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RADIATION SHIELDS FOR SHIPS AND SETTLEMENTS

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People travelling in spaceships and living in space settlements need to be protected from cosmic rays and solar flares. Three classes of radiation shield (active and passive) are examined and compared. It is concluded that adequate means of shielding ships and settlements are available, without excessive mass.

1. INTRODUCTION

RADIATION PROTECTION FOR COLONIES has been considered in Refs. 1 and 2 and applied in Ref. 3. Other NASA work has considered the limited protection of spacesuits and Apollo-type spacecraft. Here we consider radiation protection for permanent space settlements and for passenger-carrying spaceships. Current AEC recommendations (as used in Refs. 1 and 2) are for maximum doses of 5 rem/yr for radiation workers and 0.5 rem/yr for members of the general public, with allowable emergency exposures up to 25 rem. To put this in perspective, a typical sea-level dose rate is about 0.3 rem/yr, and a mountain dweller (particularly in high latitudes) can receive up to a few rem/yr. For space settlements, then, we should design for a dose rate of 0.5 rem/yr, or less. For spaceships, however, a dose rate of 5 rem/yr is more appropriate; clearly the crew of such ships can count as radiation workers, and an average member of the general public will spend only a small part (< 10%, say) of his lifetime as a spaceship passenger. For pioneering habitats or missions higher dose rates would probably be acceptable.

Cosmic rays are high-energy particles which pervade all space. Away from Earth's magnetic field or shielding bulk the total cosmic ray dose rate is $\sim$ 100 rem yr . Most of this is due to nuclei of high atomic number (Z), and the dose rate from primary protons is only about 20 rem/yr, even though protons account for about 90% of all cosmic rays. Fortunately, highly charged or low energy particles are comparitively easy to stop or deflect, despite being the most damaging to tissues. However, high energy protons can produce showers of secondary particles, so that the dose rate from low-Z particles can actually be increased by thin shields of structural mass, and this must be borne in mind. The primary and secondary dose rates are plotted in Ref. 2 *versus* areal density of shielding.

The energy spectra of solar flares and particles trapped in radiation belts are very soft (i.e., the particles are of low energy); this means that protection against these radiation sources is fairly simple, in that a shield giving adequate protection against cosmic rays will generally be effective for these sources too. The energy spectrum of cosmic rays follows $N(E)dE \propto (E_0+E)^{-2.6}dE$, where $E_0 \simeq 0.99$ GeV (the flux, composition, energy spectra and origin of cosmic rays are discussed in Ref.4). At relativistic energies ($\gtrsim$ 1 GeV) this spectrum is quite steep, suggesting that a low-energy cut-off could be applied to reduce the dose rate. According to Ref. 1 a cut-off of about 10 GeV can reduce the dose rate to 0.5 rem/yr after production of some secondaries, a value that will be used in this paper. This value may in fact be somewhat optimistic, since it depends significantly on the weight given to the lowest energy (but most damaging) primaries. Data from balloons, spacecraft and Concorde (presented in compact and useful form in Ref. 5) suggest that the dose rate may be about 1 rem/yr for a 10 GeV cut-off; this would seem to be more compatible with the known energy spectrum. Such adjustments can be easily carried through by changing the cut-off energy accordingly.

A very good introduction to the subject of cosmic ray hazards and dose rates may be found in Ref. 6. Although many of the actual numbers are now out of date, the principles remain valid, and it is hard to find a more modern paper of comparable comprehensiveness that would be available to the general reader.

2. PASSIVE SHIELDING

Passive shielding (or mass shielding) is the simplest kind of shielding that there is; it is very easy to build a passive shield (just shovel some soil around!) and it cannot go wrong! However, it is also massive. According to Ref. 2 an areal density of 2800 kg m^{-2} will reduce the dose rate to 5 rem/yr, and 5500 kg m^{-2} will reduce it to 0.5 rem/yr; this is equivalent to one or two metres thickness of soil or slag.

