Mitigating Radiation Risks on the Space Station: A Comparison of Shielding Technologies

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***Abstract*— Astronauts aboard the Space Station are continuously exposed to ionizing radiation from cosmic rays, solar particles, and trapped radiation within the Earth's magnetosphere. These radiation sources pose significant health risks, including an increased likelihood of cancer, cardiovascular diseases, and neurological disorders. This paper examines the radiation environment at an altitude of 450 km (Low Earth Orbit) with a 52° inclination. It discusses the biological effects of radiation exposure and the operational countermeasures that need to be implemented to mitigate these risks. The mission plan for astronauts inside the module includes a three to six-month rotation schedule, which helps to limit cumulative radiation exposure. However, the Space Station can also be envisioned for long-term experiments, including studies on human survival in space for a long time and potential space colony development. These initiatives are crucial for preparing future interplanetary exploration missions. If humans are to remain in space for extended periods, effective radiation protection strategies must be established. This paper further explores the comparison between passive and active shielding technologies for long-duration missions, evaluating their effectiveness in protecting spacecraft and astronauts from space radiation. Active radiation is more effective in blocking higher energy particles, requiring additional peripherals to keep it working.**

Keywords—Space radiation, astronaut health, shielding techniques, interplanetary missions, Space Station, passive shielding, active shielding, cosmic rays, solar particle events, Low Earth orbit.

I. INTRODUCTION

As human space exploration advances toward long-term missions, the development of future space stations such as the planned Space Station is needed for today's era. The space station generally consists of five modules –i. Base Module, ii. Crew Core-Docking Module, iii. Science research Module, iv. Laboratory Module and Common Working Module. One of the most critical challenges in such missions is radiation exposure. Unlike Earth, where the atmosphere and magnetic field provide protection from most forms of ionizing radiation, astronauts in Low Earth Orbit (LEO) are continuously exposed to multiple radiation sources, including Galactic Cosmic Rays (GCR), solar particles from Solar Particle Events (SPE), and trapped particles in the Van Allen Belts.

Radiation exposure poses significant health risks, including increased cancer rates, cataract formation, and cognitive impairments, particularly in long-duration missions. On average, the International Space Station (ISS) experiences a radiation dose rate of approximately 0.18 Sv/year.

According to NASA, the career-effective dose exposure limits for astronauts at the age of 30 upon first exposure are 0.475 Sv for females and 0.625 Sv for males. In free space, the equivalent dose rate is significantly higher, reaching 1.2 Sv/year.[1]. To ensure astronaut safety and protect onboard electronics from prolonged radiation exposure, it is essential to explore advanced shielding technologies. While passive shielding using traditional materials like aluminium and polyethylene has been widely used, active radiation shielding techniques such as electromagnetic and plasma-based deflection systems offer potential advantages for long-term space habitation. This paper examines the radiation environment in LEO, its biological impacts, and a comparative analysis of passive and active shielding techniques, highlighting their effectiveness in protecting astronauts and spacecraft systems during extended missions.

II. SPACE RADIATION ENVIRONMENT

A. Trapped Radiation

The Earth's magnetic field captures and traps high-energy protons and electrons, forming the Van Allen Belts—a region of intense radiation surrounding the planet. When spacecraft passes through areas such as the South Atlantic Anomaly (SAA), where the Earth's magnetic field is weaker, astronauts experience elevated radiation exposure due to an increased flux of trapped particles. The average dose rate received by an astronaut in these regions ranges from 0.1 to 0.5 mSv per day.

It is shown in Fig. 1(a), that fluence decreases as energy increases, following an approximately exponential decay pattern higher fluence at lower energies (<1 MeV), which gradually decreases as energy increases beyond 5 MeV. The maximum integral fluence reaches ~10^{14} particles/cm² at very low energies. The integral fluence reduces from 10^{14} particles/cm² at low energy (~0.1 MeV) to around 10^{6}–10^{7} particles/cm² at higher energies (~5 MeV). Low-energy electrons (<1 MeV) when accumulates over crew modules surface can cause electrostatic discharge (ESD), leading to anomalies in power systems, solar arrays, electronics when exposed to space plasma. While high-energy trapped electrons (>1 MeV) interact with spacecraft materials, producing bremsstrahlung X-rays. These X-rays can penetrate deep into spacecraft modules, increasing astronaut radiation dose.

