Practical Applications of Cosmic Ray Science: Spacecraft, Aircraft, Ground Based Computation and Control Systems, and Human Health and Safety

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Abstract. In this paper we review cosmic ray effects on the performance and reliability of microelectronic systems and human health as well as the development of the engineering and health science tools used to evaluate and mitigate cosmic ray effects in ground-based, atmospheric flight, and space flight environments. Ground based test methods applied to microelectronic components and systems are used in combination with radiation transport and reaction codes to predict the performance of microelectronic systems in their operating environments. Similar radiation transport codes are an important tool for evaluating possible human health effects of cosmic ray. Finally, the limitations on human space operations beyond low-Earth orbit imposed by long term exposure to galactic cosmic rays are discussed.

Keywords: **cosmic rays, microelectronics, aircraft, spacecraft, human health effects**
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INTRODUCTION

Three twentieth century technological developments: 1) high altitude commercial and military aircraft, 2) manned and unmanned spacecraft, and 3) increasingly complex and sensitive solid state micro-electronics systems, have driven an ongoing evolution of basic cosmic ray science into a set of practical analysis tools needed to design, test, and verify the safety and reliability of modern complex technological systems and assess possible cosmic ray effects on human health. The effects of primary cosmic ray particles, as well as the secondary particle showers produced by cosmic ray driven nuclear reactions in target materials can determine project schedule and cost for manned and unmanned spacecraft avionics systems. Similar considerations apply to commercial and military aircraft operating at high latitudes and high altitudes. Even ground based computational and controls systems can be negatively affected by secondary particle showers at the Earth’s surface, especially if the net target area of the sensitive electronic system components is large. Accumulation of both primary cosmic ray and secondary particle shower radiation dose is an important health and safety consideration for commercial and military air crews operating at high altitude/latitude and is also one of the most important factors presently limiting the scope and duration of manned space flight operations beyond low-Earth orbit (LEO) (1).

COSMIC RAY INTERACTIONS WITH MATTER

The natural space radiation environment consists primarily of energetic charged particles, primarily atomic nuclei and electrons that have been accelerated to velocities close to the speed of light by natural processes (2). Energetic charged particles interact with matter via three basic processes: 1) Energy loss (dE/dx) by direct ionization/excitation of material along the charged particle track, 2) high energy inelastic nuclear collisions triggering nuclear reactions and secondary particle showers and, 3) collisions with material nuclei that produce displacement damage.

Direct ionization/excitation effects are often described by linear energy transfer (LET) or "slowing down" are the primary cause of single event effects (SEE) and total ionizing dose (TID) effects in susceptible electronic devices as well as the primary cause of human health effects (3).

High energy inelastic nuclear collisions between cosmic ray nuclei and nuclei in target materials trigger nuclear reactions that initiate secondary particle showers (primarily protons, neutrons, and pions) in the target material. Further collisions of secondary particles with target nuclei lead to expansion and propagation of the secondary particle shower, and causes both further direct ionization of the material and more nuclear reactions. The direct cause of microelectronic and human health effects produced by secondary shower particles is primarily ionization and excitation produced by secondary particle shower tracks (1, 3).

Both primary and secondary cosmic ray particles can produce displacement damage in the crystal structure of optoelectronic materials by elastic collision processes (3).

SOLID STATE ELECTRONIC DEVICES: SINGLE EVENT EFFECTS (SEE) AND TOTAL IONIZING DOSE (TID) EFFECTS

Figure 1 shows a schematic of a transistor SEE upset process caused by: 1) direct cosmic ray ionization (left), and 2) ionization tracks produced by in-device nuclear reaction recoil products (right). Ionization tracks through the depletion region in a reverse biased PN junction leads to transient current and voltage in the external circuit that can change the state of solid state memory bits (3). SEE effects are not observed in unpowered solid state microelectronic devices.

Figure 2 shows a schematic of an n-channel field effect transistor illustrating TID radiation-induced charging of the insulating gate oxide. Figure 2 (a) represents the pre-irradiation condition and Figure 2 (b) the post-irradiation condition. The electrostatic field produced by trapped charge in SiOx layers changes device characteristics. TID damage accumulates over time even if the device is unpowered and is most important for microelectronic devices that rely on SiOx insulating layers (3).

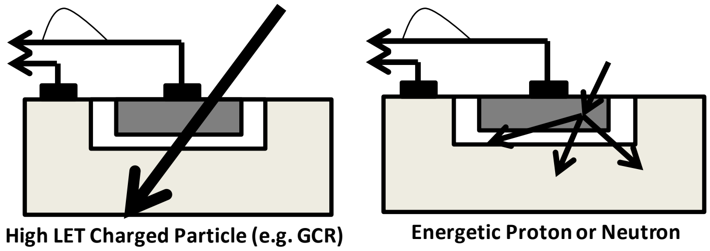

FIGURE 1. Primary and secondary cosmic ray ionization tracks through the depletion region (white) of the PN junction (P light grey; N dark grey) in a solid state device enables transient conduction that can cause a change of state in a solid state memory. The particle tracks can be caused by primary cosmic rays entering form outside or primary/secondary cosmic ray particle nuclear reactions internal to the device.

