Team Number 289

Problem Selected: A

Modelling an Active Radiation Shield for Manned Mission to Mars

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Abstract

Long duration manned mission in space needs yet to overcome a lot of enabling and enhancing technologies. One of the challenges encountered in deep space missions is harmful radiation from solar flares and galactic cosmic radiation. In the early days of manned space mission around low earth orbit and moon, radiation encounter was not a major issue, since earth's magnetic field is strong enough in this region to deflect a considerable amount of radiation flux. But long-duration manned mission to mars needs further technologies. The main constraint to use conventional passive shielding with absorbing material to block these radiations is extra mass, as an increase of payload comes with a greater trade-off with fuel. Another natural approach to attack this problem is to use active magnetic shields mimicking the earth's role toward space radiation. But this approach presents another set of complexity, like maintaining a stable static magnetic field, energy dissipation, effects of magnetic field on on-board crews. A thorough investigation of possible shortcomings and challenges associated with active shielding is considered in this paper, and possible mass needed to build the shield is estimated to be 48.346 tons.

1. Introduction

First debate that arises for protection measurement in space is whether to use active or passive shielding methods. The driving question we addressed in comparing active methods to passive methods is whether the total mass of the active shield configuration (coils, power sources, refrigeration, support structure, etc.) needed to provide some specified level of protection (as measured by radiation dose, risk, etc.) actually less than the mass of bulk material shielding needed to afford the same level of protection. Since mass consideration is one of the major concerns of space travel, we reveal a potential advantage of active shielding in this paper. Our ultimate model is a confined static magnetic field with race-track coil winding.

To advance our analysis, firstly, we stand upon some reasonable assumption of simplify the greater complexity of the problem

1. Among different shapes of habitable capsules used in space travel, the most common cylindrical-shaped compartment with a diameter of 10 m and length of 13 m is assumed to be a reasonable choice because of geometrical and maneuvering simplicity.

2. The problem statement was simplified to approach with greater clarity. A different portion of the habitable capsule such as incoming doc, internal heat management system, the interaction of the magnetic field with communication is omitted to concentrate solely on the radiation protection measurements.

3. Most deadly energetic ion of galactic cosmic radiation is comparatively less abundant in space than solar flare particles. But the major inspiration to employ magnetic shielding was to deflect high energy heavy nuclei since they cannot be blocked with only passive shielding.

4. Complicated consequence associated with the generation of secondary radiation is safely ignored up to reasonable consideration. The simulation of high energy impact with supporting structure and magnetic coil is harder to carry out.

2. Background Research

Space radiation can infiltrate living spaces, spacecraft, spacesuits and can hurt space explorers. Limiting the physiological changes brought about by space radiation introduction is perhaps the greatest test in keeping space travelers fit and sound as they travel through the close planetary system. As referenced already, ionizing radiation is a significant issue that can make harm all pieces of the body including the focal sensory system, skin, gastrointestinal tract, skeletal framework, and the blood shaping organs. In any case, organic harm because of radiation can be prevented through usage of shielding and other necessary procedure that are intended to diminish radiation presentation and its belongings.

2.1 Types of Radiation

There are three kinds of radiation in space:

- Galactic cosmic rays (GCR) originating outside the solar system;
- Solar particles emitted by the sun during solar flares (solar particle events);
- Radiation trapped by the Earth's magnetic field.

Among these, the first two are faced by the spacecraft during the phase of traveling to Mars from Earth for a very long time (500 to 1000 days approximately).



Figure 2.1- Solar and cosmic proton energy spectra [Spillantini, et al., 2000]^[6]

2.1.1 Solar Particle Events

Solar Particle Events comprise generally of low to direct vitality protons tossed into interplanetary space by coronal mass launches. SPEs can't right now be anticipated ahead of time, yet the recurrence of SPEs is associated with sun-oriented movement. Figure 1 shows normal spectra of solid SPEs. The risk to space explorers from SPEs is measurable, both in light of the fact that SPEs are generally inconsistent and on the grounds that any given SPE will just influence rocket situated in the zone of the sun oriented interplanetary attractive field lines along which SPE charged particles are obliged to travel. In any case, solid SPEs can convey conceivably deadly intense doses of radiation to unprotected space explorers. For instance, 5 Sv is commonly perceived as a deadly portion, and SPE would have presented Apollo space explorers to an expected 10 Sv. In any case, since SPE proton energies are practically all <1 GeV, they can be protected against either with passive protecting or by the proposed active protecting framework. ^[6]

2.1.2 Galactic Cosmic Radiation

Galactic cosmic radiation, comprising for the most part of protons, alpha particles, and cores of heavier components, is isotropic and overruns the close planetary system. Lower vitality GCR can be dispersed by anomalies in the sun oriented interplanetary attractive field, which spread outwards from the sun with the sun-based breeze. Since such inconsistencies are related with sunlight-based movement, the force of low-vitality GCR is hostile to associated with the sun-oriented action cycle. The impacts of dispersing decline at higher GCR energies, so the level of

variety with the sunlight-based action cycle diminishes at expanding energies. (As a matter of fact, the avoidance by attractive fields is a consolidated capacity of the energy and charge of a molecule. For a given completely ionized component, "inflexibility" increments with vitality.) Figure 1 additionally shows the GCR proton range at sun powered least and sun powered greatest.^[6]

2.2 Biological Effects

Astronauts are exposed to approximately 50-2,000 millisieverts (mSv) while on six-monthduration missions to the International Space Station (ISS), the Moon and beyond.



