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

J. Christopher Sussingham,[1] Seth A. Watkins,[2] and F. Hadley Cocks[2]

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Introduction

Solar flares are unpredictable events which cause high levels of charged particle radiation that can affect both manned and unmanned space missions. The Earth's magnetosphere allows a percentage of this radiation to reach the northern and southern magnetic polar regions. The aurora borealis and aurora australis are produced as energetic solar particle radiation collides with the upper atmosphere, and the resulting aesthetic display is a visual reminder that charged particle radiation is a hazard for satellites and manned spacecraft. In preparation for the Apollo lunar missions, the possibility of using active magnetic shielding to provide protection against the energetic solar particle radiation produced by solar flares was extensively evaluated but was never attempted. No active shielding was used on any of the Apollo missions because they were not conducted during periods of high energetic solar particle radiation activity [1]. The periodic loss of satellite systems as a result of energetic solar particle radiation, and as a result of upper atmosphere nuclear detonations, however, has led to a long series of papers related to potential shielding modalities, including active shielding. This present paper presents a comprehensive listing of more than 40 years of literature focusing on active radiation protection for spacecraft, especially protection from energetic solar particle radiation. To provide a background for the discussion of this literature, a brief historical perspective is useful.

[1]United States Air Force, Ogden Air Logistic Center, Hill AFB, Utah 84056.
[2]Duke University, Department of Mechanical Engineering and Materials Science, Durham, North Carolina, 27708-0300.

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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 1 in October, 1957, had spurred great interest in anti-satellite 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 anti-satellite 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/cm^2 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/cm^2 of water would reduce the skin dose equivalent from galactic cosmic radiation (solar minimum) and solar flares combined to 29 cSv while 22 g/cm^2 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 space-flight [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 Nb_3Sn 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 8×10^{10} ampere-turns $\times$ meters squared is required [103]. The energy requirement to produce such a magnetic shield is reduced by a factor of 2.25×10^{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

[1] ENGLISH, R.A., BENSON, R.E., BASLEY, J.V., and BARNES, C.M. "Apollo Experience Report—Protection Against Radiation," NASA, Washington DC, NASA TND-7080, p.2, 1973.

[2] SINGER, S.F. "Some Consequences of a Theory of the Radiation Belt," *9th Annual Congress of the IAF*, Amsterdam, August 26, 1958.

[3] YOSHIDA, S., LUDWIG, G.H., and VAN ALLEN, J.A. "Distribution of Trapped Radiation in the Geomagnetic Field," *Journal of Geophysical Research*, Vol. 65, 1960, pp. 807–813.

[4] STARES, PAUL B. *The Militarization of Space. U.S. Policy, 1945–1984*, Cornell University Press, 1985, pp. 107–109.

[5] KILLIAN, JAMES R., Jr. *Sputnik, Scientists and Eisenhower: A Memoir of the First Special Assistant to the President for Science and Technology*, MIT Press, 1977, pp. 186–191.

[6] CHRISTOFILOS, N.C. "The Argus Experiment," *Journal of Geophysical Research*, Vol. 64, August 1959, pp. 869–75.

[7] VAN ALLEN, J.A., MCILWAIN, C.E., and LUDWIG, G.H. "Satellite Observations of Electrons Artificially Injected into the Geomagnetic Field," *Journal of Geophysical Research*, Vol. 64, August 1959, pp. 877–91.

[8] HAWKINS, S.R. "A Six-Foot Laboratory Superconducting Magnet System for Magnetic Orbital Satellite Shielding," in K.D. Timmerhaus, Ed., *International Advances in Cryogenic Engineering, Proceedings of the Cryogenic Engineering Conference*, Plenum Press, New University of Pennsylvania, Volume 10, Sections M-U, Philadelphia, PA, August 18–21, 1964, New York, 1965, pp. 124–129.

[9] BAUMANN, R.C. "The Ariel I Satellite," *Proceedings of the Royal Society, Series A*, Vol. 281, October 1964, pp. 439–445.

[10] PIERPER, G.F., WILLIAMS, D.J., and FRANK, L.A. "Traac Observations of the Artificial Radiation Belt from the July 9, 1962, Nuclear Detonation," *Journal of Geophysical Research*, Vol. 68, February 1963, pp. 635–640.

