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Perspective

A Review of Magnetic Shielding Technology for Space Radiation

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Simple Summary: Successful human exploration beyond Earth orbit relies on solving the issue of high radiation doses received in space. Many passive and active radiation mitigation strategies have been proposed over the past several decades, but the problem remains to be solved. A promising concept exists to use superconducting magnets to effectively recreate the benefit of Earth's magnetic field and deflect incoming space radiation before it ever reaches the spacecraft. This type of radiation shielding technology has been studied since the dawn of human space exploration in the 1960s but has experienced highs and lows in its development since. This paper summarizes the findings of research on this topic and suggests that a linkage exists between studies of cutting-edge space technologies such as magnetic shielding and the overall budget for human spaceflight endeavors.

Abstract: The space radiation environment outside the protection of the Earth's magnetosphere is severe and difficult to shield against. The cumulative effective dose to astronauts on a typical Mars mission would likely introduce risk exceeding permissible limits for carcinogenesis without innovative strategies for radiation shielding. Damaging cardiovascular and central nervous system effects are also expected in these space environments. There are many potential options for advanced shielding and risk mitigation, but magnetic shielding using superconductors offers several distinct advantages including using the conditions in space to help maintain the superconductor's critical temperature and lower mass compared to equivalent passive shielding materials. Despite these advantages, the development of magnetic shielding technology has remained primarily in conceptual stages since the introduction of the idea in 1961. Over the last several decades, magnetic shielding has experienced periods of high and low attention by the human spaceflight community, leading to computational tools with single-use or other limitations and a non-uniform distribution of publications on the topic over time. Within the context of technology development and the surrounding space policy environment, this paper reviews and summarizes the available literature on the application of active magnetic shielding for space radiation protection, identifies challenges, and highlights areas for future research.

Keywords: magnetic shielding; radiation shielding; space radiation; long-duration spaceflight; radiation dose

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1. Introduction

The space radiation environment outside the protection of the Earth's magnetosphere includes the solar wind, products of solar particle events (SPEs), and galactic cosmic rays (GCRs). The solar wind is comprised of protons and some electrons and has a high fluence rate (~10^{10} cm^{-2} s^{-1}) but low energy (~0.5 to 2 keV). SPEs produce mostly protons with a time-varying fluence rate (10 to 10^3 cm^{-2} s^{-1}) and medium energy (10 MeV to 1 GeV).

GCRs consist of very high energy (100 MeV to 1 TeV+) nuclei of every atom from hydrogen (Z = 1) through iron (Z = 26) [1] with a lower fluence rate (10^{-5} to 1 cm^{-2} s^{-1}). GCR radiation in particular is highly damaging to cells and human tissue and increases the risk of a host of long-term sequelae for those exposed, including cardiac disease, neurological degeneration, and cancer [2].

In the practical setting of a space mission, solar wind is of little concern because the structural components of the spacecraft will absorb these particles. SPE protons are more concerning because of the higher energy as well as the dynamic fluence rate. Further, SPE protons will not be entirely blocked by standard structural components; additional shielding is required to mitigate exposure associated with SPEs. GCRs are most problematic because of their high energy, which makes them very difficult to shield against.

Due, in particular, to this chronic GCR exposure, astronauts on missions beyond the Earth's magnetosphere (e.g., lunar, asteroid, and interplanetary) are likely to require more advanced radiation protection technology than what currently exists for a human spacecraft. The cumulative exposure to GCRs on a typical Mars mission will be on the order of 1 Sv [3]. Terrestrial exposure in this range is often associated with an approximate 5% increase in lifetime fatal cancer [4], which in comparison would exceed NASA's permissible exposure limits [5,6]. Damaging cardiovascular and central nervous system effects are also expected in the space environment [7,8]. Thus, NASA has identified radiation as one of the highest risks to astronauts on interplanetary missions, as well as one of the least well-managed risks to date [9].

