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Paper Session I-A - Magnetic Shielding For Interplanetary Spacecraft

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Magnetic Shielding for Interplanetary Spacecraft

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Abstract

The protection of spacecraft crews from the radiation produced by high energy electrons, protons and heavier ions in the space environment is a major health concern on long duration missions.

Conventional approaches to radiation shielding in space have relied on thicker spacecraft walls to stop the high energy charged particles and to absorb the resulting gamma and bremsstrahlung photons. The shielding concept described here uses superconducting magnets to deflect charged particles before they collide with the spacecraft, thus avoiding the production of secondary particles. A number of spacecraft configurations and sizes have been analyzed, ranging from a small 'storm cellar' for use during solar flares to continuous shielding for space stations having a crew of 15-25. The effectiveness of the magnetic shielding has been analyzed using a Monte Carlo program with incident proton energies from 0.5 to 1000 MeV. Typically the shield deflects 35-99 percent of the incident particles, depending, of course on particle energy and magnetic field strength.

Further evaluation studies have been performed to assess weight comparisons between magnetic and conventional shielding; to determine magnet current distributions which minimize the magnetic field within the spacecraft itself; and to assess the potential role of ceramic superconductors.

Introduction

The radiation environment of space will be a limiting factor in the duration of interplanetary missions. The typical environment consists of electrons, protons and ions with a flux that decreases at higher energies approximately as $E^{-1.5}$[1]. Presently, shielding of spacecraft and their crews from high energy cosmic particles is foreseen through the placement of supplies, fuel, and equipment around the outer walls of the spacecraft and through the use of a thicker spacecraft.

Configuration of the Spacecraft

This paper investigates the possibility of using a dipole magnetic field to deflect those incident charged particles before they strike the spacecraft and produce a shower of damaging secondary particles. A cross-section of the spacecraft is shown in Figure 1. The craft is toroidal in shape, with a major radius of 10 m and a minor radius of 5 m. This is a large interplanetary craft or high orbit space station, with space for 15-20 crew members. For long-duration missions the spacecraft could rotate at 9.5 RPM to produce 1 g in the living areas or 3 RPM to produce 0.1 g.

The configuration of the dipole field is shown in Figure 2. The conductors are arranged on the outer surface of the toroid with all current flowing in the toroidal direction. The distribution of the current on the surface of the toroid was chosen to minimize the field within the spacecraft while producing essentially a dipole field outside the craft. To obtain this distribution we modelled the spacecraft as a coaxial solenoid and a set of 38 circular coils on the surface of the toroid. The solenoid was resistive and initially carried a large current. The toroidal coils were superconducting and initially carried no current. We then did an eddy current simulation in which the solenoidal current decayed to zero and the currents in the toroidal coils increased to exclude the field from the spacecraft interior. Notice that the interior fields are generally less than 10 mT, which value is the present US eight hour per day occupational exposure standard. Fields of 10 mT should not adversely affect the operation of electronics.

The effectiveness of various configurations of coils is shown in Tables 1-6. The effectiveness of a magnetic shield was determined using a Monte Carlo code. Each of the particles was tracked using F = V x B formulation, with a maximum step size of 0.05 times the Larmor radius. The Monte Carlo technique released 2000 monoenergetic particles at a radius of 32 m, i.e. at least 17 m from the spacecraft, with the location and direction of the particles chosen at random. Table 1 shows the shielding effectiveness on a small spacecraft, with a major radius, R_{ship}, of 3 m and a minor radius, a_{ship}, of 1 m. Four shielding coils were used in the positions in Table 2. Table 3 shows the shielding effectiveness on the $R_{ship} = 10$ m and $a_{ship} =$ 5 m configuration. The configuration of the coils and their currents are shown in Tables 4 and 5. The effectiveness of the shield against electrons is shown in Table 6 and against iron ions in Table 7. More than 400,000 particles histories have been traced in evaluating the effectiveness of the magnetic shield. Table 8 contains magnet design parameters required for shielding spacecraft of the size studied.

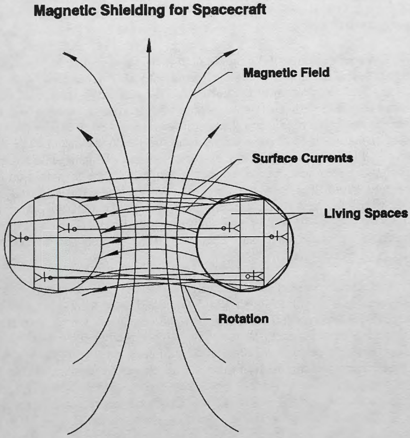

Figure 1. Cross-sectional schematic of spacecraft with a magnetic shield.

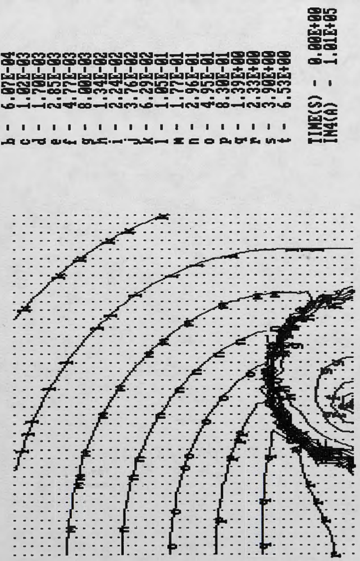

Figure 2. Field strength contours in a magnetically shielded spacecraft.