[11] TOWNSEND, LAWRENCE W., WILSON, JOHN W., and NEALY, JOHN E. "Space Radiation Shielding Strategies and Requirements for Deep Space Missions," SAE Paper 891433, 1989, pp. 326–328.

[12] WADDINGTON, C.J. "The Hazard of Corpuscular Solar Radiation to Manned Spaceflight," Journal of the British Interplanetary Society, Vol. 15, 1961–62, pp. 277–280.

[13] WILSON, R.K. "Shielding Problems for Manned Space Missions," *IEEE Transactions on Nuclear Science*, January 1963, pp. 17–23.

[14] MADEY, RICHARD "Shielding Against Space Radiation," *Nucleonics*, May 1963, pp. 56–60.

[15] HAFFNER, J.W. "Radiation and Shielding in Space," Nuclear Science and Technology, Volume 4, New York, Academic Press, Inc., 1967.

[16] SWART, H. "Some Problems of Protection from Radiation During Space Flights. III [Über Einige Probleme des Strahlenschutzes bei Kosmischen Flügen. III]," *Astronomie und Raumfahrt*, No. 2, 1967, pp. 57–64.

[17] KELLER, J.W. and SHAEFFER, N.M. "Radiation Shielding for Space Vehicles," *Elec. Eng.*, Vol. 79, December 1960, pp. 1049–1053.

[18] ROBEY, DONALD H. "Protecting Against Protons—Charged Particle Hazards to Man in Space," *SAE Journal*, November 1960, pp. 55–57.

[19] ROBEY, D.H. "Radiation Shield Requirements for Two Large Solar Flares," *Astronautica Acta* 6, FASC 4, 1960, pp. 206–224.

[20] GANGULY, N.K. and LENCE, J.T. "Shielding Manned Space Vehicles from Space Radiations," *Journal of the British Interplanetary Society*, Vol. 15, 1961–62, pp. 110–114.

[21] SHEN, S.P. "Nuclear Problems in Radiation Shielding in Space," *Astronautica Acta* LX, 1963, pp. 212–274.

[22] TOWNSEND, L.W., WILSON, J.W., SHINN, J.L., NEALY, J.E., and SIMONSEN, L.C. "Radiation Protection Effectiveness of a Proposed Magnetic Shielding Concept for Manned Mars

Missions," SAE, Intersociety Conference on Environmental Systems, 20th, Williamsburg, VA, July 9–12, 1990, SAE Paper 901343.

[23] NORWOOD, J.M. "The Combination of Active and Passive Shielding," in Atomic Energy Commission, Div. of Tech. Inform., Washington, D.C., *Protection Against Radiation Hazards in Space*, Proceedings of the Symposium at Gatlinburg, Tenn., November 5–7, 1962, pp. 819–828.

[24] FRENCH, FRANCIS W. "Solar Flare Radiation Protection Requirements for Passive and Active Shields," American Institute of Aeronautics and Astronautics, Aerospace Sciences Meeting, 7th, New York, NY, Jan. 20–22, 1969, Paper 69-15, see also *Journal of Spacecraft and Rockets*, Vol. 7, July 1970, pp. 794–800.

[25] STERN, DAVID P. "A Brief History of Magnetospheric Physics Before the Spaceflight Era," *Reviews of Geophysics*, Vol. 27, 1989, pp. 103–114.

[26] STÖRMER, C. *The Polar Aurora*, Oxford, at the Clarendon Press, 1959, pp. 292–334.

[27] KASH, S.W. "Minimum Structural Mass for a Magnetic Radiation Shield," *AIAA Journal*, Vol. 1, June 1963, pp. 1439–1441.

[28] BEEVER, E.R., and RUSLING, D.H. "The Importance of Space Radiation Shielding Weight," in *Second Symposium on Protection Against Radiations in Space*, A. Reetz Jr., Ed., NASA SP-169, NASA 1964, pp. 407–414.

[29] TRUKHANOV, K.A., RYABOVA, T. Y., and MOROZOV, D. K. *Active Shielding of Spacecraft*, translated into English from "Aktivnaya Zashchita Kosmicheskikh Korabley," 1970, by Air Force Systems Command, Wright-Patterson AFB, Ohio, Foreign Technology Div., in AD-742410, March 10, 1972.

[30] VOGLER, FRANK HENRY "Analysis of an Electrostatic Shield for Space Vehicles," *AIAA Journal*, Vol. 2(5), 1964, pp. 872–878.