Fig 2.2- Comparison of radiation doses, includes the amount detected on the trip from Earth to Mars by the RAD on the MSL (2011–2013)^[12]

| | Absorbed | Effective | Fatal risk, % (95% Cl) | |
|------------------------------|------------|-----------|------------------------|-------------------------|
| | dose (Gy)* | dose (Sv) | Men(age 40 years) | Women (age 40 years) |
| Lunar mission (180 days) | 0.06 | 0.17 | 0.68%(0.20-2.4) | 0.82%(0.24-3.0) |
| Mars orbit (600 days) | 0.37 | 1.03 | 4.0%(1.0-13.5) | 4.9%(1.4-16.2) |
| Mars exploration (1000 days) | 0.42 | 1.07 | 4.2%(1.3-13.6) | 5.1%(1.6-16.4) |

Calculations are at solar minimum, where GCR dose is highest behind a 5 g/cm². *Mean for tissues known to be sensitive to radiation and at risk of cancer including lung, colon, stomach, bladder, bone marrow, and breast and ovaries in women. Competing causes of death are included in calculations because they decrease risk probabilities if high (ie, >5%).

Table 1: Radiation risks for men and women on missions to the moon or Mars^[11]

2.3 Existing Concept for Protection

There are two main categories of approaches for shielding humans from radiation in space: passive shielding and active shielding.

2.3.1 Passive Radiation Shielding

Passive space radiation shielding consists of placing some sort of physical material in between a person and the source of radiation. Its main advantage over other forms of radiation shielding is its ability to shield against any form of radiation, be it positively charged, negatively charged, or

neutral, and it is widely-employed in Earth-based shielding applications, since weight is not an issue.^[13]

2.3.2 Active Radiation Shielding

Active space radiation shielding is inspired by the Earth's magnetic field, which serves both to deflect and to trap portions of the incoming space radiation. Since the field is still under development, a multitude of suggested approaches exist:

2.3.2.1 Electrostatic Shielding

This approach creates an electric field around an astronaut habitat, with the negative potential facing outwards to slow down negatively charged radiation. There are no known major physiological issues associated with humans in large electrostatic fields, but further investigations are required in order to verify astronaut safety with a sufficient degree of certainty.

2.3.2.2 Magnetic Shielding

Magnetic shielding consists of forming a large magnetic field around the spacecraft, usually through the use of superconducting solenoids. Unlike with electric fields, there are known and suspected physiological effects of moving within a strong magnetic field. In order to use this approach for space radiation shielding, the design must allow for a habitable region without significant magnetic field strengths. Usually, this is done by using a torus-shaped design that has a shielded region internal to the torus. These layouts allow for a small region between the solenoids that is free of magnetic fields, while still generating a magnetic field that is comparable to an ideal dipole at large distance. Charged particles are either be deflected by the magnetic field, or trapped along the magnetic field lines, well before they approach the internal shielded region of the torus.

2.3.2.3 Plasma Shielding

Plasma shielding is a field of ongoing research, fundamentally consisting of a mass of ionized particles that are entrapped by electromagnetic fields, swirling around a spacecraft enclosure and serving to deflect or ensnare charged particles.

Comparing the three types of active shields, electrostatic shields are relatively lightweight, but since they only repel negative particles, they also pull in positive particles, which creates a current influx that must be counteracted. Additionally, electrostatic shields are limited by voltage level, which in turn limits the energy level of the particles that they can deflect. Magnetic shields do not collect currents and can achieve effective shielding for all expected radiation levels. Finally, plasma shields are the most lightweight and the least power-consuming of all three approaches, but are also the least mature design approach. They are experimentally unproven, and their functionality is hotly debated.^[13]

Two types of magnetic shielding are available: confined and deployed. We developed a plan using deployed magnetic shielding for protecting humans from most radiations.

3. Justification of Our Choices

Our spacecraft model is planned using High Temperature Superconductor (HTSC) Magnesium Dibromide (MgB2) and Racetrack Toroid support structure based on the Confined Active Radiation Shield Configuration. Here 2 choices are highlighted with utmost attention-

- 1. Confined Active Radiation Shield
- 2. High Temperature Superconductor (HTSC) MgB₂

Why Confined Shielding method?