Consider a spherical habitat of radius r, which contains N people, a volume V per person and a shielding mass m_s per person for an areal shielding density ρ_a. Then for the volume we have:

$$NV = 4\pi r^3/3$$

$$\therefore \quad r = (3NV/4\pi)^{1/3}$$

For shielding we have:

$$Nm_s = 4\pi r^2 \rho_a$$

and its overall volume density is:

$$3\rho_a/r = \rho_a (36\pi/NV)^{1/3}$$

The shielding mass per person is then found to be:

$$m_s = \rho_a (36\pi V^2/N)^{1/3}$$

For a colony, we take typical numbers from Ref. 2;

$$\rho_a = 5500 \text{ kg m}^{-2}; V = 2000 \text{ m}^3/\text{person}; N = 10^6$$

and obtain:

$$m_s \simeq 42 \text{ tonne/person}$$

Although this is quite a large mass, it is not unreasonable for a colony (which does not have to move about), consider-

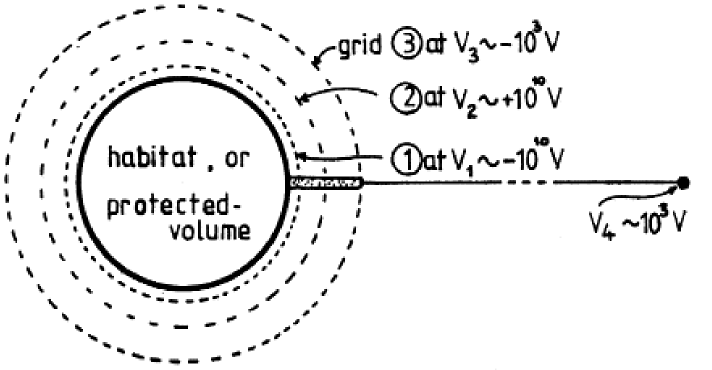

Fig. 1. Electrostatic radiation shield.

ing that the estimate of the interior mass of such a colony is $\simeq$ 53 tonne/person [2].

However, this amount of shielding material would be embarrassing on a spaceship. For example, the shuttle-tank habitats of Ref. 3 allow:

$\rho_a = 2800$ kg m^{-2}; V = 100 m^3/person; N = 250/cluster

and are suitable for occupancies of about 1 year. An intra-system passenger liner (say, Earth → Mars), with a roughly equivalent design (for 1000 berths) would have:

$$m_s \simeq 29 \text{ tonne/person}$$

When we consider that the total structural and internal mass of the habitats is $\simeq$ 4.3 tonne/person (and this is presumably about right for the liner too) and that the mass of consumables is $\simeq$ 500 kg/person (for 1 year) it is apparent that the shielding mass has become an unpleasant large fraction of the total mass. We might consider reducing the volume per person, but this would probably reduce the structural and internal mass by a similar factor: indeed, it is easy to design ships in which the volume per person remains high but the mass per person (excluding shielding) is well under a tonne.

There are several ways out of this dilemma that we might consider. One is to use propellant, consumables, wastes and cargo as the mass shield. Another is to use only $\simeq$ 400 kg/m^{-2} of shielding to remove the high-Z particles (this could be combined with the first method) and accept the remaining dose rate of $\simeq$ 30 rem/yr; we should need to provide a flare shelter for additional protection and would probably have to "ground" crews for $\sim$ 80% of the time (to keep their average dose rate to 5 rem/yr). Or we could use an active shield for good protection and low mass.

One aspect of shielding against solar flares may be noted. The flare protons come from the Sun, in a known direction, so flare-shelters for spacecraft need shielding on only one side (the shield "casts a shadow" in which there is safety). The shielding of most habitats will leave many places well-shielded from even very strong flares, places where the line of sight to the Sun goes through the mass-shield at an angle $\gtrsim 60°$ from the normal (so that the effective thickness is more than doubled).

3. ELECTROSTATIC SHIELDING

Cosmic rays consist mainly of protons (or other positively charged nuclei) which can be repelled by an electrostatic charge. Figure 1 illustrates how this can be done.