Therefore, NASA and other space agencies have been studying alternative methods for mitigation of exposure to space radiation and the associated consequences, including reduced mission duration with advanced propulsion [10], pharmaceutical or chemical countermeasures [11–14], astronaut selection criteria [15], advanced materials for passive shielding [16,17], and active shielding [18–21]. While some of these methods are effective, they are technologically immature in the case of advanced propulsion or require a high degree of individualization in the case of countermeasures and selection criteria. Despite several surges of study since the 1960s, studies on active shielding methods (including electrostatic, plasma, and magnetic) are still insufficient to demonstrate their utility [18–26].

One of the most promising approaches to date has been magnetic shielding using superconductors. Magnetic shielding works by taking advantage of the Lorentz force which acts via a magnetic field to change the direction of charge particle trajectories. The Lorentz force is defined by:

$$\vec{F} = q\vec{V} \times \vec{B} \tag{1}$$

where q is the net charge of the incident particle, $\vec{V}$ is the velocity vector of the incident particle, $\vec{B}$ is the vector of the magnetic field, and $\vec{F}$ is the vector of the resultant force. The cross-product results in particle motion perpendicular to the magnetic field and is typically manifested as a bending of the charged particle trajectory through the magnetic field. High-temperature superconductor (HTS) materials are found most efficient per unit mass for active shielding against space radiation [27]. This is due to several factors including a higher field strength per unit mass than intermediate- or low-temperature superconducting magnets, fixed magnets, electrostatic fields, or plasma fields. HTSs operating in the 70+ K region are also preferred due to the decreased need for complex cryogenic cooling systems. Several HTS materials have been studied for active shielding applications, including Yttrium-Barium-Copper-Oxide (YBCO), Bismuth Lead Strontium Calcium Copper Oxide (BSCC), and Magnesium Diboride (MgB2) [28–30]. Classical superconducting materials, including Niobium-Titanium (NbTi) and Niobium-Tin (NbSn), have also been analyzed for their applicability for active magnetic shielding [31]. This approach offers several advantages over the other forms of advanced shielding, including utilizing the conditions in space to help maintain the superconductor's critical temperature and potentially lower mass compared to a similarly effective passive shield. However, if magnetic shielding could solve one of the current barriers to interplanetary space exploration, the question remains why the concept has not been fully developed and tested. In this paper, we present a chronological summary of the studies (Figure 1) that have been published to advance magnetic shielding technology over the last five decades and examine trends and developments in the context of technology development and contemporary space policy. We conclude with proposed next steps that would serve to reinvigorate active magnetic shielding as a feasible option for the protection of the next generation of astronauts.