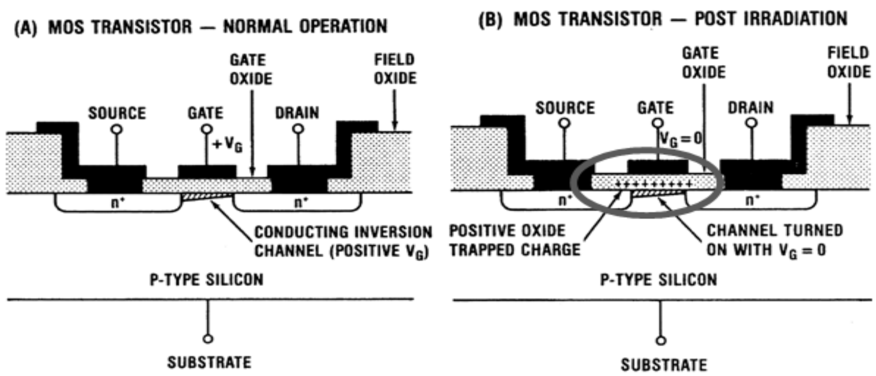

FIGURE 2. TID effects in silicon MOS devices. Accumulation of trapped charge in gate oxide applies an electrostatic field to the gate region changing channel conductance.

Cosmic Ray Effects on Ground Based and Aircraft Microelectronics

Cosmic ray SEE effects in ground based and aircraft electronics systems are caused principally by cosmic ray secondary particle shower neutrons and protons. TID effects on aircraft and ground based electronics are negligible in the natural Earth surface and aircraft operating environments simply because dose rates are typically so low (4).

Memory parity errors observed in the first Cray supercomputer at Los Alamos in 1976 were later determined to be single event upsets (SEUs) caused by atmospheric neutrons (5). Modeling and prediction of cosmic ray effects on computer memories was first reported by 1979 (6). Work continues in this area leading to a JEDEC Standard developed for test and measurement of alpha particle and atmospheric cosmic ray shower induced soft errors in semiconductor devices by 2006 (7).

Understanding and controlling SEE effects in ground based electronics is especially important for safety critical, high-production-volume electronic systems, like automobiles, military electronics, and medical instrumentation where millions of products can be in the field and only one SEE failure is unacceptable.

SEU effects on aircraft avionics systems present a hazard to military and civil aircraft operations, especially in the case of "fly-by-wire" systems, leading to the development of technical standards for management and control of SEE effects in commercial and military aircraft avionics systems (8).

Cosmic Ray Effects on Spacecraft Microelectronic Systems

The reliability and safety of spacecraft electronic systems are often determined, in practice, by the mission space radiation environment. The SEE rate depends on the primary particle flux, the extent of secondary particle production in spacecraft shielding mass, and the SEE/TID response characteristics of the target microelectronic devices (2, 3). TID effects lead to slow degradation of device performance characteristics as dose accumulates during a mission, leading, ultimately, to a wear-out like device and ultimately system failure (2, 3).

Approaches to mitigating SEE/TID effects in spacecraft electronic systems include: 1) selection of electronic parts resistant to SEE/TID, 2) the design of robust, error tolerant, system architectures, and 3) software mitigations such as error detection and correction (EDAC) and/or fault detection isolation and recovery (FDIR) software.

A rigorous component and integrated system test and analysis program is essential to demonstrate the reliability of the spacecraft electronic systems before flight. Accurate definition of worst-case natural cosmic ray (CR) and trapped radiation flight environments is essential as is applicable component and system ground based accelerated test methods. Finally, a detailed understanding of the relationship between ground-based test results and expected on-orbit electronic system failure rates is essential.

Ground based test methods include testing of individual microelectronic devices heavy ion accelerator facilities (9) at heavy ion accelerator facilities as well as testing of integrated avionics system boards and "boxes" at high energy (>200 MeV proton accelerators (10).

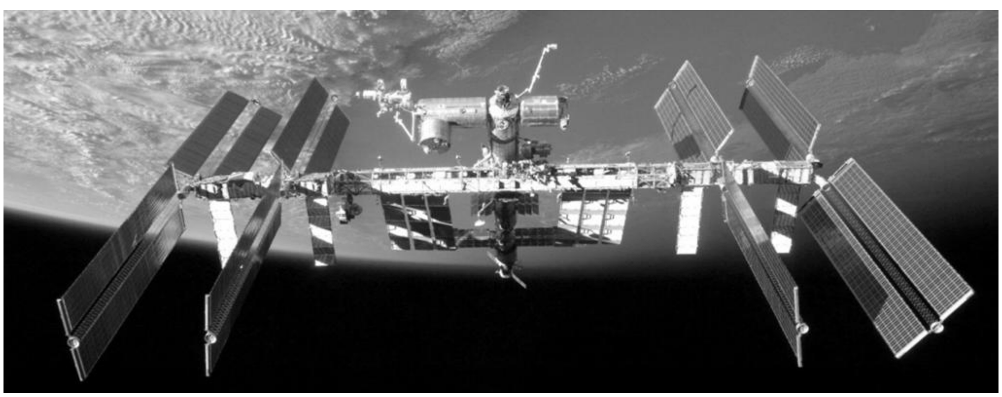

FIGURE 3. The International Space Station (ISS) in low-Earth orbit (altitude range 350 to 450 km; orbital inclination 51.6 degrees).