[31] DOW, N.F., SHEN, S.P., and HEYDA, J.F. "Evaluations of Space Vehicle Shielding," General Electric Space Sciences Laboratory Report R62SD31, April 1962.

[32] TOOPER, ROBERT F. *Electrostatic Shielding Feasibility Study* [Final Report, June 1961–Sept. 1962], Wright-Patterson AFB, Ohio, Directorate of Advanced Sys. Planning, May, 1963.

[33] FRISINA, W. "Optimizing Electrostatic Radiation Shielding for Manned Space Vehicles," *Acta Astronautica*, Vol. 12, December 1985, pp. 995–1003.

[34] VOGLER, FRANK H. "Electrostatic Shielding for Space Vehicles," Institute of Aerospace Sciences, Annual Meeting, 31st, New York, NY, Jan, 21–23, 1963, Paper 63-12, see also *AIAA Journal*, Vol. 2, May 1964, pp. 872–878.

[35] FELTEN, JAMES E. "Feasibility of Electrostatic Systems for Space Vehicle Radiation Shielding," *Journal of the Astronautical Sciences*, Vol. 11, 1964, pp. 16–22.

[36] RYABOVA, T.Y. and TRUKHANOV, K.A. "Possibility of Utilizing Electric Fields in Space for Radiation Protection from Protons and Electrons (Protection from Charged Particles Using High Voltage Electric Fields)," in *Its Proceedings Of the 6th Ann. All-Union Winter School on Space Phys., Part I*, 1969, pp. 277–278.

[37] KOVALEV, E.E., MOLCHANOV, E.D., NAZIROV, R.U., RIABOVA, T.Y., and SHNEIDER, Y.G. "Electrostatic Shielding Against Cosmic Radiation and Its Earth Applications," International Astronautical Congress, 24th, Baku, Azerbaidzhan SSR, Oct. 7–13, 1973.

[38] KOVALEV, E.E., and RIABOVA, T.Y. "Study of Basic Electrostatic Radiation Shield Characteristics on Board the Cosmos 605 Satellite," in *Life Science and Space Research XIV; Proceedings of the Open Meeting of the Working Group on Space Biology*, May 29–June 7, 1975, and Symposium on Gravitational Physiology, Varna, Bulgaria, May 30, 31, 1975, Berlin, East Germany, Akademie-Verlag GmbH, 1976, pp. 251–253.

[39] KOVALEV, E.E., MOLCHANOV, E.D., PEKHTEREV, YU. G., RYABOVA, T. YA., TIKHOMIROV, B.I., and KHOVANSKAYA, A.I. "An Investigation of the Basic Characteristics of Electrostatic Shielding from Cosmic Radiations on the Artificial Earth Satellite Kosmos 605. I. Measurement Procedure and the Complex of Scientific Apparatus," *Cosmic Research*, Vol. 13(5), pp. 687–692 (translated into English from *Kosmicheskie Issledovaniya*, Vol. 13(5), pp. 771–777).

[40] KOVALEV, E.E., MOLCHANOV, E.D., PEKHTEREV, YU. G., RYABOVA, T. Y., and TIKHOMIROV, B.I. "An Investigation of the Basic Characteristics of Electrostatic Shielding from Cosmic Radiations on the Artificial Earth Satellite Cosmos 605. II. Results of Measurements," *Cosmic Research*, Vol. 14, 1976, pp. 113–118 (translated from *Kosmicheskie Issledovaniya*, Vol. 14(1), pp. 126–132).

[41] RYABOVA, T.Y. "Electrostatic Shielding Against Cosmic Radiation (Current Status and Prospects)," Joint Publications Research Service, Arlington, VA, May 1983 (translated from

Space Biol. And Aerospace Med. (Kosmich. Biiol. I Aviakosmich. Med) (Moscow), Vol. 17(2), March–April 1983, pp. 4–7).

[42] LEVY, RICHARD H. and FRENCH, FRANCIS W. "Plasma Radiation Shield—Concept and Applications to Space Vehicles," *Journal of Spacecraft and Rockets*, Vol. 5, May 1968, pp. 570–577.

[43] LEVY, RICHARD H. and JANES, G. SARGENT "Plasma Radiation Shielding," *AIAA Journal*, Vol. 2, October 1964, pp. 1835–1838.