From a distance the sphere appears to have a slight negative potential; not enough to be noticed by cosmic rays, but enough to dissuade thermal electrons from wandering through the outer grid (3). This potential can be maintained by trailing a light metal ball on a long cable and making it slightly positive (set $V_4 - V_3$ by a voltage source, say solar cells); thermal electrons are attracted to (4), maintaining the negative potential at (3).

A cosmic ray proton, on passing through (3), sees grid (2) ahead and its high positive potential. The proton is slowed down and, if its energy was less than 10^{10} eV, is brought to a stop and pushed back out again (strictly speaking, this refers to the radial component of the motion). It departs back into the Universe with its original energy (well, almost; there is some bremsstrahlung loss) without ever reaching the interior of the sphere.

A cosmic ray electron, however, passing through (3), is accelerated towards grid (2) and passes it, having gained 10^{10}eV. Now it sees grid (1) ahead and its high negative potential. It slows down and, if its *original* energy was less than 10^{10}eV, it is stopped, pushed back through (2), slows somewhat before passing back out through grid (3) with its original energy.

This shield can therefore protect the interior of the sphere from all charged particles up to a cut-off of 10^{10}eV (a physically arbitrary limit which is used in Ref. 1 to ensure a dose rate < 0.5 rem/yr. An electron synchrotron could be used to set up and maintain the large potential differences (which could be reduced to about 10^9 V for a 5 rem/yr dose rate).

Ignoring the small overall potential, the charges on the grids obey:

$$Q_1 + Q_2 + Q_3 = 0$$

Remembering that for a sphere the self-capacitance is given by:

$$C = 4\pi\epsilon_0 R = Q/V$$

and putting $V_1 = -E$, $V_2 = +E$ (where E is the cut-off energy in electron volts per electronic charge) we obtain:

$$Q_1 = 4\pi\epsilon_0 E R_1 \, (-2/(1-R_1/R_2))$$

$$Q_2 = 4\pi\epsilon_0 E R_1 \, ((R_2/R_1)/(1-R_2/R_3))$$

$$Q_3 = 4\pi\epsilon_0 E R_1 \, (2/(1-R_1/R_2) - (R_2/R_1)/(1-R_2/R_3))$$

The work done in setting up these potential differences is:

$$W = 4\pi\epsilon_0 E^2 R_1 (2/(1-R_1/R_2) + (R_2/2R_1)/(1-R_2/R_3))$$

We can write this more conveniently by defining $q \equiv -Q_2/Q_1$ and $r \equiv R_1/R_3$. Then:

$$W = 4\pi\epsilon_0 E^2 R_1 \, (2q+3+1/q)/(1-r)$$

It is apparent that the energy stored can be minimised by letting $r \to 0$ (that is, by making $R_3 \gg R_1$) and by letting $q = \sqrt{2}/2$.

Now the forces on grid (2) can be balanced by making q = 2 (in practise, it would be advantageous to have (2) in tension, for stability, with q slightly greater than 2), in which case:

$$W = 4\pi\epsilon_0 E^2 R_1 \, (15/2)/(1-r)$$

An efficient structure, using material with a yield strength Y and a density ρ, can contain $\sim (Y/\rho)$ of energy per unit structural mass. For example, a spherical charged membrane can store a specific electrical energy of $2(Y/\rho)$. An optimal structure is one in which all structural members are in tension. Unfortunately, in this case the outermost grid (3) is in compression, and this complicates the design.

Compression members (particularly inflatable ones) between inner (1) and outer (3) grids provide a mass-efficient design; most simply, we could pressurise the region between R_1 and R_3 with a suitable gas. In such a scheme the minimum structural mass is:

$$M_s = W(1+r)(1+r^2)/(2Y/\rho)$$

We must also add in the mass of the pressurising gas; unless very light or very hot gas is used, this mass will be significant:

$$M_g = W\,r\,(1+r+r^2)\,(\mu/3kT)$$

where μ is the molecular mass and T is the temperature. Taking as typical values:

$E = 10^{10}$V; $r = 0.5$; $(Y/\rho) = 2.5\times10^6$ J kg^{-1};

$(kT/\mu) = 1.2\times10^6$ J kg^{-1}

appropriate to a long-term colony with Kevlar structures inflated with hydrogen gas at room temperature (300K) we obtain:

$$M_s \simeq (62 \text{ tonne m}^{-1})\,R_1$$

$$M_g \simeq (38 \text{ tonne m}^{-1})\,R_1$$

However any compression members or gas would have to be able to withstand the strong electric field without breakdown.