Table 1

Magnetic Shield Effectiveness of a Small Toroidal Spacecraft

Major radius	R_{ship}	3.00 m
Minor radius	a_{ship}	1.00 m
Volume	V_{ship}	59.22 m^3
Outside Area	A_{ship}	118.44 m^2

Shielding Effectiveness Against Protons

Io ==>	1.0 MA	2.5 MA	5.0 MA
Energy (MeV)	(percent deflected)		
0.5	79.	100.	100.
1.	81.	100.	100.
5.	41.	80.	99.
10.	43.	67.	87.
30.	23.	49.	71.
50.	18.	42.	56.
100.	6.	28.	43.
300.	5.	19.	52.
500.	13.	5.	32.
1000.	0.	8.	29.

Baseline: 149.20 strikes per 2000 protons with no field

Table 2

Small Spacecraft Coil Configurations

Coil	a (m)	z (m)		I(MA)	
1	2.0	0.0	1.0	2.5	5.0
2	2.4	0.8	1.0	2.5	5.0
3	2.4	-0.8	1.0	2.5	5.0
4	4.0	0.0	0.1	0.25	0.5

Table 3

Magnetic Shield Effectiveness Against Protons

Major radius	R_{ship}	10.00 m
Minor radius	a_{ship}	5.00 m
Volume	V_{ship}	4934.80 m^3
Outside Area	A_{ship}	1973.92 m^2
Floor Area (2.5 m ht)	A_{flr}	1439.55 m^2 15495.36 ft^2

	(percent deflected) I_o		
Energy (MeV)	2.5 MA	10.0 MA	38. Coils
0.5	99.	100.	100.
1.	90.	100.	100.
5.	68.	99.	100.
10.	61.	94.	100.
30.	36.	91.	94.
50.	35.	92.	89.
100.	24.	81.	69.
300.	6.	50.	43.
500.	3.	41.	53.
1000.	3.	35.	33.

Baseline: 140.69 strikes per 2000 protons with no field

Table 4

Four Coil Configuration for Large Spacecraft

Coil Number	a (m)	z (m)	I (MA)	
1	5.00	0.00	2.5	10.0
2	7.00	4.00	2.5	10.0
3	7.00	-4.00	2.5	10.0
4	15.00	0.00	0.5	5.0

Table 6

Shield Effectiveness Against Electrons

Major radius	R_{ship}	10.00 m
Minor radius	a_{ship}	5.00 m
Volume	V_{ship}	4934.80 m^3
Outside Area	A_{ship}	1973.92 m^2
Floor Area (2.5 m ht)	A_{flr}	1439.55 m^2 15495.36 ft^2

(percent deflected)

Energy (MeV)	CURRENT 5.0 MA	 10.0 MA
0.5	100.	100.
1.	100.	100.
5.	100.	100.
10.	100.	100.
30.	100.	100.
50.	100.	100.
100.	50.	100.
300.	25.	88.
500.	25.	62.
1000.	-.	47.

Baseline: 148.42 strikes per 2000 electrons with no field

Table 7

Shield Effectiveness Against Iron Ions

Major radius	R_{ship}	10.00 m
Minor radius	a_{ship}	5.00 m
Volume	V_{ship}	4934.80 m^3
Outside Area	A_{ship}	1973.92 m^2
Floor Area (2.5 m ht)	A_{flr}	1439.55 m^2
		15495.36 ft^2

Iron ions
Shield Effectiveness
(percent deflected)
38 coils

Energy (MeV)	Fe^{+26}	Fe^{+3}
10.	100.	86.
30.	100.	57.
50.	100.	38.
100.	99.	37.
300.	94.	7.
500.	89.	8.
1000.	75.	
2000.	52.	
3000.	51.	
5000.	33.	

Baseline: 149.60 strikes per 2000 ions
with no field

Table 8

Magnetic Shield Design Calculations

Rship	10.000 m	major radius of spacecraft
aship	5.000 m	minor radius of spacecraft
Vship	4,935 m^3	volume of spacecraft
Aship	1,974 m^2	external surface area
Aflr	1,440 m^2 15,495 ft^2	Floor area with 2.5 m ceilings
J net	200 A/mm^2	net current density
rho cond	4000 kg/m^3	density of conductor
I cond	25 kA	conductor current
t ins	50 mm	thermal insulation thickness
A cool	10 mm^2	coolant channel area
t el ins	0.1 mm	electrical insulation thickness
w cond	11.72 mm 0.461 inch	overall conductor width
m wi	25,693 kg	total mass of windings
N total	1179 turns	total turns
rho Al	2700 kg/m^3	density of aluminum
t eq Al	15.15 mm 0.596 inch	equivalent Al thickness

Conclusions

A magnetic shield has been shown to be effective in deflecting incident protons, electrons and heavy ions at energies typical of the space environment. The mass of the required magnets is less than of the additional spacecraft wall thickness needed to shield the incident radiation. In addition, by diverting particles to strike the spacecraft in certain sectors by means of magnetic fields, conventional shielding can be used more effectively.

References

1. "Human-Nuclear Radiation Issues for Exploration Missions," Alan J. Willoughby, Analex Corporation, Steven M. Stevenson, NASA Lewis Research Center, and Wesley E. Bolch and J. Kelly Thomas, Department of Nuclear Engineering, Texas A&M University.