[44] LEVY, R.H. and JANES, G.S. *Plasma Radiation Shielding*, Avco-Everett Research Lab, Everett, MA. NASA-CR-71254, AMP-179, December 1965.

[45] LEVY, R.H. and JANES, G.S. *Plasma Radiation Shielding*, Avco-Everett Research Lab, Everett, MA. RR-192, AD-448095, September 1964.

[46] LEVY, R.H. and JANES, G.S. "Plasma Radiation Shielding for Deep Space Vehicles," *Space/Aeronautics*, Vol. 45, February 1966.

[47] [Plasma Radiation Shielding] Final Report, AVCO-Everett Research Lab., Everett, MA, NASA CR-70802, January 1966.

[48] LEVY, RICHARD H. and FRENCH, FRANCIS W. "The Plasma Radiation Shield: Concept, and Applications to Space Vehicles," Avco-Everett Research Lab., Everett, MA, NASA-Cr-84420, Avco-Everett Res. Rept.-258, April 1967.

[49] LEVY, RICHARD H. and FRENCH, FRANCIS W. "The Plasma Radiation Shield: Concept, and Applications to Space Vehicles," Avco-Everett Research Lab., Everett, MA, NASA-CR-61176, October 9, 1967.

[50] [Study of Plasma Radiation Shielding] Quarterly Progress Report, March 24–June 23, 1967, Avco-Everett Research Lab., Everett, MA, NASA-CR-86614, July 1967.

[51] LEVY, RICHARD H. and FRENCH, FRANCIS W. "The Plasma Radiation Shield: Concept, and Applications to Space Vehicles," in *Protection Against Space Radiation*, Reetz, Arthur, Jr., and Keran O'Brien, Eds. Proceedings Of the Spec. Sessions on Protect. Against Space Radiation at the 13th Ann. Meeting of the Am. Nucl. Soc., San Diego, Calif., June 11–15, 1967. NASA, 1968, pp. 93–187.

[52] LEVY, R.H. and JANES, S. "Plasma Radiation Shielding," NASA, Washington 2d Symp. on Protec. against Radiations in Space, 1965, pp. 211–215.

[53] *Study of Plasma Radiation Shielding*, Final Report, Avco-Everett Research Lab., Everett, MA, NASA-CR-61640, May 1968.

[54] MOLTON, P.M. "The Protection of Astronauts Against Solar Flares," *Spaceflight*, Vol. 13, 1971, pp. 220–224.

[55] LEVY, R.H. "Radiation Shielding of Space Vehicles by Means of Superconducting Coils," Avco Corp., Avco Everett Div., Res. Lab., Res. Rep. 106 (AFBSD TN 61–7), April 1961. (also in *ARS Journal*, Vol. 31, November 1961, pp. 1568–1570.)

[56] DOW, NORRIS F. "Structural Implications of the Ionizing Radiation in Space," *Proceedings of the Manned Space Stations Symposium*, Los Angeles, California, April 20–22, 1960.

[57] EDMONSON, N., VERWERS, C.D., and GIBBONS, F.L. "Shielding of Space Vehicles by Magnetic Fields," in Atomic Energy Commission, Div. of Tech. Inform., Washington, D.C., *Protection Against Radiation Hazards in Space*, Proceedings of the Symposium at Gatlinburg, Tenn., November 5–7, 1962, pp. 808–818.

[58] LEVY, RICHARD H. "Author's Reply to Willinski's Comment on 'Radiation Shielding of Space Vehicles by Means of Superconducting Coils'," *ARS Journal*, Vol. 32, 1962, p. 787.

[59] LEVY, R.H. "The Prospects for Active Shielding," Avco-Everett Research Lab., Everett, MA, AMP-94, November 1962.

[60] TOOPER, R.F. and DAVIES, W.O. "Electromagnetic Shielding of Space Vehicles," IAS Paper No. 62–156, June, 1962.

[61] TOOPER, R.F. "Electromagnetic Shielding Feasibility Study," Armour Research Foundation Summary Technical Report on Contract AF 33(616)-8489, September, 1962.

[62] WILLINSKI, MARTIN I. "Comment on 'Radiation Shielding of Space Vehicles by Means of Superconducting Coils'," *ARS Journal*, Vol. 32, 1962, p. 787.