External compression members would avoid this difficulty, but the minimum structural mass would be somewhat greater. For external support using balloons (membranes in tension, inflated with gas):

$$M_s = W((1+r)/(1-r))/(2Y/\rho)$$

and

$$M_g = W\,r\,(1+r+r^2)\,(\mu/2kT)$$

which, using the same typical values as above, yield

$$M_s \simeq (98 \text{ tonne m}^{-1})\,R_1$$

and

$$M_g \simeq (60 \text{ tonne m}^{-1})\,R_1$$

Oxygen gas would be 16 times more massive than hydrogen; however, the mass of gas can be reduced by increasing the outer radius (as can the structural mass, to a lesser extent).

Now, electric fields of $\sim 10^8$ Vm^{-1} can draw significant currents from surfaces even in a vacuum, so the minimum radius that can conveniently be protected to 10 GeV is $\sim$ 1 km (or $\sim$ 100m to 1 GeV). This suggests that a pure electrostatic shield is not suited to the protection of spaceships, in general, but to providing moderate protection for large spherical volumes.

A typical use of an electrostatic shield might be in shielding the large work volume of an SMF (Space Manufacturing Facility). If we use a cut-off energy of 1 GeV this will yield a dose rate below 5 rem/yr (from cosmic rays) and give almost complete protection against solar flares (most flare particles have energies well below 1 GeV/nucleon). Oxygen (from lunar soil, for instance) would be freely available as the pressurising gas, and fibreglass or fused silica as the

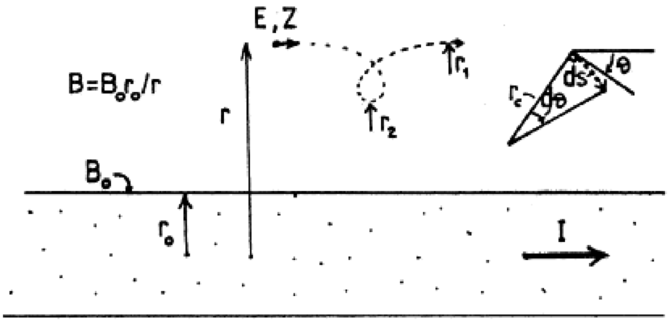

Fig. 2. Cosmic ray trajectory near wire.

supporting structure ($M_s \sim 10^3$ tonne for $\sim$ 1 km radius).

It would also be possible to use magnetic fields to provide repulsion between inner and outer grids (although not with spherical symmetry); there would also be a magnetic insulation effect, allowing stronger electric fields to be used. However, this would complicate the cosmic ray dynamics, and would really be a hybrid (electrostatic plus magnetic) shield.

We note that the protected volume could be at potential V_1 (as the above analysis assumed) or at some other potential, such as V_3 (about zero); this makes only a small difference to the analysis. A more interesting change would result from the use of non-spherical geometries (shielding a toroidal volume, for instance).

4. MAGNETIC SHIELDING

Charged particles can be deflected by magnetic fields; for a relativistic cosmic ray particle of energy E (eV) and charge Z the radius of curvature in a magnetic field B is:

$$r_c = E/ZcB$$

Consider the trajectory of a charged particle near a current-carrying wire (Fig. 2). We have:

$$d\theta = ds/r_c = ds\,.\,ZcB/E$$

$$dr = ds\,.\,\sin\theta$$

$$\therefore \quad \sin\theta\,.\,d\theta = (ZcB/E)\,.\,dr$$

For an infinitely long wire:

$$B = B_o r_o/r$$

So that

$$\sin\theta\,.\,d\theta = (ZcB_o r_o/E)\,.\,dr/r$$

Integrating from $\theta=0$ to π we obtain:

$$\ln(r_1/r_2) = 2E/ZcB_o r_o$$

To protect the region within r_o we want $r_2 \gtrsim r_o$; at the limiting energy we have:

$$E = (ZcB_o r_o/2)\,\ln(r_1/r_o)$$

For a loop of wire (say, a toroidal habitat) it is apparent that the maximum effective value of r_1 is $\simeq r_t$ (where r_t is the toroidal radius and $r_o = r_p$ is the poloidal radius). Thus if a current flows on the surface of such a torus there will be no magnetic field inside (by symmetry) and the interior volume will be protected from cosmic rays up to an energy:

$$E = (ZcB_o r_o/2)\ \ell n\Lambda$$

where $\ell n\Lambda = \ell n\ (8r_t/r_o) - 2$

The inductance of the torus is:

$$L = \mu_o r_t\ \ell n\Lambda$$

The energy stored is:

$$W = \tfrac{1}{2}LI^2$$

where $I = 2\pi B_o r_o/\mu_o$

$$\therefore \quad W = (2\pi r_t)\ (E/Zc)^2(4\pi/\mu_o)/\ell n\Lambda$$

The torus must bear a tension around its length which is:

$$T = (\mu_o/4\pi)I^2(\ell n\Lambda + 1)$$

$$\therefore \quad 2\pi r_t\ T = W\ (\ell n\Lambda + 1)/\ell n\Lambda$$

The inward pressure on the tube $(B_o^2/2\mu_o)$ could be balanced by an internal toroidal field (using a poloidal current flow); this would increase the stored energy by a factor $(1 + 1/2\ell n\Lambda)$ and *decrease* the tension to $(\mu_o I^2/4\pi)$ $(\ell n\Lambda + \tfrac{1}{2})$, making $(2\pi r_t T/W)$ equal to unity. However, more commonly we should use gas pressure to balance the magnetic pressure; this removes the $(B_o^2/2\mu_o)$ term without changing T. The structural mass is:

$$M_s = 2\pi r_t\ .T.\ (\rho/Y)$$

$$\therefore \quad M_s = (\rho/Y)\ W\ (1 + 1/\ell n\Lambda)$$

The mass of pressurising gas is:

$$M_g = (\mu/kT)\ W/(2\ell n\Lambda)$$

For the protection of a colony (a Stanford Torus, for example), using Kevlar tension members and O_2/N_2 as the pressurising gas (at 300K) we use the parameters

$E = 10^{10}$eV; $r_t/r_p = 10$; $(Y/\rho) = 2.5\times10^6$ J kg^{-1};

$(kT/\mu) = 8.5\times10^4$ J kg^{-1}

to obtain:

$$M_s \simeq (17 \text{ tonne m}^{-1})\ r_t$$

$$M_g \simeq (72 \text{ tonne m}^{-1})\ r_t$$

and also:

$$B_o \simeq (28 \text{ T m})/r_o$$

Notice that for $r_o \gtrsim 56$m (poloidal radius) we have $B_o \lesssim 0.5$T (the pressure exerted by 0.5T is approximately 1 atmosphere), so the internal atmosphere of the habitat will generally be enough to overcome the magnetic pressure.

The magnetic field is produced by superconducting coils. If the superconductor has density ρ_{sc} and carries a current density J, then:

$$M_{sc} = (\rho_{sc}/J)\ (2\pi r_t)\ (2\pi/\mu_o)\ B_o r_o$$

which, using the parameters given above, and also (for niobium-tin composite superconductor, $(\rho_{sc}/J) \simeq 2\times10^{-5}$ kg m^{-1} A^{-1}, gives:

$$M_{sc} \simeq (18 \text{ tonne m}^{-1})\ r_t$$

For a small spaceship the degree of protection can be reduced. As an example of a minimal shield take

$B_o = 0.5$T; $r_p = 2$m; $r_t = 100$m; $(Y/\rho) = 2.5\times10^6$ J kg^{-1}

and find that the shield is effective up to:

$$E \simeq 0.6 \text{ GeV}$$

This should reduce dose rate to about 5 rem/yr and provide adequate protection against all solar flares. We have:

$$M_s \simeq 3.1 \text{ tonne}$$

$$M_{sc} \simeq 63 \text{ tonne}$$

$$M_g \simeq 9.2 \text{ tonne}$$

$$V \simeq 7900 \text{ m}^3$$

Such a spaceship could carry up to ∿ 1000 tonne of cargo or ∿ 300 people in the protected volume, which would mean a shield mass of about 250 kg per person. An increase in the current density carried by the superconductor would reduce the mass considerably ($J \simeq 2\times10^9$ Am^{-2} has been achieved for Nb_3Sn wires, a factor of ∿ 10 improvement upon the value quoted above).