Among all other shielding methods Confined and Deployed Shielding methods are studied highly to solve mars mission problems. From Størmer's theorem, it can be shown that the shielding capacity of deployed coils decreases dramatically as the radius of the coil increases and the magnetic moment is held constant. Numerical simulations and the proper use of the analysis by Stormer [1955] demonstrate that magnetic shields consisting of deployed circular coils of wire are not practical for shielding energetic particles such as GCRs from spacecraft.^[1] According to Stormer's theory to apply this deployed mechanism to a circular coil of wire, the radius of the coil must be much smaller than the dimension of the region being shielded which is the first reason we have given priority to Confined mechanism over the deployed shielding. Our spaceship is about 1000 m³ and the deployed mechanism cannot cover the whole region of the spaceship as it has to oblige the mentioned criterion. Deployed magnetic shields have reduced energy requirements and magnetic field strengths relative to confined systems, therefore, they also have a significantly reduced capacity for protecting the occupants of the desired shielded region. However, confined shielding covers the whole region of the spaceship and doesn't extend much beyond the craft which leads us to overcome the dilemma and therefore choose confined magnetic field as the shielding method.

HTSC or LTSC?

Magnets based on low-temperature superconductors (LTS) (i.e., niobium-titanium (NbTi) and niobium-tin (Nb₃Sn)) require that the conductors be kept at low, near liquid helium (4.2 K) temperature in absolute rigid assemblies. Even superconductor movements on the order of microns under the effect of acting Lorentz forces generate enough energy to heat the conductor locally above its critical temperature and thus the superconductivity of the magnet is lost. Based on the design concept of such LTS magnets, it was again inconceivable that magnetic shielding could be used for radiation shielding in space.

However,HTS represent a realistic alternative due to the lower critical and provide interesting possibilities for the space mission's enable magnet operation up to the temperature of liquid nitrogen (77 K) and do not need costly liquid helium (at a temperature of 4K), where the enthalpy of all materials is orders of magnitude larger than at the operational temperatures needed for LTS magnets.. The only requirement for needed support structures is containment of the magnetic pressure acting in the coils. Accordingly, with HTS, ultralightweight coils become feasible, and magnets with flux densities ranging from one to several tesla and volumes of hundreds to several thousand m³ can be considered for space applications. MgB2 has a clear advantage of the cheap preparation technology ^[5] over YBCO (yttrium-barium-copper-oxide) while YBCO demands high manufacturing cost and poor mechanical properties.

4. Time Selection for Voyage

Solar activity has an 11-year cycle, known as the solar cycle, which culminates in solar maxima, a dramatic increase in the number and intensity of solar flares, especially during periods when there are numerous sunspots. Lower energy GCR can be scattered by irregularities in the solar-interplanetary magnetic field, which propagates outward from the sun with the solar wind. The effects of scattering decrease at higher GCR energies, so the degree of variation with the solar activity cycle decreases at increasing energies. But, Anti-correlation between solar activity and the intensity of low-energy GCR is an important point for time selection of interplanetary travel.

Since detrimental damage of GCR is less than the solar particle event, we propose to conduct the voyage in time of solar maxima.



Figure 4: Sunspot cycle over year Image Source: NASA

5. Proposed Plan

5.1 Fundamentals of Magnetic Deflection

• Charged particles can be either absorbed in a relatively uncontrolled way by various materials or actively reflected by stationary electric and/or magnetic fields.

• During the process of absorption, the composition and spectrum of the radiation changes. Particles with kinetic energy less than 1GeV/nucleon can be safely absorbed into material, but higher energy particles can produce secondary particles, also known as spallation radiation, which were not present in the incoming radiation (e.g. neutrons) can be produced in the shielding material and enter the habitable zone.

• Since magnetic field does no work on charged particles, reflection does not alter the composition of the radiation nor no new particles are created; it just diverts them. Thus, at all energies, the radiation penetrating the habitable zone is never greater than the incident radiation.

Above a kinetic energy of 4 GeV/nucleon, cosmic rays lose energy at a constant linear rate; so, for example, an alpha particle (charge 2) will lose ~120 MeV passing through a human body whether its total energy is 10 or 100 GeV/nucleon. Below about 1 GeV/nucleon, however, cosmic ray energy loss goes like $1/v^2$; so, an alpha particle with 500 MeV/nucleon will deposit all of its energy in the human body, a total of 2 GeV, or sixteen times as much as a 10-100 GeV/nucleon alpha. For this reason, our focus will be limited to block out the particles of the 2-4 GeV/nucleon energy range. ^[6]

5.2 High Temperature Superconductor Wire

There are two competing classes of high temperature superconductors (HTSC) -

- 1. Yttrium-barium-copper-oxide (YBCO): YBCO superconductors are manufactured in the form of a 4-mm-wide tape with a thickness smaller than 0.2 mm. The density of the material is 6.3 gm/cm³.
- 2. Magnesium diboride (MgB₂): The magnesium diboride superconductors are produced in cable form; the individual MgB2 wire elements are brittle and require a rigid support. It becomes superconducting at $T_c = 39$ K. The density of the material is 2.57 gm/cm³, which is 2.4 times less than YBCO.