[63] GOOD, R.C., SHEN, S.P., and DOW, N.F. "Active Shielding Concepts for the Ionizing Radiation in Space" [Final Report, 1 Sep. 1962–31 Aug. 1963], General Electric Co., Philadelphia, PA, Space Sciences Lab. NASA-CR-58950, January 31, 1964.

[64] TRUKHANOV, K.A., RIABOVA, T. IA., and MOROZOV, D. KH. "Active Protection of Space Vehicles (Aktivnaia zashchita kosmicheskikh korablei)," Moscow, *Atomizdat*, 1970.

[65] MOROZOV, D. KH., RIABOVA, T. IA., TRUKHANOV, K.A., SEDIN, G.Z., and TSETLIN, V.V. "Some Aspects of Active Shielding Against the Radiation in Space," in International Congress on the Protection Against Accelerator and Space Radiation, Geneva, Switzerland, April 26–30, 1971, *Proceedings, Volume 1*, Geneva, Organisation Europienne pour la Recherche Nuclaire, 1971, pp. 501–507, discussion, p. 508.

[66] PETROV, A. "The 'Magnetic Walls' of a Cosmic Ship," *Nauchn-Tekhn Obshchestva SSSR (Moscow)*, No. 6, 1964, pp. 60–61; see also Air Force Systems Command, Wright-Patterson AFB, Ohio, Foreign Technology Div., AD 661766, March 31, 1967.

[67] HOAG, E.D. and STEKLY, Z.J.J. *Superconducting Coil Technology*, NASA-CR-64915, AMP-134, July 1964.

[68] KELM, S. and ODELGA, P. "Employment of Superconductors in Spaceflight [Über Die Anwendung Von Supraleitern Für Die Raumfahrt]," Wissenschaftliche Gesellschaft für Luft-und Raumfahrt and Deutsche Gesellschaft für Raketentechnik und Raumfahrtforschung, Jahrestagung, Berlin, West Germany, Sept. 14–18, 1964; see also *Zeitschrift für Flugwissenschaften*, Vol. 14, May 1966, pp. 242–247.

[69] BERNERT, R.E. and STEKLY, Z.J.J. "Magnetic Radiation Shielding Using Superconducting Coils," in NASA, Washington 2d Symp. on Protec. against Radiations in Space, 1965, pp. 199–209.

[70] MCDONALD, P. F. *An Annotated Bibliography on Motion of Charged Particles in Magnetic Fields and Magnetic Shielding Against Space Radiation*, Brown Engineering Co., Inc., Huntsville, AL. Research Labs; NASA-CR-68657, November 1965.

[71] PRESCOTT, A.D., URBAN, E.W., and SHELTON, R.D. "The Application of the Liouville Theorem to Magnetic Shielding Problems," in NASA, Washington 2d Symp. on Protec. against Radiations in Space, 1965, pp. 189–198.

[72] HELGESEN, J. O. and SPAGNOLO, F. A. "The Motion of a Charged Particle in a Magnetic Field Due to a Finite Solenoid with Application to Solar Radiation Protection," American Institute of Aeronautics and Astronautics, Aerospace Sciences Meeting, 4th, Los Angeles, CA, June 27–29, 1966, Paper 66–512.

[73] LEVINE, S.H., BHATTACHARJIE, A., and LEPPER, R. "Forbidden Regions Produced by Parallel Dipoles," *AIAA Journal*, Vol. 4, 1966, pp. 654–658.

[74] LEVINE, S. H. and LEPPER, R. "Analogue Studies of Magnetic Shields," American Institute of Aeronautics and Astronautics, Aerospace Sciences Meeting, 4th, Los Angeles, CA, June 27–29, 1966, Paper 66–513, see also *AIAA Journal*, Vol. 6, April 1968, pp. 695–701.

[75] LEVY, R.H. "Comment on 'Mass and Magnetic Dipole Shielding Against Electrons of the Artificial Radiation Belt,'" *AIAA Journal*, Vol. 3, 1965, pp. 988–989.

[76] KASH, S.W. "Magnetic Space Shields," American Institute of Aeronautics and Astronautics, and Northwestern University, Biennial Gas Dynamics Symposium, 6th, Evanston, IL, Aug. 25–27, 1965, Paper 65–629; see also Advances in Plasma Dynamics, American Institute of Aeronautics and Astronautics; and Northwestern University, Biennial Gas Dynamics Symposium, 6th, Evanston, IL, August 25–27, 1965, Proceedings, T.P. Anderson and R.W. Springer, Eds., Northwestern University Press, 1967, pp. 135–166.