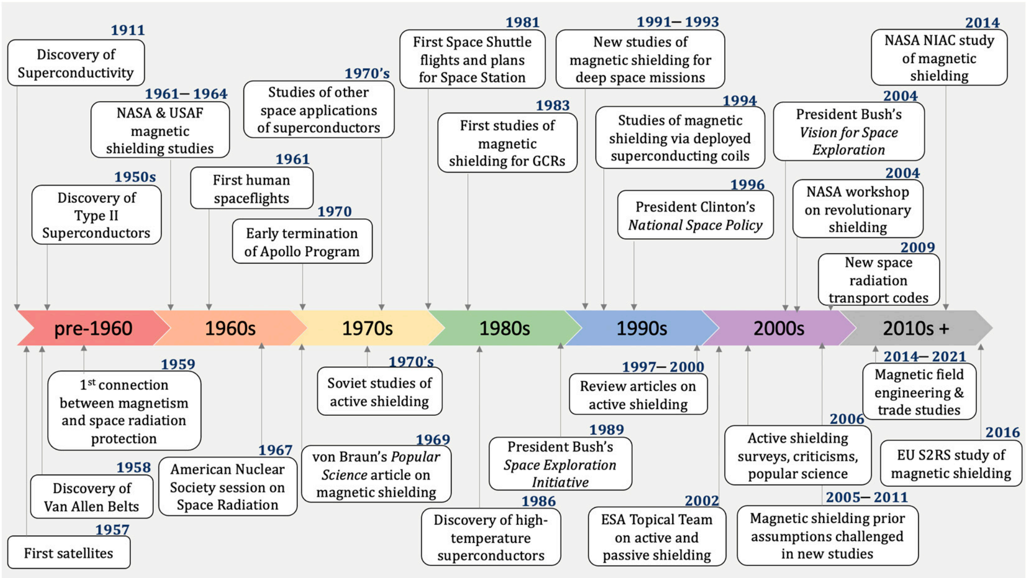

Figure 1. 50+ Years of Magnetic Shielding Studies.

2. 50+ Years of Magnetic Shielding Studies

2.1. The Pre-NASA Era

The discovery of superconductivity was made by Onnes in 1911 [32]. However, a sound and theoretical understanding of the phenomenon was not complete until the discovery in the 1950s of Type II superconducting materials that can retain superconducting properties in high magnetic fields [33,34]. At that point, scientists and engineers began to conceive the idea of applying magnetism and superconductivity for space radiation protection. However, the unique historical context at the time indicated that "such research and development was oriented, of course, toward the advancement of rocket-borne weapons rather than rockets for space exploration and other peaceful purposes" [35], including protection of satellites from natural and man-made radiation sources [36] after the first U.S. satellites discovered the Earth's trapped radiation belts [37].

2.2. The 1960s

In 1962, U.S. President John F. Kennedy's Rice University address and resulting space policy accelerated the objectives of the first three U.S. human spaceflight programs (Mercury, Gemini, and Apollo), aiming for a first human landing on the Moon by the end of the decade, with Mars missions not far behind [35,38]. Recognizing the potential of electromagnetic shielding for space radiation protection of human spacecraft, the U.S. Air Force and NASA sponsored several studies and workshops on magnetic shielding for lunar and interplanetary missions in the 1960s [39–50].

These studies and workshops covered the basis of several sweeping assumptions based on the current knowledge of the environment and technology available at the time. Thus, these studies focused primarily on mass comparisons with passive shielding [51]. Further, the analysis was performed only for moderate-energy solar protons (~200 to 500 MeV) and electrons [52]. The low dose rate GCR ions were omitted from the analysis because the acute risk to astronauts from the solar activity was considered to be the more serious space radiation risk at the time [53]. In addition, secondary particle showers created in passive shielding materials were mostly ignored in these studies, likely due to the limited computing capability to conduct radiation transport simulations. Moreover, because only low-temperature superconductors were known at the time, these designs included complex cryogenics systems to maintain the superconducting coils at liquid helium temperatures. The added complexity and power requirements of the cryogenics systems limited the possible shielding configurations. Finally, these early studies on active shielding in general assumed that engineering solutions would solve any technology gaps.

Towards the end of the decade, however, magnetic shielding had almost become a mainstream concept, with active shielding topics dominating discussions at the "Special Sessions on Protection Against Space Radiation" at the American Nuclear Society meeting in 1967 [54], and Wernher von Braun published a report on magnetic shielding in Popular Science in 1969 [55].

2.3. The 1970s

Magnetic shielding development stagnated in the U.S. throughout the 1970s. During the same time, many investigations were reported on other space applications of superconductors, including spacecraft propulsion by magnetic induction, high field magnets for particle physics analysis, magnetometers, digital electronics, microwave and infrared detectors, gravitational instruments, and high-Q superconducting cavities and oscillators [56].

Concurrently, the promise of a near-term Mars mission dwindled following the early termination of the Apollo program [57] and U.S. President Richard Nixon's announcement to focus on low earth orbit with the development of the Space Shuttle [58]. This redirection of U.S. space priority reduced NASA's interest in developing exploration technologies, and thus, U.S. studies on active shielding ground to a halt. The Soviets, however, began investigating active shielding concepts during this time [59–61].