Figure 4.2: Yttrium-barium-copper-oxide tape ^[9]

| Superconducting | Tc in Kelvin | coherence length | Mass Density | Current |
|------------------|--------------|------------------|--------------|-------------------------|
| Compound | | ξ (nm) | (g/cm^3) | carrying |
| | | | | capacity |
| MgB ₂ | 39 | 5 | 2.57 | ~ 200 A/mm ² |
| YBCO | 70 | <<1 | 6.3 | 300 A/1-cm |
| | | | | tape |

A decision matrix can be created based on three parameters of these two-existing material.

Table 2: Comparison between MgB₂ and YBCO^[7]

The coherence length ξ is a key parameter that determines the maximum distance that guarantees superconducting coupling between adjacent particles (the longer the better). Manufacturing methods significantly benefits from a long ξ , thus even though the superconducting temperature of MgB₂ is in lower range than YBCO. Between the two choices, MgB₂ has more potential to be a workable superconductor wire, because of our mass constraint.

5.3 Coil Configuration Cylindrical Habitable Capsule

The shield coil must produce maximum bending of charged particles for minimum mass of coils, structure, and cryogenics. But operating temperatures of the HTSC materials (~25 K) do not require the use of liquid helium, which represents a significant advantage in view of the technical difficulties, which guarantees the stability of the cryogenic system in space with further cryogenics. The structure required to support the coils is minimized if the windings utilize the pure-tension 'D' contour.

There are several proposals for magnetic coil configuration in current literature. Magnet shield configurations based on the high-temperature superconductors (HTSC) yttrium-barium-copperoxide (YBCO) and magnesium diboride (MgB2) were evaluated in the European Space Agency (ESA), National Iranian American Council (NIAC), and the Space Radiation Superconducting Shield study.

"Pumpkin" Structure or 6 + 1 extendable solenoid shield Structure - This is a design developed by the European Space Radiation Superconducting Shield working along with CERN. It is an unconfined magnetic field and would be able to envelope the spacecraft in a magnetic field without surrounding it in solenoid-type electromagnets ^[8]. This geometry has the advantage of producing a field outside of the confining material, meaning the generation of secondary particles is significantly reduced; however, it is a complicated design and would require more superconducting tape to construct compared to other designs.



Figure 4.3.1: Single extendable solenoid shield and full deployment, developed by Advanced Magnet Lab (aml)^[9]

• Counter-wound Spool or double-helix solenoid coil - Like the pumpkin structure, this is an unconfined magnetic field. The counter-wound spools of superconducting wire are angled to produce a magnetic dipole that would surround the spacecraft. Like the pumpkin structure, this geometry greatly diminishes the generation of secondary particles. Though it uses less tape than the pumpkin structure, the two integral coils increase its complexity compared to the solenoid-type and require a greater current to generate a similar field.



Figure 4.3.2: Two-layer winding used to produce the double-helix solenoid field and full deployment ^[9]

• Continuous race-track configuration - ESA's study on racetrack coil toroid is composed of MgB2 superconducting cable. The field integral of the 12-racetrack coil toroid is 4.9 Tm. The racetrack geometry is commonly used in high energy physics. The dimensions of the low-temperature superconducting racetrack toroid of the Atlas experiment at the Large Hadron Collider (LHC-CERN) are comparable with the dimensions required for a radiation shield in the space application. The multiplication of the number of coils in the continuous- coil design reduces the force acting on a single coil. The result is an overall reduction of the magnet shield mass and a greater mechanical tolerance for the toroid assembly.



Figure 4.3.3: single racetrack coil (lower left) and the 120-coil toroid (lower right) are shown with the Al-B4C support cylinder (gray) that surrounds the Columbus habitat (blue-green). Each coil (yellow) is supported by a 0.6-mm-thick KEVLAR sheath (cyan).^[9]

| | Manufacturability | Shielding Effectiveness | Overall mass | Supercondu ctor in use | Bending power (BL) |
|-------------------------------|--|----------------------------|-----------------|---------------------------|--|
| Pumpkin | Difficult | Good | Much | YBCO | For 4m diameter cylinder ~4 Tm |
| Counter- wound | Difficult | Better | Less tape | YBCO | For 8m diameter cylinder Average 6.3 |
| Continuo us race- track | Already deployed in, Atlas experiment, ESA Columbus scientific module ISS | Moderate | Less | MgB2 | For 12 race-track ~4.9Tm |

Table 3: Comparison among different coil configuration^[9]

Better practicability is achieved in the case of race-track coil configuration since it has already proven a possibility in space.