[77] VON BRAUN, W. "Will Mighty Magnets Protect Voyagers to the Planets?," *Popular Science*, January, 1969, pp. 98–100, 198.

[78] URBAN, E. W. "Superconducting Magnets for Active Shielding," in *Radiation Phys. Res. at MSFC: Rse. Achievements Rev.*, v. 3, 1969, NASA, Marshall Space Flight Center, Huntsville, Ala., pp. 13–18.

[79] BALDWIN, A.E. *et al.* "Feasibility of Magnetic Orbital Shielding System," Lockheed Missiles & Space Company, Sunnyvale, California, AD 483301, May 1964.

[80] CAMBEL, A. B. "MHD for Spacecraft," *Science Journal*, January 1970, pp. 69–73.

[81] ENGELBERGER, J. F. "Space Propulsion System," U.S. Patent Number 3,504,868, Filed November 20, 1963, issued April 7, 1970.

[82] LEPPER, R. and LEVINE, S.H. "The Quasi-Hollow Conductor Magnet as a Space Shield Against Electrons (Magnetic Shield Simulator Study of Quasi-hollow Conductor as a Shield for Small Volume Toroidal Vehicle)," in *Protection Against Space Radiation*. Reetz, Arthur, Jr., and Keran O'Brien, Eds. Proceedings of the Spec. Sessions on Protect. against Space Radiation at the 13th Ann. Meeting of the Am. Nucl. Soc., San Diego, CA, 11–15 Jun. 1967. NASA, 1968, pp. 189–214.

[83] GRISHIN, S.D., ZAVADSKII, V.A., OGORODNIKOV, S.N.and ORLOV, R.V. "Experimental Investigation of Magnetic Shields," Soviet Physics - Technical Physics 23(3), March, 1978.

364–366 (translated into English by Dave Parsons from *Zhurnal Tekhnicheskoi Fiziki*, Vol. 48, 1978, pp. 617–621).

[84] LEVINE, S.H. and LEPPER, R. "A Study of Charged Particle Motion in Magnetic Radiation Shielding Fields," Final Technical Report, Northrop Corp., Hawthorne, CA, Northrop Corporate Labs; NASA-CR-98074, NCL-68–28R, 1968.

[85] MODISETTE, J. L., SNYDER, J. W., and JUDAY, R. D. "Space Radiation Environment," in *Protection Against Space Radiation*, Reetz, Arthur, Jr., and Keran O'Brien, Eds. Proceedings of the Spec. Sessions on the Protect. against Space Radiation at the 13th Ann. Meeting of the Am. Nucl. Soc., San Diego, CA, 11–15 Jun. 1967, NASA, 1968, pp. 1–17.

[86] REETZ, A, JR. and O'BRIEN, K., Eds. *Protection Against Space Radiation*, Proceedings of the Spec. Sessions on Protect. against Space Radiation at the 13th Ann. Meeting of the Am. Nucl. Soc., San Diego, CA, June 11–15 1967. NASA-SP-169, 1968.

[87] LEVINE, S.H. and LEPPER, R. "An Active Radiation Shield for Cylindrically Shaped Vehicles," *Journal of Spacecraft and Rockets*, Vol. 8, July 1971, pp. 773–777.

[88] KROGER, H. and LABELLE, P. "Computer Simulation of a Magnetic Shield in a Realistic Space Environment," *ESA Journal*, Vol. 12(4), 1988, pp. 491–497.

[89] KASH, S.W. "Magnetic Space Shields," in Advances in Plasma Dynamics - Proceedings of the Sixth Biennial Gas Dynamics Symposium, Thomas P. Anderson and Rovert W. Springer, Eds., Northwestern University Press, 1967, pp. 135–166.

[90] NORWOOD, J.M. and GIBBONS, F.L. "Studies of Magnetic Shielding and Superconductivity," General Dynamics, Fort Worth, TX, AD-423178, November 4, 1963.

[91] STEKLY, Z.J.J. "Magnetic Energy Storage Using Superconducting Coils," Avco-Everett Research Lab., AMP 102, January 1963.

