since otherwise particles will penetrate the superconductor into a region where there is no field. Finally, $r_e$ must not be so small that the critical field of the material is exceeded, that is:

$$\gamma_e \gtrsim \frac{\mu_0 I}{2 \pi B_c}$$
The best value of $r_e$ will almost always be given by $r_e = \frac{1}{2} aA_s$ since the structural mass clearly falls with $r_e$. Numerically, we may consider the structural material to be aluminum with $\rho_s = 2.7 \times 10^3$ kg/m$^3$ and $\sigma_w = 3.5 \times 10^8$ newtons/m$^2$ (about 50,000 psi, a reasonably conservative value).

To determine the mass of superconductor required we note that

$$ M_C = 2\pi a A_c \rho_c $$

but since the current is given by

$$ I = A_c j_c $$

we obtain

$$ M_C = \frac{2\pi \rho_c}{j_c} I a $$

For the Niobium-Tin compound under consideration $\rho_c = 8.4 \times 10^3$ kg/m$^3$, and we can take $j_c = 10^5$ amps/m$^2$ and $B_c = 10$ webers/m$^2$ although, as mentioned before, these figures should not be regarded as the ultimate in superconductors. However, they do serve to bring out the interesting fact that the cross section of the conductor will, in general, be a hollow tube. For consider a solid wire of radius $b$, carrying $\pi b^2 j_c$ amps, and having a field at the surface $\frac{1}{2} \mu_0 b j_c$ webers/m$^2$. For this to be less than 10 we must have $b < 1.6$ cm, and the current is then less than about $8 \times 10^5$ amps. This will be shown later to be insufficient for shielding purposes. For the hollow tube configuration, if the thickness is $\Delta r$, we have

$$ A_c = 2\pi r_e \Delta r, $$

and

$$ I = 2\pi r_e \Delta r j_c $$

and the field at the surface is $\mu_0 j_c \Delta r$ webers/m$^2$, so that $\Delta r < .8$ cm as long as $\Delta r \ll r_e$.

We can, in addition, consider very roughly the thermal insulation of the coil. The following remarks are based upon information given to the author by Dr. Stekly (22). An approximate optimization was carried out to determine, for a flight of moderate duration, how much liquid helium should be carried, and how much fixed insulation. The result is that both helium and insulation together will weigh roughly $\frac{1}{2} \sqrt{T}$ kg/m$^2$ of surface area, where $T$ is the duration of the mission.
in hours. Thus, for a two-week mission we might take \( \sigma_1 = 10 \text{kg/m}^2 \), while in general we can write this mass as:

\[
M_1 = 4\pi^2 \sigma_1 a r_e
\]

This quantity will turn out to be quite small compared to the structural mass.

We conclude then that the mass of the structure, conducting material and insulation may be added to give:

\[
M = \frac{\pi^2 \rho_s}{2\sigma_w} \left(1 + \ln \frac{a}{r_e}\right) \int_a^2 a + 2\pi r_e \int_a^2 a + 4\pi^2 \sigma_1 a r_e
\]

It will appear that large currents are required for shielding. When this fact is combined with the observation that the first term in the above expression (representing the coil structure) varies as \( I^2 \), it will be evident that the limitation on how light the device can be made is more a function of structural materials than of superconductors.

**Applications**

We are now in a position to combine our knowledge of the characteristics of particle orbits in the field of a circular coil with our study of the weight of the structure required to support the coil together with the weights of the coil itself and the necessary insulation. We have

\[
\lambda = \frac{a}{c} = \sqrt{\frac{h}{e B_o}} \sqrt{\frac{2}{a}} = \sqrt{\frac{h}{e}} \sqrt{\frac{4}{\mu_o I}}
\]

where \( B_o = \mu_o I/2a \) is the field at the center of the coil. Thus \( \lambda \) can be described as the square root of the ratio of the Larmor radius at the center of the coil to half the radius of the coil. Alternatively it can be written as the product of two quantities, the first of which involves only the proton momen-
tum to charge ratio (and is plotted in Fig. 9), and the second
depends only on the current (and is plotted in Fig. 10).

