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CONCEPTUAL DESIGN OF A CREWED SPACECRAFT WITH ACTIVE HTS MAGNETIC SHIELDING AND MONTE CARLO EVALUATION OF ITS RADIOBIOLOGICAL PERFORMANCE USING GEANT4

Abstract

Crewed deep-space missions face significant exposure to ionizing radiation originating from galactic cosmic rays (GCR) and solar energetic particles (SEP). Measurements performed by the RAD instrument aboard the Mars Science Laboratory reported average dose rates close to 1.8 mSv/day during interplanetary transit to Mars, implying cumulative doses on the order of 0.6–0.7 Sv for a round-trip mission ($\sim$ 900 days), values approaching historically established NASA exposure limits. These radiation levels are associated with an increased stochastic cancer risk and potential degenerative effects, while conventional passive shielding presents limitations due to structural mass penalties and the generation of secondary radiation.

This work proposes the conceptual design of a crewed spacecraft equipped with an active magnetic shielding system based on a toroidal configuration using high-temperature superconductors (HTS). The architecture considers an array of toroidal coils surrounding the habitable module, capable of generating magnetic fields in the 2–5 T range in the external region, establishing an effective deflection radius primarily for SEP protons (10–500 MeV) and the lower-energy fraction of GCR. The design integrates a closed-loop cryogenic subsystem (20–70 K) with redundant cryocoolers, multilayer insulation, a mass-optimized support structure, and a power system based on deployable solar arrays with energy storage and active current control for magnetic field stabilization.

The radiological performance evaluation is conducted through Monte Carlo simulations using GEANT4 to model the transport of protons and light nuclei in the presence of idealized magnetic fields derived from the Biot–Savart formulation. The relativistic dynamics of charged particles are solved via numerical integration using the Boris algorithm to compute particle evolution under the Lorentz force, ensuring numerical stability and energy conservation under strong magnetic fields. Three scenarios are compared: no shielding, mass-equivalent passive shielding, and active magnetic shielding.

Biological response is estimated through calculations of absorbed dose and equivalent dose within a water-equivalent virtual tissue phantom, incorporating linear energy transfer (LET) distributions and simplified estimates of relative biological effectiveness (RBE). Additionally, spectral modification induced

by magnetic deflection and the potential generation of secondary particles are analyzed. The results enable quantification of realistic reductions in accumulated dose, identification of minimum magnetic field thresholds required for significant mitigation, and preliminary evaluation of the feasibility of a hybrid active–passive architecture as an integrated radiation protection strategy for future long-duration human space missions.