[92] BERNERT, R.E. and STEKLY, Z.J.J. "Magnetic Radiation Shielding Systems Analysis," HOAG, E.D. and STEKLY, Z.J.J., Superconducting Coil Technology, NASA-CR-64915, AMP-134, July, 1964.

[93] BROWN, G. V. "Magnetic Radiation Shielding," in *High Magnetic Fields*, H. Kolm, B. Lax, F. Bitter and R. Mills, Eds. The MIT Press, Cambridge, 1962, pp. 370–378.

[94] BHATTACHARJIE, A. and MICHAEL, I. "Mass and Magnetic Dipole Shielding Against Electrons of the Artificial Radiation Belt," *AIAA Journal*, Vol. 2, December 1964, pp. 2198–2201.

[95] EGGLESSON, G. A. and MURPHY, G. "Superconducting Coils for Shielding in Space," in American Institute for Aeronautics and Astronautics, and American Astronautical Society, Stepping Stones to Mars Meeting, Baltimore, MD, March 28–30, 1966, pp. 282–287.

[96] KASH, S.W. "Minimum Structural Mass for a Magnetic Radiation Shield," *AIAA Journal*, Vol. 1, June 1963, pp. 1439–1441.

[97] KASH, S.W. and TOOPER, R.F. "Active Shielding for Manned Spacecraft," *Astronautics*, Vol. 7, September 1962, pp. 68–75.

[98] KASH, S.W. and TOOPER, R.F. "Correction on Active Shielding for Manned Spacecraft," Astronautics, January 1963, p. 43.

[99] MANUILOV, V.G. "Optimum Magnetic Radiation Shields," *Soviet Physics—Technical Physics*, Vol. 12(7), January 1968, pp. 892–894 (translated into English from *Zhurnal Tekhnicheskoi Fiziki*, Vol. 37, July 1967, pp. 1230–1232).

[100] TRUKHANOV, K.A. and MOROZOV, D. KH. "Optimization of a Magnetic Radiation Shield," *Soviet Physics - Technical Physics*, Vol. 15(6), December 1970, pp. 949–953 (translated into English from *Zhurnal Tekhnicheskoi Fiziki*, Vol. 40, June 1970, pp. 1229–1235).

[101] KHOLODOV, YU. A. "Space Biology and the Magnetic Field" (translated into English from Kosmicheskaya Biologiya I Magnitnoye Pole, Priroda (Moscow) no. 4, 1966, 114–115, by Air Force Systems Command, Wright-Patterson AFB, Ohio Foreign Technology Div., January 31, 1967).

[102] "The Role of Superconductivity in the Space Program: An Assessment of Present Capabilities and Future Potential," National Bureau of Standards, Boulder, Colorado, 1978.

[103] COCKS, F. H. "A Deployable High Temperature Superconducting Coil (DHTSC)—A Novel Concept for Producing Magnetic Shields Against Both Solar Flare and Galactic Radiation During Manned Interplanetary Missions," *Journal of the British Interplanetary Society*, Vol. 44, March 1991, pp. 99–102.

[104] HILINSKI, E. J. and COCKS, F. H. "Deployed High-Temperature Superconducting Coil Magnetic Shield," *Journal of Spacecraft and Rockets*, Vol. 31, 1994, pp. 342–344.

[105] DORN, R.V., Jr. and DORN, G. A. "Protecting Humans from Ionizing Radiation in Space," *Analog Science Fiction & Fact*, Vol. 111, Mid-December 1991, pp. 34–50.

[106] COCKS, J. C., WATKINS, S. A., COCKS, F. H., and SUSSINGHAM, C. "Applications for Deployed High Temperature Superconducting Coils in Spacecraft Engineering: A Review and Analysis," *Journal of the British Interplanetary Society*, Vol. 50, 1997, pp. 479–484.

[107] TOWNSEND, L.W., NEALY, J.E., WILSON, J.W., and ATWELL, W. "Large Solar Flare Radiation Shielding Requirements for Manned Interplanetary Missions," *Journal of Spacecraft and Rockets*, Vol. 26(2), March-April 1989, pp. 126–128.

[108] SIMONSEN, LISA C., NEALY, JOHN E., TOWNSEND, LAWRENCE W., and WILSON, JOHN W. "Space Radiation Shielding for a Martian Habitat," SAE, Intersociety Conference on Environmental Systems, 20th, Williamsburg, VA, July 9–12, 1990, SAE Paper 901346.