2.4. The 1980s

U.S. human spaceflight plans were rejuvenated in the early 1980s as the Space Shuttle took flight and plans for Space Station Freedom were initiated under U.S. President Ronald Reagan [62,63]. However, deeper exploration missions were not considered a near-term priority. In addition, the years 1986–1987 were consumed with the investigation of the Space Shuttle Challenger accident, resulting in a halt of all other mission priorities and a focus on near-term safety improvements [64].

Despite these obstacles, NASA began to consider using magnetic shielding to protect against cosmic ray ions as well as electrons and solar protons [65,66], though most of the analyses remained focused on mass savings as compared to passive shielding.

2.5. The 1990s to Early 2000s

The discovery of high-temperature (70 to 100 K) superconducting materials in 1986 [67], newly available advanced computing capabilities, the success of large magnets within particle accelerators [68], U.S. President George H.W. Bush's announcement of the Space Exploration Initiative in 1989 [69,70], and the U.S. Congressional report Exploring the Moon and Mars: Choices for the Nation in 1991 [71] sparked new activities related to magnetic shielding for deep space missions in the early 1990s [72–75].

If configured correctly, the new high-temperature superconductors could reach an equilibrium temperature in their superconducting range in space without the need for complex cryogenic refrigeration. Without the constraints of a massive cryogenic cooling system, the concept of deployed high-temperature superconducting coils was introduced in the mid-1990s. In this concept, thin, flexible films coated with superconducting powder are deployed far from the spacecraft, reducing the current and stored energy required to produce the same level of shielding as a spacecraft-mounted coil [76]. However, the size and complexity of deploying such a system hindered further development of the concept.

In the late 1990s and early 2000s, and under U.S. President Bill Clinton's 1996 National Space Policy [77], NASA focused on the Space Shuttle and International Space Station programs, and there was little motivation to further develop enabling technologies for interplanetary human spaceflight. The concept of magnetic shielding was again tabled, though several review articles were published on the topic [78–81] and the European Space Agency chartered a Topical Team in 2002 to study questions related to passive and active shielding for solar radiation. The ESA team recommended magnetic shielding technology be developed for solar particle event storm shelters by 2025 [82]. However, as Townsend points out in his review, even into the 21st century "very few analyses of the efficacy of active shielding methods for protecting spacecraft crews consider the total spectrum (GCR and SPE) likely to be encountered on a deep space mission. Nearly all analyses have focused solely on SPE protons, thereby ignoring the biologically damaging GCR spectrum" [81].

The loss of Space Shuttle Columbia in 2003 further set back exploration plans, as NASA grounded all flights for over two years to focus on the accident investigation and to implement technical and cultural safety improvements [83].

2.6. The Mid to Late 2000s

In 2004, U.S. President George W. Bush announced the Vision for Space Exploration, officially targeting human missions to the Moon and Mars by the 2020s [84–86]. Subsequently, the question of how to best protect the astronauts against interplanetary space radiation was again brought to light, and a workshop was held at NASA Marshall Space Flight Center in 2004 to assess a list of "Revolutionary Physical Sciences Radiation Protection Strategies" assembled by NASA Headquarters. Active shielding methods dominated the discussion, and results of the meeting were published via survey articles [82,87], criticisms [88], and even popular science [89,90] detailing the four major categories of active shielding: electrostatic, plasma, confined magnetic field and unconfined magnetic field.

NASA's report from the 2004 workshop of the Advanced Radiation Protection Working Group identified the pros and cons of the four different types of active shielding:

- The electrostatic shield concept is to use a strong electric field to deflect incoming solar and cosmic ray particles. The electric field required is on the order of 10^{10} volts. The concept was dismissed as infeasible because radiation due to secondary particles would be a concern.
- The plasma shield concept is to use a magnetic field to trap charged particles, creating a plasma that will induce a strong electric field to deflect incoming solar and cosmic ray particles. These implementations involve a large magnetic field and a large induced electric field. The accelerated development of trapped radiation belts quickly reduces the effectiveness of this type of shield; thus, the concept was also dismissed as infeasible.
- The confined magnetic field concept is to use a strong magnetic field to deflect incoming solar and cosmic ray particles using a magnetic coil configuration that minimizes or eliminates fringe fields. A double-walled torus was suggested to prevent the crew from experiencing high magnetic fringe fields. Previous studies found that the mass required for the implementation was greater than the mass of comparable passive shielding material, thus this concept was also dismissed as infeasible.
- The unconfined magnetic field concept is to use a strong magnetic field to deflect incoming solar and cosmic ray particles using a magnetic coil configuration that permits fringe fields to act on particles at large distances from the magnet. Many possible permutations of an unconfined magnetic field were considered: concepts, where superconducting magnet coils were housed inside the vehicle, were deemed infeasible due to the mass required for cooling and magnetic field exposure to the crew, while concepts, where superconducting magnets were deployed outside the vehicle, were reviewed more favorably. However, the calculations on the amount of stored energy required for a fully deployed superconducting shield were approximately

10^{15} joules. A very large, very weak field, produced via multiple coils, would be required but was possible.

In summary, the first three types of active shielding were deemed infeasible due to mass, power, and safety concerns, while the unconfined magnetic field option was flagged for further study [87].

In the mid to late 2000s, several assumptions and simplifications from previous active shielding models were challenged [88]. The assumptions from the 1960s and 1970s focused only on solar particles, tracking only primary radiation, to allow magnetic fields to penetrate the habitable volume, and broadly assume engineering would solve any lagging technology gaps that severely oversimplified the problem. More detailed studies on effective dose behind shielding [91], magnetic field neutralization inside spacecraft [92], and advanced superconducting materials [29] emerged that tracked these important variables and updated the effective dose estimates for interplanetary missions. Advanced radiation transport codes were developed (HZETRN), or modified (FLUKA) for space radiation applications to enable more complex simulations of active and passive shielding methods [93].

In the National Research Council's 2008 report "Managing Space Radiation Risk in the New Era of Space Exploration," several knowledge gaps relating to magnetic shielding feasibility were identified and recommendations were provided for future studies. These recommendations included accurate modeling of the space radiation environment to include all relevant particle types and energies as well as detailed transport analysis that considers the production and interaction of secondary particles [94].

By the end of the decade, the small satellite revolution was underway, beginning with the 1.3 kg, 10 cm $\times$ 10 cm $\times$ 10 cm CubeSat, and the miniaturization of space hardware was a hot topic. Mini-magnetic shields were proposed for satellites, for propulsion as well as for radiation protection [95].

2.7. The 2010s and Early 2020s

Into the 2010s and early 2020s, Mars remained the ultimate target destination for NASA, despite setbacks including the cancellation of the Constellation program in 2010 [96] following recommendations from the Augustine Commission [97]. Several studies were commissioned to further develop magnetic shielding technology through simulated field configurations, engineering trade studies, and comparisons to advanced passive shielding methods [20,21,98–114], and an updated analysis on the limits of magnetic shielding was also published [115]. The European Union commissioned the Space Radiation Superconducting Shielding (EU FP7 SR2S) project in 2015 to complete Monte Carlo simulations of active magnetic shielding [18].

In 2017, U.S. President Donald Trump's Presidential Memorandum on Reinvigorating America's Human Space Exploration Program, details the priority for NASA, "Beginning with missions beyond low-Earth orbit, the United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations" [116]. In 2022, U.S. President Joe Biden announced an updated national space policy that extended International Space Station operations through 2030, enhanced support for commercial space development, and continued the Moon to Mars initiative via the Artemis program [117].

3. Discussion

The development of magnetic shielding as an enabling technology appears to depend on the prospect of near-term human exploration missions. Figure 2 shows the total NASA budget since inception corrected for inflation to 2018 U.S. dollars and the number of publications on magnetic shielding for each year since 1958. Important milestones are also marked to provide additional context.