The integral flux of trapped proton (Fig. 1(b)) shows that high fluence values are observed at lower energies (<50 MeV), indicating a strong presence of low-energy trapped protons. The fluence drops significantly for protons above 200 MeV, though they can still penetrate shielding materials and cause deep-seated damage. The highest fluence (~10^{10} particles/cm²) is at low energies, declining to ~10^{6}–10^{7}

particles/cm^2 in the 400 MeV range. Low-Energy Protons (<50 MeV) can cause Single-Event Effects (SEE) in microelectronics, leading to bit flips, latch-ups, and functional failures in spacecraft systems which can risk life of astronaut. High-Energy Protons (>200 MeV) though lower in fluence, but high-energy protons can penetrate deep into shielding materials, increasing the risk of internal organ exposure and secondary radiation production in astronauts.

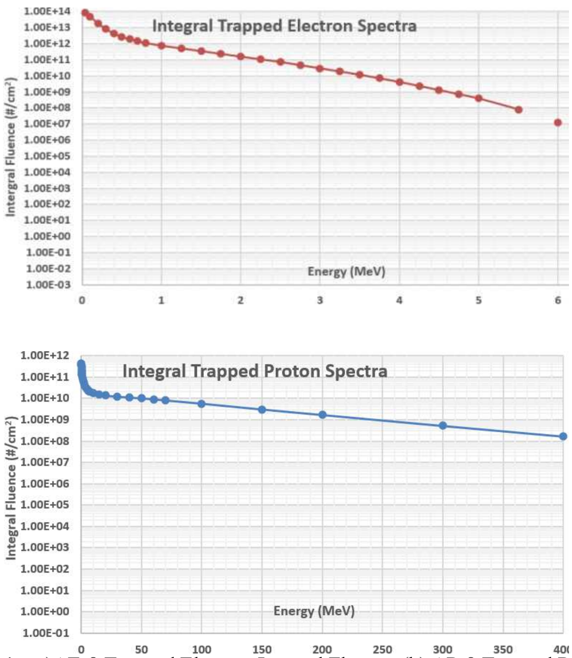

Fig. 1. a)AE-8 Trapped Electron Integral Fluence (b) AP-8 Trapped Proton Integral Fluence for 20 years mission life at 450Km at 520 inclinations.

B. Galactic Cosmic Rays (GCR)

Galactic Cosmic Rays (GCR) are high-energy particles originating from outside the solar system, primarily composed of protons ranging from 100 MeV upto10 GeV (can also be extended to PeV levels), helium nuclei like α-particles can

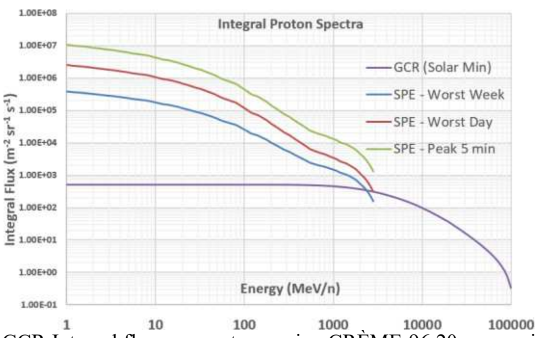

Fig. 2. GCR Integral fluence spectrum using CRÈME-96 20 years mission life at 450Km at 520 inclinations.

range approx. from (100 MeV/n – 10 GeV/n), and heavier ions like C, O, Fe, etc. can range from~100 MeV/n – 10 GeV/n (up to 100 GeV/n for Fe). Due to their extremely high energy levels, GCRs can penetrate deep into spacecraft structures and human tissue, making them one of the most hazardous sources of radiation in space. The average dose rate from GCR exposure for astronauts in Low Earth Orbit (LEO) is estimated to be 0.2 to 0.4 mSv per day. [5].

It is shown in fig 2 Galactic Cosmic Rays (GCR) during Solar Minimum (purple curve) also with Solar Particle Events (SPEs) with different intensities: a)Worst Week (blue)

b)Worst Day (red) c)Peak 5-Minute Flux (green). GCR spectrum is relatively constant over a wide energy range but dominates at high energies (>1 GeV). SPE flux is significantly higher at lower energies (<100 MeV) and decreases with increasing energy. Persistent exposure to high-energy protons (>1 GeV) contributes to chronic radiation dose accumulation can cause deep tissue damage, increased cancer risk, and neurological effects due to secondary radiation production in body tissues.