5. COMPARISON

The results from the previous sections show that passive shielding is very much more massive than active shielding; even a very small region needs at least ten tonnes of passive shield (to 5 rem/yr, using $\rho = 2800$ kg m^{-3} for the shield material), whereas an active shield for ∿ 1m^3 would have a mass ∿ 1 tonne. Active shields become even more attractive for greater volumes, because $M_{passive} \propto R^2$ whereas $M_{active} \propto R$.

Nevertheless, passive shielding is an attractive choice for colonies and fixed settlements for several reasons. It is simple and cannot break down; it shields against neutral particles (such as neutrons from nuclear explosions) and against meteorites, colliding spacecraft, bombs and so forth. The shielding can also be one with the hull of the habitat: several metres thickness of fused silica or slag would have great strength, foamed surface layers (metres thick themselves) would stop and trap meteorites far from the hull itself and cushion impacts and explosions, rocks and soil piled on inside (adding extra shielding) would provide for the habitat's internal geography.

We have already seen that for shielding large spherical work-volumes an electrostatic shield would be appropriate (a magnetic shield could be used instead) when a passive shield would be far too massive.

For spaceships or mobile settlements a magnetic shield is the obvious choice. It is light, its construction is straightforward, and the internal atmosphere has a natural role in overcoming the magnetic pressure. The geometry is naturally toroidal, a shape which is appropriate for other reasons (smooth progression between linear and angular acceleration to provide a constant "artificial gravity"). The magnetic field can also be used as part of the propulsion system (this is true for a wide range of propulsion concepts) and as a store of energy.

In Ref. 1 it was claimed that the structural mass of a magnetic shield was much more than the mass of a comparable passive shield intended to reach 0.5 rem/yr in a toroidal habitat (r_t = 900m, r_p = 60m). This is in direct contradiction with my results in Section 4 (which yields $M_s \simeq 12 \times 10^6$ kg, in comparison with 12×10^9 kg for a passive shield, that is, a ratio of a thousand). Where does this difference come from? Well, the equation given in Ref. 1 is appropriate for the protection of a sphere, radius (½C_{st}) from the centre of the torus, with the radius $\gg r_t$; evidently the author was considering the protection of the whole volume about the torus to several toroidal radii. This is excessive (it would increase the mass by $\simeq$ 20 times). Then again, if aluminium is used instead of Kevlar, fibreglass or silica for the structural mass, the mass can be increased by a factor $\simeq$ 30. Even so, this still leaves the magnetic shield with a clear lead, and I am forced to conclude that Ref. 1 is in error.

Because an active shield for a spaceship can be made with such low areal densities, using suitably strong materials, there will be no significant production of secondary radiation and the cut-off energies could therefore be reduced somewhat (say to 5 GeV for the 0.5 rem/yr limit), provided that the areal density inside the shield is not higher than about 250 kg m^{-2}.

Hybrid electrostatic-magnetic shields are also possible (the 'plasma radiation shield' in Ref. 1 is a case in point), and of course it is possible to combine active and passive shielding (for example, in a toroidal colony with a thick hull and a magnetic field, or a planet like Earth). Such combinations may be appropriate in particular circumstances; they can be analysed in the same way as the three basic types and will have similar mass requirements.

6. CONCLUSIONS

Both active and passive shields are available for protecting the passengers of spaceships and the inhabitatants of space settlements. Low-mass magnetic shields are appropriate for spaceships and simple mass-shields for space settlements. In neither case is the mass penalty excessive.

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