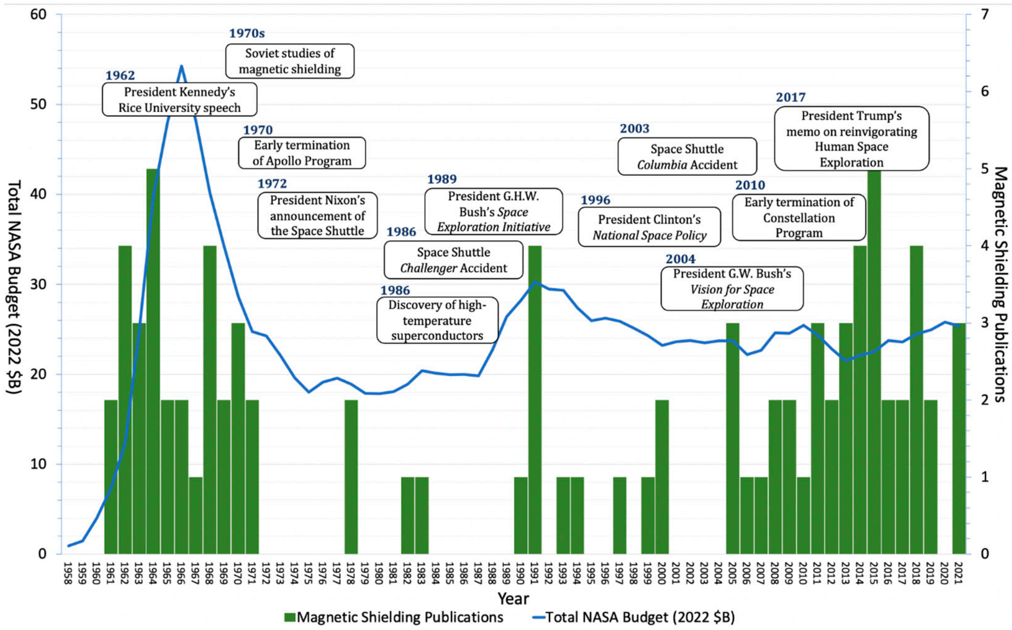

Figure 2. Timeline of magnetic shielding publications with additional contextual information.

Motivating funding agencies to allocate precious space exploration funding for advanced technology development, regardless of the current space policy environment, requires solid justification from science studies that show the feasibility of the technology for further analysis and engineering studies that design, build, and test prototypes. Compared to initial studies conducted in the 1960s, magnetic shielding studies from 2010 to today are dramatically more complex and realistic. Current studies are based on varying fidelity models of the space radiation environment, spacecraft, and shielding configurations. Various radiation transport codes (FLUKA, HZETRN, GEANT4, among others) are employed to simulate the complex interactions of the environment with the space hardware but several limitations exist. Challenges include the inability of many codes to model electromagnetic fields and/or heavy ions, licensing issues, etc., and must be solved to move towards the development and testing of prototypes for active shielding.

Nevertheless, further research is needed on a complete active shielding system in order to answer remaining unknowns and thereby provide a rigorous scientific framework in which to assess the merit of magnetic shielding. In particular, studies must include accurate models of the space radiation environment, realistic models of an interplanetary spacecraft, dosimetry methods that can accurately estimate effective radiation dose for exposure-induced cancer risk to humans, laboratory-based prototyping and testing for model validation, and sensitivity analysis of many mission factors (e.g., mission type and duration, solar activity, shielding type, field strength, and crew characteristics). If such studies show favorable results, it would provide justification for space agencies to increase funding for active magnetic shielding technology development.

4. Conclusions

The human spaceflight community needs to decide whether to invest substantial funding for further development of magnetic shielding methods. Scientific and tangible results and data will be helpful to guide the decision-makers on a sound space policy over the next 10–20 years. Near-term projects must provide detailed simulation data and experimental results to guide future investment and technology development strategies for magnetic shielding. Further, engineering studies should follow to demonstrate the technical feasibility and design the magnetic shielding systems that could enable long-duration interplanetary missions.

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