Now it is clear from Fig. 7 that as $\lambda$ grows, the
shielded region, which varies like $\Delta s$, falls rapidly; hence,
we cannot tolerate a large value of $\lambda$. In fact, as will shortly
appear, we may expect to work with values of $\lambda$ on the order
of 0.6. This in turn will imply that, if we consider protons
in the energy range 100 Mev to 1 Bev, we are required to
carry a current in the coil of from $1.3 \times 10^7$ to $5.0 \times 10^7$
amps.

Now, assuming that $a/r_e \approx 20$, the current at which
the weights of the superconductor and structure become equal
is about $2.7 \times 10^6$ amps. Hence, we can now justify our
earlier assertion that the structure will, in general, be
heavier than the actual superconductor. This statement will
be true a fortiori when superconducting materials with prop-
erties superior to those considered here are developed. For
these reasons, it is of great interest to attempt to find ways
of integrating the structure of the coil into the structure of
the vehicle as a whole; but it is not proposed to discuss any
such schemes in the context of this paper.

Turning now to the problem of coil design, we can
proceed as follows: we wish to find, for a given proton
momentum, what is the smallest total coil mass which will
provide a definite shielded volume $V$. The shielded volume
$V$ may be defined as $\frac{1}{4} \pi^2 a^2 (\Delta s)^6$. The method of procedure
is as follows: given $\pi$ proton momentum, by picking a value
for the current we determine $\lambda$, and hence $\Delta s$. Then the
given value of $V$ then leads to a value for $a$, so that all the
parameters necessary to determine the mass $M$ are known.
The type of information obtained in this way is illustrated in
Fig. 11 for the case of 100 Mev protons. We note the im-
portant result that for a given shielded volume there is a
definite minimum mass, and that as asserted above, this
occurs in the neighborhood of $\lambda = 0.6$.

The existence of a minimum is a consequence of the
fact that as the radius of the device is increased, the shielded
volume first grows as $a^3$, but when the radius gets larger
than some fraction of the Stormer radius, $\Delta s$ starts to fall
off exponentially with $\lambda$.

The various minimum masses for different volumes
and incident proton energies are shown in Fig. 12 and in a
sense this figure contains the essential results of this paper.
However, certain other points remain to be made in connec-
tion with it.

In the first place, a coil of the type discussed here
will shield against all charged particles, the effectiveness
depending, of course, only on the momentum to charge ratio
of the particle in question. As a result a shield which will
Fig. 9 Proton Based on Component of $\lambda$. 
Fig. 10 Current Based Component of $\lambda$. 

-27-
Fig. 11 Mass of Superconducting Radiation for 100 Mev Protons.
Fig. 12 Optimized Shielding Weights.
repel a 50 Mev proton will also repel a 320 Mev electron. As no concentration of electrons in space having anything remotely approaching this energy is known to exist, all electron impacts can be ignored. This has the important subsidiary effect that the X-rays produced in stopping the electrons are also absent.

Next, it is thought that in a solar flare the radiation is quite isotropic as a result of various scattering mechanisms. This remark excludes the first few moments of arrival of fast protons which are, in general, highly collimated. Now it is clear that the solid shielding problem for a collimated beam is much simpler than that for an isotropic flux—obviously a long cylinder with solid shielding only at the ends would be used. However, there is no advantage in such a design if an initially collimated flux later becomes isotropic. On the other hand, a magnetic shield shows a definite advantage in such a situation. For suppose for a moment that all the particles of a collimated beam were approaching the coil parallel to the axis of the coil; then for each particle the value of $\gamma$ as defined in (3) would be zero. The shielding that results is greatly superior, inasmuch as the most dangerous particles (i.e., those which have $\gamma = \gamma_c$) are absent. In the case of a dipole, for example, the shielded zone instead of being given by (8) becomes

$$\rho = \sqrt{\sin \theta}$$

which extends (on the axis) to a distance of one Stormer radius instead of the fraction implied in (8). This effect is also applicable to a coil, and is illustrated in Fig. 13. In addition to this, a further advantage accrues; for a coil will tend to line itself up with the local direction of the magnetic field, and it is along just this direction that any collimated beam must travel. The moment tending to achieve this alignment is proportional to the magnetic moment of the coil and field strength. The period of small oscillation about the position of equilibrium is $2 \pi \sqrt{Mk^2/mH}$ where $k^2$ is the radius of gyration of the vehicle and $H$ the local field strength. This number may typically be of the order of 10 minutes for fields as low as $10^{-4}$ gauss. By means of this mechanism, advantage may be taken of the fact (always assuming, of course, that the model discussed is valid) that at the beginning of a flare, when the radiation is at its most intense, it is strongly collimated.

