Forty Years of Development of Active Systems for Radiation Protection of Spacecraft

J. Christopher Sussingham, Seth A. Watkins, and F. Hadley Cocks

Abstract

A comprehensive survey of the literature relating to active spacecraft shielding is presented, including electrostatic and plasma as well as magnetic methods. A literature discussion is provided in order to give an overview of this field. The advent of high temperature superconductors may make magnetic shielding against charged particle radiation practical in spacecraft engineering.

Introduction

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Historical Perspective

The orbiting of Explorer I on January 31, 1958, was a milestone achievement. In addition to being the first satellite launched successfully by the United States, this satellite carried James Van Allen's experimental payload that identified the radiation belt that now bears his name. That same year, shortly after the discovery of this radiation hazard, the need for radiation shielding was recognized [2]. At that early time in the space program, manned missions were several years away and the primary issue was the deleterious effects of radiation on satellite electronics. Van Allen's cosmic ray detector, a Geiger-Mueller tube, had been saturated by the incident radiation, thus demonstrating that space-borne electronics and sensors are susceptible to radiation induced malfunctions [3].

 Concurrently, nuclear weaponry for use in space was also being developed. The Soviet launch of Sputnik I in October, 1957, had spurred great interest in antisatellite measures. At the same time, intercontinental ballistic missile development generated interest in anti-missile measures, especially with the U.S. Atlas D and Soviet SS-6 ICBMs operational in 1959–60. Nicholas Christofilos, an engineer working for the Department of Energy, postulated that the detonation of an atomic bomb above the atmosphere would create an artificial radiation belt, consisting mainly of high energy electrons trapped in the earth's magnetic field, and that this artificial radiation belt could be used to disable Soviet satellite systems. An artificial radiation belt induced by a nuclear detonation could disrupt radio and radar, disable satellites, affect intercontinental ballistic missiles and produce lethal levels of radiation [4–5]. Christofilos' theory was tested and confirmed during Operation Argus, conducted in 1958, when three 1 to 2 kiloton devices were detonated at high altitudes and caused extremely intense radiation, especially over the South Atlantic [6]. These new, but temporary, radiation belts created by the Argus devices were studied by the Explorer 4 satellite [7].

On July 9, 1962, the explosion of a 1.4 megaton nuclear device 250 miles above Johnston Island (Project STARFISH) produced an artificial radiation belt. Primarily comprising fission-decay electrons with energies up to 7 Mev, and with a peak radiation dose rate of approximately 120,000 rads/hr at an altitude of 800 miles, the radiation belt clearly demonstrated the long-term hazard of high altitude nuclear explosions [8]. The detonation resulted in the loss of three orbiting satellites, the Ariel 1 [9], the Transit Research and Altitude Control (TRAAC) spacecraft [10], and the Transit 4B, due to degradation of their solar cells. The loss of U.S. satellites in particular served to highlight the vulnerability of the United States to antisatellite detonations.

At the same time that artificial radiation belts were being studied, several massive solar flares occurred. The solar events of February, 1956 and November, 1960 were among the most potent ever recorded, with the 1956 flare having an integrated fluence on the order of $10^9$ protons per square centimeter, and energy levels approaching 1000 Mev [11]. The space race turned to manned missions when Yuri Gagarin orbited the Earth on April 12, 1961 in Vostok 1. The radiation hazards faced by humans and the spacecraft design challenges of manned space flight subsequently emerged as a priority [12–16]. Early work centered on mass shielding, and it was immediately recognized that the engineering challenge was to shield from solar protons, which are significantly more penetrating than electrons [17].
Various shielding materials were considered, and one early estimate showed that 500 g/cm² of carbon would have been required to reduce the radiation dose of the February, 1956 flare to a few rem [18]. Carbon, evaluated alongside materials such as aluminum, was initially thought to be especially useful, due to its very short penetration range for flare protons and concomitantly optimized shielding weight, increased attenuation of secondary neutrons, and minimized production of bremsstrahlung (deceleration radiation). Carbon-rich layers could also be effective as heat sinks and for ablation [19–20]. By 1963, it was conceded that radiation shielding goals must be "modest;" passive spacecraft shielding could not efficiently or practically provide the same level of protection as is provided by the Earth's magnetic field and atmosphere [21].