C. Solar Particle Events

Solar flares and Coronal Mass Ejections (CMEs) during Solar Particle Events (SPE) release large amounts of high-energy protons and other ions. These particles can reach Earth and pose acute radiation hazards for astronauts, particularly during extravehicular activities (EVAs). Average dose rate is 0.1 to 1 mSv /day received by astronaut [5].

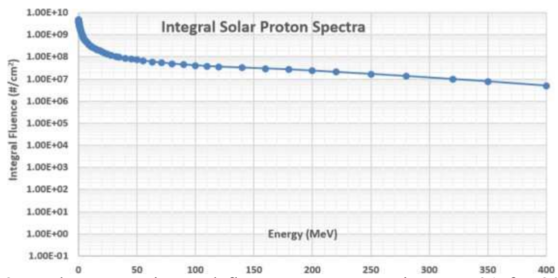

Fig. 3. Solar proton integral fluence spectrum using JPL-91 for 20 years mission life at 450Km at 520 inclinations.

Here is the graph in Fig. 4 showing the fluence of solar proton during worst case solar events. The fluence decreases exponentially as the proton energy increases. High fluence values are observed at lower energies (<50 MeV) while the fluence drops significantly for protons above 200 MeV. The highest fluence appears close to 10^{10} particles/cm^2, reducing to ~10^6–10^7 particles/cm^2 in the 400 MeV range. Low-energy protons (<50 MeV) pose a significant risk for single-event effects (SEE) in electronics and biological radiation dose for astronauts. Medium-energy protons (50–200 MeV) these protons contribute significantly to total ionizing dose (TID) and displacement damage in solar panels and semiconductor devices. High-energy protons (>200 MeV) although their fluence is lower, they are capable of penetrating deeper into shielding materials. Hence Multi-layered shielding approaches should be considered for crewed modules.

III. BIOLOGICAL IMPACT ON ASTRONAUTS

A. ACUTE RADIATION EFFECTS

Short-term exposure to radiation levels exceeding 500 mSv can lead to Acute Radiation Syndrome (ARS), characterized by symptoms such as nausea, vomiting, fatigue, and immune system suppression. While ARS is rare in Low Earth Orbit (LEO) due to the shielding provided by spacecraft, it remains a critical concern during Solar Particle Events (SPEs), where sudden spikes in radiation can significantly increase exposure levels (NASA STD-3001 [1]).Beyond immediate physiological effects, prolonged radiation exposure has been linked to mental health issues, including anxiety, depression, cognitive decline, and impaired decision-making—factors that could severely impact astronaut performance during extended missions (ICRP, Publication 103 [2]). Additionally, Galactic Cosmic Rays (GCRs) have been associated with neurodegenerative diseases and long-term brain function deterioration, raising serious concerns for deep-space missions such as those to Mars and beyond.

B. Long-Term Effects

During a six-month mission aboard the International Space Station (ISS), astronauts receive an average radiation dose of 80–160 mSv, correlating with an estimated 1.5–3% increase in lifetime cancer risk according to NASA and the International Commission on Radiological Protection (ICRP) [2]. NASA projects that long-term space radiation exposure could elevate cancer risk by approximately 3% for male astronauts and 5% for female astronauts [1]. One of the most severe consequences of prolonged radiation exposure is DNA damage, particularly double-strand breaks (DSBs), where both strands of the DNA helix are compromised. These breaks are difficult to repair, significantly increasing the likelihood of cancerous mutations. Additionally, radiation exposure triggers the formation of reactive oxygen species (ROS), which cause cellular damage, accelerate aging, and contribute to tissue degradation. Other long-term health concerns include cataract formation due to radiation-induced damage to eye lenses. Cardiovascular diseases, as radiation exposure has been linked to arterial damage and increased risk of heart attacks and strokes (NASA Human Research Program [5]).

The Linear No-Threshold (LNT) model [2], as depicted in the graph, suggests a direct proportional relationship between radiation dose and cancer risk, meaning that even low doses

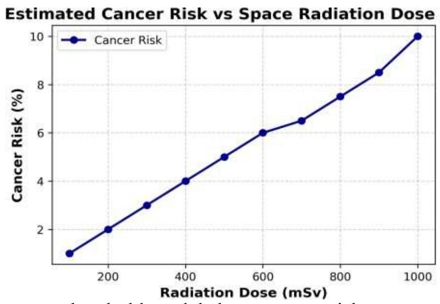

Fig. 4. Linear no threshold model shows cancer risk versus radiation dose. Ref [2]

contribute to long-term health risks. The graph shows a steady increase in cancer risk with rising radiation exposure, reaching nearly 10% at 1000 mSv. This is particularly concerning for astronauts, as a six-month ISS mission results in 80–160 mSv exposure, increasing cancer risk by 1.5–3%. For deep-space missions, exposure could exceed 1000 mSv, significantly elevating long-term health risks. To mitigate this, advanced shielding techniques, materials and medicines.