To conclude this section, it will be of interest to
pick a particular shielding condition and examine in some detail the design of a coil which will provide appropriate protection. For this purpose we will choose a shield which will protect a volume of 100 m$^3$ from incident protons of 1 Bev; this condition might be suitable for an interplanetary flight of a year's duration involving at least twenty or thirty crew members. We have then, $V = 100$ m$^3$, $p/e = 5.6$. Now the optimum value of $\lambda$ is about 0.7. Hence, we find $\Delta s = 0.095$, and, knowing the shielded volume we find $a = 13$ m. The perimeter of the device is then 82 m and the cross-sectional radius is 62 cm. Shapes with larger cross-sectional radii and smaller perimeters, having the same total volume, involve non-optimum values of $\lambda$ and will in consequence be heavier. Next, we find the current to be $I = 3.7 \times 10^4$ amps; the field at the coil is 12 webers/m$^2$ which is not an improbable value for future superconductors. The energy stored in the device is $3.4 \times 10^{10}$ joules. The cross section of the aluminum structure required to support the coil amounts to 1.56 m$^2$, and the mass of this structure is $M_\theta = 3.47 \times 10^5$ kg. The cross section of the conductor required to carry the current, however, is only 367 cm$^2$, giving a conductor mass of $M_\zeta = 2.54 \times 10^4$ kg. The surface area of the device is 320 m$^2$ and the insulation weight may be taken as $M_\eta = 3.2 \times 10^3$ kg. Thus, the total weight of the device is $3.76 \times 10^5$ kg of which 93 per cent is structure. Plainly, higher strength structural materials will be useful in this application! By way of comparison we note that if we ignore secondary radiation, an H$_2$O shield would have a thickness of 3.21 m. If this is used to shield the same volume (100 m$^3$) in a spherical shape, we find the radius of the shielded region to be 2.9 m. The mass of water involved is $8.5 \times 10^5$ kg, over twice as much as the coil without even considering the secondary radiation.

**Conclusions**

On Fig. 12 are plotted the estimated weights of the superconducting coil (together with structure and insulation) required to shield a given volume against protons having energies up to the values indicated. On the same graph are shown the weights of hollow spherical water shields required to stop protons up to the same energies. The following remarks concerning this graph are appropriate.

First, the thicknesses of water are based on electronic collisions, and no nuclear interactions are assumed. This is a highly idealized situation, but it is useful for a simple comparison. It must be remembered, however, that secondary particles, especially neutrons, are likely to be of great importance in calculating doses. The neutrons will
Fig. 14 Schematic of Superconducting Coil for Radiation Shielding.
tend to travel considerable distances in the shielding material and this will require that the shield be thickened materially to provide for greater moderation.

Second, the reason for the curvature at low volumes of the lines representing the weights of the water shields is purely geometric and arises from the poor efficiency of placing a large thickness of material around a small sphere.

The conclusions to be drawn from Fig. 12, in particular, and from the analysis in general are as follows:

1. In the case where it is required to shield against low energy (\textasciitilde 100 Mev) radiation the weight advantage lies clearly with solid shields. At high energies (\textasciitilde 1 Bev) as required for long trips the advantage seems to be clearly with the magnetic shield. It is felt that for the intermediate cases the approximate analysis is sufficient only to demonstrate that there are no gross differences in weight between the two devices. Further development and analysis is needed to permit a definite choice to be made.

2. In all cases shielding weights are high. It must be realized that, in the absence of some entirely new scheme, such as chemical reduction of human sensitivity to radiation\textsuperscript{(24)}, shields of these general weights will certainly have to be reckoned with in any contemplated manned missions to the planets.