5.4 Structural Design

Proposed cylindrical habitable capsule has a dimension of radius 5m and length 13m to accommodate a volume of 1000m³. From earlier comparison, continuous race-track configuration has proven to have most promising implication with example in practical situation. The major structure is divided into three parts

Al-B4C support cylinder: To mount the whole structure rigidly and support accessory instruments, and also to shield a portion of secondary radiation with passive shielding mechanism

Thick KEVLAR sheath: To support the winding coil and dissipate high energy radiation as they pass through them

MgB2 coil: To provide high current to produce desired magnetic field lines.



Figure 5.4: Conceptual design of the capsule and radiation shield

5.5 Simple Simulation with Toroidal Magnetic Field

Modeling the racetrack coil as a perfect toroid with the inverse relationship between magnetic field and distance, we simplify the greater complexity of produced magnetic field from this coil arrangement. We primarily used non relativistic treatment for force equation of omit complexity and not-linear differential equation.



Figure 5.5.1: Model in consideration

Current carrying superconductors around each KEVLAR sheath produce a toroidal magnetic field as shown below





I (amp) with turn ratio per unit length (m), N, magnetic field strength at co-ordinate point (x,y) can be determined as

$$B(x, y) = |B|\cos(\theta + 90^\circ) i + |B|\sin(\theta + 90^\circ) j$$

Where magnitude of B and angle θ is

$$B = \frac{\mu NI}{2\pi\sqrt{x^2 + y^2}}$$
$$\theta = \arctan \frac{x}{y}$$

Using current level of I = 800 A, N = 3000 and other parameters, maximum magnetic field is obtained 0.5 T. Though this strength is below desirable value, mass constraint doesn't permit us to increase the turn ratio by adding an extra layer of wire. But the simulation result shows promising result.

Now, from Lorentz force equation

$$\vec{F} = q\vec{v} \times \vec{B}$$

To compose the equation of motion for a charged particle with nuclear number Z and charge q, we use

$$\vec{F} = m\vec{a}$$

$$\begin{bmatrix} F_{x} \\ F_{y} \\ F_{z} \end{bmatrix} = q \begin{bmatrix} v_{x} \\ v_{y} \\ v_{z} \end{bmatrix} \times \begin{bmatrix} -|B|sin(\theta) \\ -|B|cos(\theta) \\ 0 \end{bmatrix} = m \begin{bmatrix} x'' \\ y'' \\ z'' \end{bmatrix}$$

Carrying out the cross product,

$$\begin{bmatrix} -z'|B|\sin(\theta) \\ -z'|B|\cos(\theta) \\ x'|B|\cos(\theta) + y'|B|\sin(\theta) \end{bmatrix} = \frac{zmp}{q} \begin{bmatrix} x'' \\ y'' \\ z'' \end{bmatrix} \qquad \dots (1)$$

This system of 2nd order differential equation can be numerically solved with the help of Matlab. We obtained Euler method to approximate the vector $\begin{bmatrix} x \\ y \\ z \end{bmatrix}$ with an initial position vector and velocity vector.

Worst and approximation would be to have a

Worst case scenario would be to have a particle incident on the field perpendicularly. The projected trajectory of an alpha particle is shown below.



Figure 5.5.3: Alpha particle trajectory in the toroidal magnetic field A trajectory for initial velocity of 30° inclination with respect to the x axis is given below

Path trajectory of 1GeV aplha particle in toroidal magnetic field



Figure 5.5.4: Alpha particle trajectory with 30° inclination

A trajectory for initial velocity of equal component in all axis is given below



Path trajectory of 1GeV aplha particle in toroidal magnetic field

Figure 5.5.5: Alpha particle trajectory with equal component in all axis

For energy range of 0.01GeV to 4GeV, the performance of the toroidal magnetic field is measured with deflection angle, defined as the slope of the particle trajectory, $\frac{\partial z}{\partial x}$, at time when $|x| < R_2$. With this definition, the following graph is obtained.



Deflection angle vs Kinetic energy of aplha particle in toroidal magnetic field

Figure 5.5.6: E_k vs deflection angle (degree)

It is noteworthy that, as the energy of the particle is increased, the variation in deflection angle saturates and the value is considerably small to be deflected all together from the habitant compartment. But KEVLAR sheath and supporting cylinder in the race-track coil configuration has a crucial role of reducing particle energy as they travel through the inter space of the magnetic field. The secondary low energy particles, which has a greater deflection angle, get blocked by the supporting cylinder or deflected gradually.

Nuclear number vs deflection angle





Figure 5.5.7: Deflection vs Z, nuclear number

As predicted, an increase in nuclear number result in smaller deflection angle.

5.6 Heat Shield

Recent development of JWST (James Webb Space Telescope) is required to be cooled below 40 K to block the thermal noise from the Sun, allowing the instrumentation to investigate deep-space, infrared phenomena. This requirement, and the development of the telescope's heat shield, may be usable with the race-track coil shield. This technology is investigated here, comparing the cooling potential and the issues of configuration.