IV. Current and Future Radiation Shielding Technologies

The International Space Station (ISS) employs aluminium shielding to protect astronauts from Galactic Cosmic Rays (GCRs) and Solar Particle Events (SPEs), with typical thicknesses ranging from 5 to 10 cm. In the current scenario, the Half-Value Layer (HVL) for aluminium is approximately 2.5 mm for high-energy protons, which are the dominant radiation component during solar particle events. A 5 mm aluminium layer effectively blocks 30–40% of lower-energy protons, while further increasing Aluminium thickness gets saturated with dose rate.

Additionally, water and polyethylene are used as supplementary shielding materials due to their high hydrogen content, which enhances protection against high-energy particles by reducing secondary radiation effects. These materials are particularly effective against neutron and proton radiation, further improving astronaut safety in space.

A. Passive Radiation Shielding

Passive shielding involves the use of materials like aluminium or polyethylene to block or absorb radiation. While effective against lower-energy particles such as protons from SPEs, passive shielding struggles with GCRs, which can produce harmful secondary particles when interacting with shielding materials. Over time, these secondary particles can

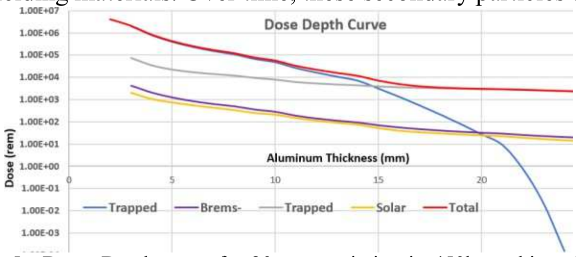

Fig. 5. Dose -Depth curve for 20 years mission in 450km orbit and 520 inclinations for Aluminum shielding.

accumulate, leading to higher doses of radiation exposure. The dose-depth curve (Fig. 6) shows the nearly saturation of dose after given amount of thickness of aluminium. Also, use of passive shielding increases the weight of spacecraft which in turn increases the cost of launch. Additionally, the Fig. 5 does not consider the dose accumulation due to GCRs.

B. Active Radiation Shielding

The Active radiation shielding involves a mechanism for deflection of space particle with the help of generated Electric field or Magnetic field. As of now three different types of active radiation shielding are proposed –

(i) *Electrostatic shielding*: High electric field is generated between two plates of capacitor at extremely high voltage which decelerate the charged particle, thereby preventing energetic the charged particle to enter in the habitable zone of spacecraft. However, the method of electrostatic shielding requires billions of volts which demands large electrostatic generators and to prevent dielectric breakdown, structure of size of around 20km is required [16].

(ii) *Magnetic Shielding*: As Space environment consists as particles such as electrons, protons and ions which can be deflected by magnetic field. The magnetic shielding is of two types-one is confined magnetic shielding and other one is unconfined magnetic shielding. As name suggests, confined magnetic shielding (shown in Fig.7) is the one where magnetic field is confined within region such as toroid and unconfined magnetic shielding is the one with no confinement of magnetic field. The unconfined shielding is not recommended for spacecraft because magnetic field in the unconfined structure may interact with electromechanical component causing malfunctioning. Furthermore, the confined shielding such as toroid structure leaks very minimal magnetic field. The multiple superconducting toroid magnet coil of weak magnetic field shows the practicality in shielding the spacecraft habitat.

(iii) *Plasma shielding*: The plasma containing several coulombs of electrical charges produces by several billions of Volts for shielding GCR. This method is also not suitable for practical usage due to plasma instabilities [16].

V. Magnetic Shielding

The magnetic field deflects the trajectory of charged particle governed by Lorentz force by an amount proportional to *BL/R*, where *B* is the field flux density, *L* is the length of confined magnetic field and *R* is the particle rigidity, defined as *R=pc/Ze* (*Z* is the number of charge, *e* is the charge of electron and *c* is speed of light).