3. While the weight of the solid shield is determined by purely physical questions such as proton stopping power, neutron production, etc., the weight of the magnetic shield is determined almost entirely by structural considerations. In view of this, it may be hoped that improved structural materials will be developed having far higher strength to weight ratios. Possibly the cryogenic environment will prove a help in this problem.

4. For short space flights in the immediate future much reliance will have to be placed in the forecasting of solar flares, especially at solar maximum.

\textbf{Symbols}

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m_p)</td>
<td>Proton rest mass, (1.66 \times 10^{-27}) kg</td>
</tr>
<tr>
<td>(a)</td>
<td>Proton acceleration m/sec(^2)</td>
</tr>
<tr>
<td>(e)</td>
<td>Proton charge, (1.6 \times 10^{-19}) coulombs</td>
</tr>
<tr>
<td>(c_0)</td>
<td>Speed of light, (3 \times 10^8) m/sec</td>
</tr>
<tr>
<td>(v)</td>
<td>Proton velocity, m/sec</td>
</tr>
<tr>
<td>(p)</td>
<td>Proton momentum, kg m/sec</td>
</tr>
<tr>
<td>(B)</td>
<td>Magnetic field, weber/m(^2)</td>
</tr>
<tr>
<td>(r, \theta, \phi)</td>
<td>Spherical polar coordinates, m</td>
</tr>
<tr>
<td>(t)</td>
<td>Time, sec</td>
</tr>
<tr>
<td>(A_\phi)</td>
<td>Vector potential, weber/m</td>
</tr>
<tr>
<td>(Q)</td>
<td>(r \sin \theta \delta /\nu)</td>
</tr>
<tr>
<td>(\gamma)</td>
<td>Constant of integration, m(^2)/sec</td>
</tr>
</tbody>
</table>
m  Magnetic moment, weber \( m \)

a  Radius of coil, m

c  Stormer radius, m

\( A_\phi \)  \( \frac{4\pi a^2}{m} \)  A \( \phi \), Non-dimensional

\( \rho \)  r/c,  Non-dimensional

\( \Psi \)  \( \gamma \) mp/pc,  Non-dimensional

\( \lambda \)  a/c,  Non-dimensional

\( \mu_0 \)  Permeability of free space, \( 4\pi \times 10^{-7} \) henry/m

I  Current, amps

k 2  Argument of elliptic integrals, Non-dimensional

C, E, K, B  Complete elliptic integrals, Non-dimensional

\( \gamma_c \)  Critical value of \( \gamma \), Non-dimensional

s  \( r/a \),  Non-dimensional

\( \Omega \)  Critical value of \( s \), Non-dimensional

\( s_0 \)  Maximum value of \( s \) in shielded region, Non-dimensional

\( s_1 \)  Minimum value of \( s \) in shielded region, Non-dimensional

\( \Delta s \)  \( s_0 - s_1 \)

Jc  Current carrying capacity, amps/m²

\( \rho_c \)  Conductor density kg/m³

M  Mass of conductor, kg

Bc  Critical field of superconductor, webers/m²

A  Cross-sectional area of conductor, m²

\( \rho_\tau \)  Insulation density, kg/m²

rc  External cross-sectional radius of conductor, m

M  Mass of Insulation, kg

As  Cross-sectional area of structure, m²

\( \sigma_w \)  Working stress, newtons/m²

\( \rho_s \)  Density of structure, kg/m³

Ms  Mass of structure, kg

M  Total mass = M_c + M_I + M_s, kg

\( \Delta r \)  Thickness of conductor, m

Bo  Field at center of coil, weber/m²

V  Shielded volume, m³

E  Magnetic energy stored, joules

References


Avco-Everett Research Laboratory, Everett, Massachusetts
Unclassified report

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1. Space vehicles - Radiation shielding.
2. Radiation shielding.

I. Title.
II. Levy, R. H.
III. Avco-Everett Research Report 106.
V. Contract AF 06(647)-278.
Avco Everett Research Laboratory, Everett, Massachusetts

(Avco Everett Research Report 106; AFOSR TN-61-7)
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