[109] HERRING, J.S. and MERRILL, BRAD J. "Magnetic Shielding for Interplanetary Spacecraft," in Space Congress, 28th, Cocoa Beach, FL, Apr. 23–26, 1991, Proceedings, Cape Canaveral, FL, Canaveral Council of Technical Societies, 1991, pp. 1–30 to 1–38.

[110] SIMONSEN, LISA C. and NEALY, JOHN E. "Radiation Protection for Human Missions to the Moon and Mars," NASA Technical Paper 3079, February 1991.

[111] MARVIN, D.C. and GORNEY, D.J. "Solar Proton Events of 1989—Effects on Spacecraft Solar Arrays," *Journal of Spacecraft and Rockets*, Vol. 28, 1991, pp. 713–719.

[112] GOLDHAMMER, L.J. "Recent Solar Flare Activity and its Effect on In-Orbit Solar Arrays," IEEE Photovoltaic Specialists Conference, 21st, 1990, Vol. 2, pp. 1241–1248.

[113] WRENN, GORON L. "Conclusive Evidence for Internal Dielectric Charging Anomalies on Geosynchronous Communications Spacecraft," *Journal of Spacecraft and Rockets*, Vol. 32, 1995, pp. 514–520.

[114] ANDERSON, P.C. and KOONS, H.C. "Spacecraft Charging Anomaly on a Low-Altitude Satellite in an Aurora," *Journal of Spacecraft and Rockets*, Vol. 33, 1996, pp. 734–738.

[115] NORMAND, EUGENE "Single-Event Effects in Avionics," *IEEE Transactions on Nuclear Science*, Vol. 43, 1996, pp. 461–474.

[116] TABER, A., and NORMAND, E. "Single Event Upset in Avionics," *IEEE Transactions on Nuclear Science*, Vol. 40, 1993, pp. 120–126.

[117] BUTLER, J. M., Jr. "Mars Missions and Bases—A Recent Look," *Proceedings of the Eighteenth Electronics and Aerospace Conference*(EASCON), IEEE, NY, Catalogue Number 85CH 2213-7, 1985, pp. 211–222.

[118] HANNAH, E.C. "Radiation Protection for Space Colonies," *Journal of the British Interplanetary Society*, Vol. 30, August 1977, pp. 310–314.

[119] JOHNSON, RICHARD D. and HOLBROW, CHARLES, Eds. *Space Settlements: A Design Study*, NASA, Washington, SP-413, 1977.

[120] BIRCH, P. "Radiation Shields for Ships and Settlements," *Journal of the British Interplanetary Society*, Vol. 35, November 1982, pp. 515–519.

[121] PALUSZEK, M.A. "Magnetic Radiation Shielding for Permanent Space Habitats," in *The Industrialization of Space*, Proceedings of the Twenty-third Annual Meeting, San Francisco, CA, American Astronautical Society, Univelt, Inc., 1978, pp. 545–574.

[122] MAULDIN, JOHN H. *Prospects for Interstellar Travel*, San Diego, Univelt, Inc., American Astronautical Society, Science and Technology Series, Vol. 80, 1992, pp. 196–202.

[123] HERRING, J. STEPHEN "Magnetic Shielding for Spacecraft," in *NTSE-92: Nuclear Technologies for Space Exploration*, American Nuclear Society, 1992, pp. 738–746.

[124] LANDIS, GEOFFREY A. "Magnetic Radiation Shielding—An Idea Whose Time has Returned?," in *Space Manufacturing 8 - Energy and Materials from Space;* Proceedings of the 10th Princeton/AIAA/SSI Conference, Princeton, NJ, May 15–18, 1991, Washington, D.C., American Institute of Aeronautics and Astronautics, 1991, pp. 383–386.

[125] HANNAH, E.C. "Meteoroid and Cosmic Ray Protection," in *Space Manufacturing Facilities (Space Colonies)*, Proceedings of the Princeton/AIAA/NASA Conference on Space Colonization, J. Grey, Ed., AIAA, March 1977.

[126] TOWNSEND, L.W. "HZE Particle Shielding Using Confined Magnetic Fields," *Journal of Spacecraft and Rockets*, Vol. 20, November–December 1983, pp. 629–630.