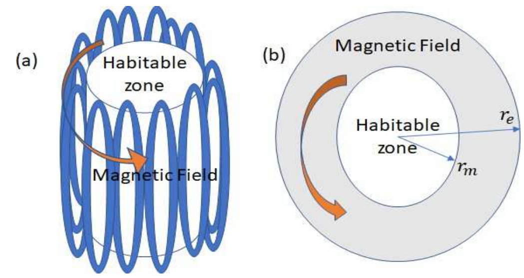

Fig. 6. Confined Magnetic field in toroidal structure for cylindrical shaped habitable zone.

In confined magnetic shield configuration (Fig. 6), since magnetic field does not degrade the particle energy and secondary particle production is limited to the coil and supporting structures. The radiation risk represented by the secondaries is expected to be considerably less than for the punch through particle created by a passive absorber. The capability of the structure for deflecting the charged particle is estimated using 'bending power' defined as follow:

$$Bending\ power\ (\beta) = \int_{r_m}^{r_e} B(l).dl = \frac{\mu_0 N i}{2\pi} \ln\left(\frac{r_e}{r_m}\right) \quad (1)$$

Here, the $B(l)$ is the magnetic field as a function of coordinate l, N is the number of coil, i is the current and, magnetic field is confined between radius r_m and r_e (shown in Fig. 6). As per [8], the cut-off energy per nucleon is given by:

$$E \le \frac{m_0 c^2}{\eta}\left(\sqrt{\left(\frac{q\beta}{m_0 c(1 - sin\phi)}\right)^2 + 1} - 1\right) \quad (2)$$

Here, m_0 is the rest mass of incident particle, c is the speed of light, η is the nucleon number, β is the bending power and ϕ is angle of incidence.

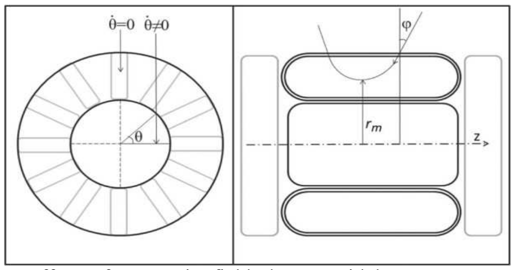

Fig. 7. FEffect of magnetic field due Toroidal structure on incoming charged particle incident along radial direction orthogonally to the toroidal axis and at an angle. Ref [6]

The confined magnetic shielding can be achieved using toroidal solenoid with radius R and N number of turns. The value generated magnetic field intensity (B) is given by:

$$B = \frac{\mu_0 N I}{2\pi R} \quad (3)$$

With the choice of $B = 5T$ to 7T and width of confined magnetic field $(\Delta) = 1m$ to $2m$, 70% to 90% reduction of the cosmic ray flux inside habitable zone is observed. To reduce the penetrating flux to 1% of the nominal intensity, one has to achieve bending power (β) ~30 Tm which requires current (I)=30MA for R~4m-5m. Reference [6] shows that the bending power of 5 Tm reduces the cosmic ray flux by 4.5 times with a cut-off energy of about 1 GeV for 0^0 incident protons. The configurations used for analysis in shown in Fig7.

A. Magnetic Pressure

The various configuration requires trapping of high value of magnetic field intensity with current flowing inside the coil, which exerts the magnetic pressure on the coil. The value of magnetic pressure is given as:

$$P = \frac{B^2(r)}{2\mu_0} = \frac{\mu_0 n^2 i^2}{8\pi^2 r^2} \quad (4)$$

Here, n is the number of turns per unit length, i is the current flowing inside the coil and r is the radius. The superconducting coil should be kept in a structure capable enough to withstand the magnetic pressure exerted by the coil. NASA-LARC, JNL,NIA have jointly synthesized long highly crystalline Boron Nitride nanotubes (BNNT). These nanotubes have better strength and high temperature stability [6]. It can be used for load bearing structure for supporting superconducting magnets.

B. Cryocooler

The magnetic shield structure also requires to be maintained at low temperature considering the margin with critical temperature of superconductor. High temperature superconductors (HTS) such as MgB2 and YBCO having critical temperatures 32K and 90 K are proposed for the usage in magnetic shielding. The cryocooler is required for maintain the required temperature of superconductor. The mass of cryocooler (m_{cryo} in kg) is estimated in [17] based on net input work require (W_{net} in $Watt$):

$$m_{cryo} = 0.0711\, W_{net}^{0.905} \qquad (5)$$

The required net input work is derived in terms of efficiency of cryocooler (η), Amount of heat removed (Q_l), temperature of heat sink (T_H) and operating temperature of superconductor (T_{op}) is given as:

$$W_{net} = \frac{1}{\eta} Q_l \left(\frac{T_H}{T_{op}} - 1\right) \qquad (6)$$

C. Mass Budget for Magnetic Shielding

The mass of a 1-meter YBCO tape superconductor with a width of 5 cm is 40 grams. At an operating temperature of 25 K, YBCO with a width of 5 cm can carry a current of up to 11 kA [6]. Considering the bending power of the magnetic shield system as 5 Tm, the required number of turns is around 89,000. The values of $r_e = 3m$ and $r_m = 5m$ are considered. The calculation shows that the mass of the superconducting coil is 22 tons. Considering the thermal conductivity $(\kappa) = 0.01 \frac{W}{m-k}$ and emissivity $(\epsilon) = 0.05$ for MLI insulation, the heat leakage is obtained as 1.387 W, hence the mass of cryocooler is around 10Kg.

Therefore, the total mass required for confined magnetic shielding is 22 tons. The required mass seems to be high. However, this structure of active magnetic shielding ensures that protons below the energy of around 1 GeV would not pass through the habitable zone, which significantly reduces the dose. Also, it prevents majority of heavy ions from GCR. The cryogenic fluid to be used in structure can be liquid Helium or Hydrogen which also acts as shield against space radiation. The effect of shielding from cryogenic fluid is not considered in the paper. Additionally, the operation of Active radiation shielding requires additional solar panels and power systems, whose mass is not considered.

D. Mass Budget for Passive Shielding

The Dose depth curve (in Fig. 5) suggests the dose at Silicon for 20 years mission is saturated at approx. 1000 rad (~10 Sv) in the 450 Km orbit with 52^0 inclinations irrespective of thickness of aluminium after 7nm. Moreover, it does not account for GCR spectrum in the estimation of dose which raises the accumulated dose. This clearly shows the conventional passive shielding technique is not suitable for designing space habitat or long duration interplanetary mission.

VI. Discussions

Active radiation shielding effectively reduces space radiation particle flux, thereby lowering the radiation dose rate within the habitable zone. However, implementing active shielding introduces structural complexities due to the need for additional subsystems, which can increase the risk of mechanical failures and pose challenges to system reliability. Furthermore, active magnetic shielding requires significant power generation, necessitating reliance on larger solar panel arrays or nuclear power sources, which adds further design constraints. On the other hand, passive shielding is structurally simpler but is often insufficient in reducing the radiation dose rate to safe limits for long-duration space missions. Achieving radiation protection equivalent to active shielding using only passive materials would impose a significant mass penalty, making spacecraft design inefficient. Certain hydrogen-rich materials such as polyethylene, water, and lithium hydride have been proven to be more effective radiation shields compared to conventional materials like aluminium or tantalum, as they provide superior protection against high-energy protons and secondary radiation. A hybrid shielding approach, involving use of hydrogen-rich material for making structures of active radiation shielding that combines the effects of both active and passive shielding techniques, offers a promising solution by optimizing weight efficiency while effectively minimizing radiation dose accumulation. This approach can balance the structural simplicity of passive shielding with the high effectiveness of active shielding, ensuring a safer environment for long-term human space missions.

VII. Conclusions

Radiation exposure remains a major challenge for astronauts aboard the Space Station and other long-duration space missions. While the International Space Station (ISS) has established a baseline for radiation protection, future missions—particularly those planned by India and other spacefaring nations—will require advanced shielding materials and medical countermeasures to ensure astronaut safety. Both passive and active radiation shielding have their own advantages and limitations. Passive shielding is structurally simpler but becomes ineffective for extended missions due to secondary particle generation and excessive mass requirements. Active shielding, on the other hand, is a more reliable solution against space radiation, but its feasibility is constrained by high power consumption, engineering complexity, and the need for cryogenic cooling of superconductors.

For long-term missions, particularly those involving deep space exploration, active magnetic shielding emerges as the most promising radiation protection strategy. It offers substantial confidence in blocking even higher energy particles. However, further advancements in energy systems, cryogenic cooling, and superconducting materials are necessary to make active shielding a practical and reliable solution for future space missions.

Future developments in high-temperature superconductors such as REBCO and MgB_2, along with compact nuclear power sources and lightweight cryocoolers, are likely to address current limitations. Space agencies like NASA and ESA are already exploring hybrid shielding strategies, combining the strengths of passive and active methods to balance safety, efficiency, and feasibility. This integrated approach is expected to play a central role in ensuring astronaut health for interplanetary exploration and permanent space habitation.

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