The first consideration is the photovoltaic solar array system. The heat shield is intended to block the thermal load, mostly dominated by the Sun, but not to obstruct power generation via solar

arrays. The obvious solution is to place the solar panels between the Sun and the heat shield, allowing the solar panels to work normally, and also to block some of the incoming heat load.

While the back-emissive temperature of the solar panels is subject to the insulation used, and said insulation is subject to its effect on the panel performance, the temperature is assumed to be 300 K.

The panels designed here were to be placed at the tail end of the spacecraft, and sized to block the full circular surface area of the confined race-track coil shield.

The heat shield was sized to shade the coils. This configuration features the solar panels and heat shield to be deployed from the logistics module, thereby driving the pointing requirement of the spacecraft.

For the heat shield to work most effectively, it must stand between the Sun and the coils.

Assuming a pointing accuracy of 5°, the minimum width of the heat shields necessary to overcome any possible solar exposure can be determined:

Assuming Heat shield is 1 m from coils and spacecraft coil length is 15 m and overall width is 10 m, we get

Total length (coil length + distance between heat shield and coils) = 16 m

For rough calculation, θ = pointing accuracy = 5°

w = extra width of heat shield = $16tan\theta = 1.4 m$

Minimum apothem (radius) = 0.5 * (2 * 1.4 + 10)m = 6.4m

This sizing consideration is dependent on the pointing accuracy and the dimensions of the racetrack coil shield. As such, it is subject to those dimensions and is scalable.

The thermal insulating performance of a heat shield, or any spacecraft thermal insulation material, is determined by the emissivity, e^* . This parameter is determined by the quality and number of layers of the heat shield design. To facilitate a parametric analysis, the values of 0.01 is assumed for a single insulation layer, 0.002 for multiplayer insulation, and 0.000001 for a heat shield of JWST quality, also named as sunshield.

The thermal load on the coils can be calculated:

 $Q = F_{12} * A_1 * e^* * \sigma * (T_1^4 - T_2^4)$

Where,

 F_{12} = the view factor between the solar array and heat shield, assumed to be 1 here

 A_1 = the area of the entire solar array system = 3.1416*6.4² m² = 113.0976 m²

 σ = Stefan-Boltzmann constant = 5.67*10⁻⁸ (Wm⁻²K⁻⁴)

 $e^* = 0.01, 0.002, \text{ or } 0.000001$

 $T_1 = 300$ K, the back-surface temperature of the solar arrays

 $T_2 = 30$ K, the desired temperature on the surface of the coils.

The thermal load on the coils is then calculated to be 519.37 W, 103.87 W, or 0.052 W, depending on the heat shield emissivity of 0.01, 0.002, or 0.000001 respectively.

As the emissivity goes down, the thermal load on the coils also goes down. Therefore, it is good to almost completely cool the coils from the external environment using a JWST-type heat shield as the emissivity of it is very low.

5.6.1 Result Analysis

Using JWST-type heat shield we find out that, there is 0.052 W thermal load on the coils (through calculations), which we are actually neglecting as it is so poor amount. But if we consider this, we have to use cryocoolers with flexible, low-pressure helium gas circulation loops driven by low-pressure head helium fans, would be used to actively cool the coils.

But cryocooler technology is far less developed and reliable than heat shield technology, so we avoid this technology.

5.6.2 Passive Thermal Design Recommendations

After considering the passive thermal control needs and options, the following recommendations are made to thermally insulate and cool the coils of the spacecraft:

- 1. Point the tail end of the spacecraft at the sun.
- 2. Position the solar arrays in front of the heat shield.
- 3. Size the heat shield to account for 5° pointing accuracy. Distance from center to outside edge = 6.4 m.
- 4. Use a JWST-type heat shield. Then, only 0.052 W radiates in coils.

5.7 Interplanetary magnetic Field

Interplanetary Magnetic Field (IMF) is a part of Sun's magnetic field, which has a magnetic dipole field of 10⁻⁴ T flux density near its surface. IMF is brought into interplanetary by solar wind and its field lines are considered to be "frozen in" solar wind plasma. As the space is not pure vacuum this magnetic field doesn't follow inverse cubic reduction formula. The estimated value of flux density is actually in the order of 2-40 nT. Due to sun's continuous rotation ,the IMF travels in a spiral pattern like the solar wind and its distribution in interplanetary space begets a complex field.



Figure 5.7: Interplanetary magnetic Field

During interplanetary mission, the spacecraft's own magnetic field produced from HTSC coils, interacts with ambient IMF which creates disturbance torque in return.