More recent detailed computational studies of potential shielding material have evaluated the blood-forming-organ (BFO) dose equivalent for aluminum and for water shields. These calculations conclusively showed that water is more effective as a shield than is aluminum. In particular, using the solar flare of August, 1972, the use of 22 g/cm² of water would reduce the skin dose equivalent from galactic cosmic radiation (solar minimum) and solar flares combined to 29 cSv while 22 g/cm² of aluminum would only reduce the dose to 46 cSv. Considering the solar flare radiation alone, the reduced doses became 5 cSv and 13 cSv for water and for aluminum respectively [22]. Spurred by the task of providing adequate shielding using mass alone, early designers turned to the possibilities of combined passive and active shielding concepts [23–24]. While mass shielding provided a passive approach, novel shielding technologies such as magnetic, electrostatic, and plasma shielding were heralded as new solutions, and a significant body of literature developed.

Active Shielding

Seminal research on energetic particle behavior in the presence of a magnetic field was conducted by Kristian Birkeland and Henri Poincaré [25], and the Scandinavian scientist Carl Störmer developed the basic mathematical models for charged particle behavior near a dipole [26]. Störmer's models are especially useful in magnetospheric studies. By recognizing the possibility of deflecting incident particles with magnetic fields, it was felt that mass savings might be achieved either by using magnetic fields alone or by combining an active magnetic shield with mass shielding [27].

Electric and plasma shielding were initially considered, but eventually abandoned. Electric shielding involves setting up an electric field around a spacecraft, essentially transforming the spacecraft into an electrical condenser [28–34]. Three suggested configurations—a charged sphere, a sphere and a grid, and concentric solid shells—were considered [35]. The Soviet Union actually tested electrostatic shielding on the satellite Kosmos 605, and reported success in demonstrating the concept [36–41]. Plasma shielding involves the combination of electric and magnetic shielding techniques [42–52]. In this concept a positively charged plasma is used to protect against incident protons, with the plasma contained by a magnetic field [53]. However, the high voltages (hundreds of millions of volts) involved with both electrostatic and plasma shielding pose a critical engineering barrier to practical application in manned systems. In addition, because interplanetary space contains about 10 particles per cubic centimeter serving as conductors, electrostatic and plasma shielding appear impractical due to the continuous flux of conducting particles and the concomitant difficulty of maintaining the required electrostatic potentials in the presence of this flux [54].
The concept of magnetic shielding using superconducting coils can be traced to the suggestion of S. F. Singer, and was initially investigated prior to manned spaceflight [55–57]. Active development continued during NASA’s Mercury program [58–63]. Concurrent magnetic shielding research was also conducted in the Soviet Union and, as was the case with U.S. designs [64–65], the extreme mass requirements of shipboard coils (coil mass plus the mass needed to restrain very large, magnetic-field induced forces) were recognized during early Soviet studies [67]. As NASA moved into the Gemini program, active research on magnetic shielding still continued [67–75]. Engineering challenges included the manufacture of superconducting coils capable of producing very high magnetic fields, cryogenic systems for cooling the coils, and coil charging systems [76].

Shortly after the first Apollo mission, Wernher Von Braun publicized the promise of active shielding techniques [77], as advances in superconducting magnet designs were realized [78]. The Air Force commissioned a feasibility study aimed at determining whether radiation-sensitive components orbiting in space could be protected by magnetic fields generated by superconductors [79]. The concept of magnetic shielding was eventually extended to space propulsion systems [80], and a patent was granted in 1970 covering such technology [81]. Models of magnetic shields were built [82], including a vacuum chamber, a conductor, and electron guns [83]. The original studies concerning the behavior of energetic particles in magnetic fields were also incorporated in magnetic shielding research [84], as were new discoveries concerning the space radiation environment [85–86]. Particular spacecraft configurations incorporating magnetic shields were proposed [87]. Additionally, recent advances in the study of the space environment have allowed more accurate modeling involving the effectiveness of magnetic shields [88].

Magnetic shielding was originally intended to make use of low temperature superconductors, principally based on NbTi or Nb3Sn materials [89–92]. This mandated the placement of superconducting coils onboard the spacecraft, due to the liquid helium refrigeration [93–95]. A number of investigators attempted to optimize the mass and geometry for the shields [96–100], and it was soon realized that the masses of the coils needed to shield reasonable volumes, together with the associated support structures, resulted in questionable weight savings over mass shielding alone. The high energies stored in the field-generating coils also present a major hazard. An additional concern with ship-board coils was the effect of high magnetic fields on living organisms [101].

Although NASA had previously studied potential applications of low temperature superconductors in space systems [102], the advent of high temperature superconductors reinvigorated these studies due to an enormously reduced refrigeration requirement [103–105].

Deployed high temperature superconductor coils offer large reductions in the magnetic field energy and mass needed to produce effective shielding and could even allow the possibility of shielding against galactic cosmic radiation. For any given degree of protection, the energy required to raise the shield decreases approximately as the third power of the radius of the coil used to generate the field [106]. Furthermore, the minimum mass of the coil needed is inversely related to the coil radius, because of the need for fewer turns as the enclosed coil area is increased. In addition, since the required persistent currents also decrease dramatically with increasing coil size, so too do the magnetically induced stresses and the associated restraint mass. For example, to provide protection against 3 GeV galactic protons, a
magnetic moment of \(8 \times 10^{10}\) ampere-turns \(\times\) meters squared is required [103]. The energy requirement to produce such a magnetic shield is reduced by a factor of \(2.25 \times 10^8\) as the field-generating coil radius is increased from 10 meters to 10,000 meters [106].

Without the use of radiation shielding, long duration manned missions beyond the Earth’s magnetic influence cannot be carried out safely. For example, a massive solar flare might impart a potentially lethal dose of radiation even with the mass shielding inherent in a spacecraft hull. Indeed, spallation radiation caused by high energy proton interaction with the hull might be more damaging than the original proton radiation itself. The U.S. announcement in the 1980s of planning for a manned interplanetary mission to Mars renewed interest in using magnetic shields for radiation shielding on long term missions outside the magnetosphere [107–110].

**New Challenges for Radiation Shielding**

Large solar proton events that occurred late in 1989 caused significant degradation of the solar cells on numerous satellites in geosynchronous and polar orbits [111], with current outputs decreasing by as much as five percent [112]. In January, 1994, several communication satellites had failures due to high energy electron fluxes [113]. Similar electrostatic discharges also caused malfunctions on a Defense Meteorological Satellite Program spacecraft in 1995 [114]. In addition, the hazards of solar radiation are not limited to space borne systems. Increasing reliance on electronics in aircraft has led to a new danger: single-event upsets in avionics static random-access memories (SRAM’s) and fiber-optic systems caused by cosmic rays [115]. It has been reported that approximately one single-event upset occurs in avionics systems during each flight [116]. Recent experiences with satellites and aircraft may offer a new opportunity for active radiation shielding technologies. Although radiation-hardened semiconductors are now frequently employed, limitations on the tolerance of such devices present long-term challenges for reliability of electronic systems.

Any long duration manned mission outside the protection of the Earth’s magnetosphere will require some form of radiation protection. A manned mission to Mars, in particular, will require some form of protection against charged particle radiation for the crew. This protection could potentially be provided by a storm-cellar in the middle of the main fuel tank. Since a Mars mission will require many months in orbit, the reduction in bone density and muscle strength that appears inevitably to accompany weightlessness has lead to some designs for Mars mission ships that include provision for artificial gravity provided by the rotation of the crew habitat areas around the ship axis. Coriolis effects and associated physiologic responses require that the rotation rate of the habitats be no more than 4 revolutions per minute and that these habitats be located approximately 66 meters from the rotation axis to produce a one-gravity field [117]. Furthermore, with such a geometry, the fuel tanks would inevitably be located near the rotation axis, and a storm cellar within the fuel tank would present certain difficulties. Such a large, rotating geometry is especially well adapted to large-coil magnetic shielding.

As permanent space settlements are considered [118–123], active shielding deserves attention as a viable means of radiation protection [124]. Additional shielding challenges will include micrometeoroid protection, as well as protection against the dangers of the high energy, heavy ion component of galactic radiation [125–126].
Conclusions

Over the more than forty years since it was first suggested, a substantial body of literature has developed concerning active shielding of satellites and manned spacecraft. A comprehensive review of this literature has been presented.

References


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