Magnetic disturbance torque determination

The instantaneous magnetic disturbance torque T_m is the vector cross-product of the spacecraft's effective dipole moment M and the local magnetic flux density B ^[2]

$$T_m = M \times B$$

So, this disturbance torque tries to change direction of the spacecraft which leads to a great danger. As the main methodology of our spacecraft is established by its own magnetic field, optimization of magnetic dipole of the spacecraft is not a solution to reduce IMF disturbance. If a rocket propulsion system is mounted 10 m from the center of gravity, a propulsion force of less than 5 N is sufficient to counteract the maximum torque acting on the shielding array. The linear force (as opposed to torque) on the coils is proportional to the gradient of the interplanetary magnetic field. ^[3]

5.8 Mass determination in active shielding method

Refer to figure 5.3.3, to cover 1000 m^3 with active shielding method, the Columbus habitat radius and height is assumed 5m and 13m respectively.

Mass of grey base cylinder

Volume of cylinder, $V_{cyl} = \pi h_c (r_{out}^2 - r_{in}^2)$ Mass of cylinder, $m_{cyl} = \rho_{Al-B4C} V_{cyl}$ (i) Here, height of the support cylinder, h_c =15m Inner radius, r_{in} = radius of Columbus habitat=5 m Outer radius, r_{out} = (5+.001) m = 5.001m Density of Al-B4C, ρ_{Al-B4C} =2700 kg/m³ From (i) we get, m_{cyl} = 1273kg

Mass of racetrack coil

 $m_{race} = N_{race} wht_{kevlar} \rho_{kevlar}$ Here, N_{race} = Number of race track coil=120 w = racetrack width = 5m h = racetrack height = 15m t_{kevlar} = depth of KEVLAR sheath = 0.6mm ρ_{kevlar} = density of KEVLAR sheath = 7800-8000 kg/m³ So m_{race} = 43200 kg = 43.2 tons

Again, $m_{coil} = 2(w + h)N_L \pi r_{coil}^2 \rho_{MgB2}$ Number of coil layers, $N_L = 3$ Radius of a coil, $r_{coil} = 1$ mm $\rho_{MgB2} = 2570 \text{ kg/m}^3$ $\therefore m_{coil} = 3873 \text{kg}$:. Total extra mass, $m_{extra} = m_{cyl} + m_{race} + m_{coil}$

Extra fuel consideration for extra mass from shielding

From rocket equation,

$$\Delta v = v_e ln \frac{m_o}{m_f}$$

We consider two separate case for a maneuver with shielding instrument and another for not. To maintain an equal final velocity, we set the parameter $\Delta v/v_e$ constant.

Now, case 1, $m_{o1} = m_{propellant1} + m_{f1}$

$$m_{f1} = m_{habitant}$$

For second case, $m_{o2} = m_{propellant2} + m_{f2}$

$$m_{f1} = m_{habitant} + m_{shielding}$$

Now comparing two fractions, we get

$$ln\frac{m_{o1}}{m_{f1}} = ln\frac{m_{o2}}{m_{f2}}$$
$$\frac{m_{propellant2}}{m_{propellant1}} = 1 + \frac{m_{shielding}}{m_{habitant}}$$

6.Critical Analysis

Strength

- HTSC is more accessible for general use and host of energy-saving process. It is costeffective and HTSCs have high current density between 50-100 kA/cm^2.
- For racetrack structure, the cooling process is relatively easy. Other spaceship structures demand Cryocooler for the cooling process which is too expensive. However, the heat shield system in our spaceship is quite sufficient to handle heat production.
- An extra mass requirement of HTSC confined active radiation shielding method is much less than that of passive radiation shielding method.

Polyethylene is a good passive shielding material because it has high hydrogen content, and hydrogen atoms are good at absorbing and dispersing radiation.

However, the presence of extremely energetic heavy ions in the GCR spectrum, such as Fe56+, that can penetrate tens of centimeters of shielding materials, producing a secondary particle cascade, is a big concern for both the human crew and the electronics inside the spacecraft.^[4]

| For | Toroid | shape | inner | radius = | r |
|-----|--------|-------|-------|----------|---|
| | | | ~ | | |

Outer radius = R

Volume of toroid = $2\pi^2 Rr^2$ (i)

and Surface area= $4\pi^2 Rr$ (ii)

As the shielding covers 1000 m³ area, we assume that

Outer Radius, R=10m

Inner Radius, r=2.25 m

Calculating (i) Surface area. S=889 m²

Here,

Total areal density of passive shielding=14.7 g/cm² (Using areal density of 14.7g/cm² passive coating layer consisting of Al2219. Nextel, Kevlar Epoxy)^[4]

:. Total extra mass in passive shielding=130 tons

The extra mass required in Passive shielding method is about 130 tons while the amount is about 48.5 tons in Active radiation shielding method.

• Minimize charged particle flux into spaceship habitat and secondary particle production in shielding coil material is reduced

Weakness

- MgB2 cannot operate at higher than 4T magnetic field. However, we have used magnetic field within the range of 3T. However, it suffers from flux jump problem at high-density magnetic field even in low temperatures.
- Communication disruption due to high flux density of magnetic field.
- Extra thrust required to overcome IMF issues.
- Around 0.052W heat entry in spite of using heat shield.

Conclusion

Major motivation of using active shielding was the innovation high-temperature superconductors which were a difficult hurdle to overcome in the past. Our developed plan uses this fruitfulness using a continuous coil race-track coil shield that would protect the human crew from most of the harmful radiation in interplanetary travel. An additional mass of 48.346 tons would need to be brought on the journey to protect the habitat of 1000 cubic meters.

We have compared different methods like deployed shielding, poly-ethylene coating, doublehelix solenoid coil shield, etc. with our applied method and the analysis results show potential implications. Though it cannot solve problems like reliable communication or hundred percent protection from GCR. Our proposed JWST-type heat shield, containing a very low emissivity, is a very useful instrument for reducing thermal load on the coils from KW or W range to mW range. However, our simplified model doesn't address all the problems arise in the practical situation but it surely gives enough mass reduction and guarantee towards tolerable radiation protection.

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Resource : Matlab 2018a

Appendix

Matlab code for solving the 2nd order differential using Euler method

```
%Parameters
R1 = 5; \%m
R2 = 10;
mu = 12.57*10^{-7};
N = 3000;
I = 800;
Z = 4;
mp = 1.6*10^{-27};
m = Z^*mp;
q = 2* 1.6*10^{-19};
k = m/q;
%Fucntions
B = @(x,y) (sqrt(x.^2 + y.^2)) > R1 \& sqrt(x.^2 + y.^2) < R2)*...
  mu*N*I/(2*pi*sqrt(x.^{2} + y.^{2}));
%Associated Fucntions to solve ODE
co = @(x,y) cos(atan(y/x));
si = @(x,y) sin(atan(y/x));
x_dot = @(x,y,z,vx,vy,vz,t) vx;
vx_dot = @(x,y,z,vx,vy,vz,t) - vz^*B(x,y)^*co(x,y)/k;
y_dot = @(x,y,z,vx,vy,vz,t) vy;
vy dot = @(x,y,z,vx,vy,vz,t) - vz^{*}B(x,y)^{*}si(x,y)/k;
z_dot = @(x,y,z,vx,vy,vz,t) vz;
vz_dot = @(x,y,z,vx,vy,vz,t) B(x,y)*(vx*co(x,y) + vy*si(x,y))/k;
```

%variables $t_{min} = 0.5e-7;$ $t = linspace(0, t_min, 1000);$ h = t(2) - t(1);n = length(t);x = zeros(1,n);vx = zeros(1,n);y = zeros(1,n);vy = zeros(1,n);z = zeros(1,n);vz = zeros(1,n);%initial condition Ek = 1; % GeV $G = 10^{9} * 1.6 * 10^{-19}$; % constant to convert to J from GeV x(1) = -R2; % initial position $c = 3*10^8;$ $vx(1) = sqrt(c^{2}(1 - (m^{*}c^{2}/(Ek^{*}G + m^{*}c^{2}))^{2}));$ % relativistic velocity y(1) = 0;vy(1) = 0;z(1) = 0;vz(1) = 0;for i=2:n x(i) = x(i-1) + ...x_dot(x(i-1),y(i-1),z(i-1),vx(i-1),vy(i-1),vz(i-1),t(i-1))*h; vx(i) = vx(i-1) + ...vx_dot(x(i-1),y(i-1),z(i-1),vx(i-1),vy(i-1),vz(i-1),t(i-1))*h; y(i) = y(i-1) + ...y_dot(x(i-1),y(i-1),z(i-1),vx(i-1),vy(i-1),vz(i-1),t(i-1))*h; vy(i) = vy(i-1) + ...vy_dot(x(i-1),y(i-1),z(i-1),vx(i-1),vy(i-1),vz(i-1),t(i-1))*h; z(i) = z(i-1) + ...z_dot(x(i-1),y(i-1),z(i-1),vx(i-1),vy(i-1),vz(i-1),t(i-1))*h; vz(i) = vz(i-1) + ... $vz_dot(x(i-1),y(i-1),z(i-1),vx(i-1),vy(i-1),vz(i-1),t(i-1))$ *h; end figure; plot3(x,y,z,'LineWidth',1.5); title('Path trajectory of 1GeV aplha particle in toroidal magnetic field'); xlabel('x(m)'); ylabel('y(m)');

```
zlabel('z(m)');
hold on;
```

%Toroid drawing

th = 0:pi/50:2*pi; plot3(R2 * cos(th), R2 * sin(th),zeros(length(th)),'LineWidth',2);

hold on;

plot3(R1 * cos(th), R1 * sin(th), zeros(length(th)), 'LineWidth', 2);