The International Space Station (ISS) provides an instructive example of an integrated system test and analysis program. The in-flight geographic distribution of ISS SEUs in a particular ISS memory device, as detected by the device EDAC code, is shown in Figure 4 and displays the expected higher density of SEUs at high latitude (more galactic CRs) and in the South Atlantic Anomaly (trapped protons). ISS component SEE rates were predicted successfully before flight using microelectronic component level accelerator test data combined with both the CREME-96 on-line SEE modeling and prediction tool as well as the Petersen Figure of Merit (FOM) method

(11). ISS system level failure rates were then calculated using combinatorial analysis (12). More recently, use of the FLUKA Monte Carlo nuclear reaction and transport code (13) has produced even more accurate estimates of ISS SEE rates, with better accounting for secondary particle showers in ISS shielding mass as shown in Table 1 (14). FLUKA based estimates of SEE rates for 11 different microelectronic devices in 7 different Earth orbiting and interplanetary spacecraft are compared to in-flight data as well as CRÈME-96 and FOM estimates as shown as a regression plot in Figure 6 and in the least squares predictive method performance metric equations (1), below (14).

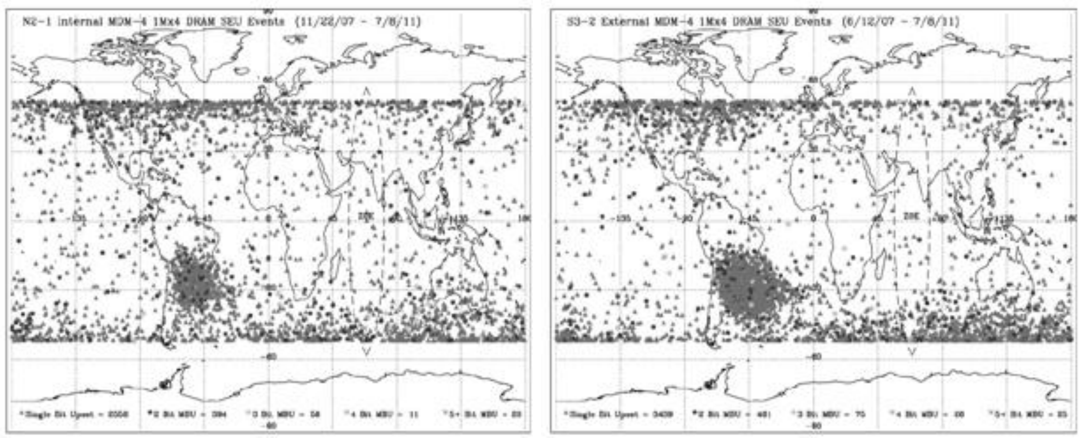

FIGURE 4. ISS complementary metal oxide (CMOS) dynamic random access memory (DRAM) single event upset maps for both internal and external memory locations.

TABLE 1. Shielding Mass Rate Ratio = (Rate 10 g/cm^2)/ (Rate 40 g/cm^2) Note that only FLUKA correctly quantifies the shielding mass (i.e. secondary particle shower) effects for the ISS TI CMOS DRAM.

ISS Texas Instruments (TI) CMOS DRAM Device	**In-Flight Rate Ratio**	**FLUKA Rate Ratio**	**CRÈME-96 Rate Ratio**	**FOM Rate Ratio**
TMS 44400	1.2	1.2	3.5	3.7
SMJ41640	0.9	1.8	3.4	5.3

As shown in equations (1), the FLUKA based rate calculations show the smallest least squares error and overall acceptable performance compared to the industry standard CREME-96 and the Petersen FOM, providing some validation for the FLUKA based methods (14).

The Institute of Electrical and Electronics Engineers (IEEE) sponsors an annual symposium focusing on microelectronics SEE/TID effects, the Nuclear and Space Radiation Effects Conference or NSREC (15). Also, the NASA Electronic Parts and Packaging Program (16) at NASA Goddard Space Flight Center and the Office of Safety and Mission Success at the NASA Jet Propulsion Laboratory (17) are both essential resources for spacecraft microelectronics in general and management of SEE/TID effects in particular.

COSMIC RAY EFFECTS ON HUMAN HEALTH

Earth surface ionizing radiation dose environments are dominated by natural radioisotope decay and man-made radiation source with Radon gas is the most important contributor (18). Annual radiation doses from natural sources at Earth's

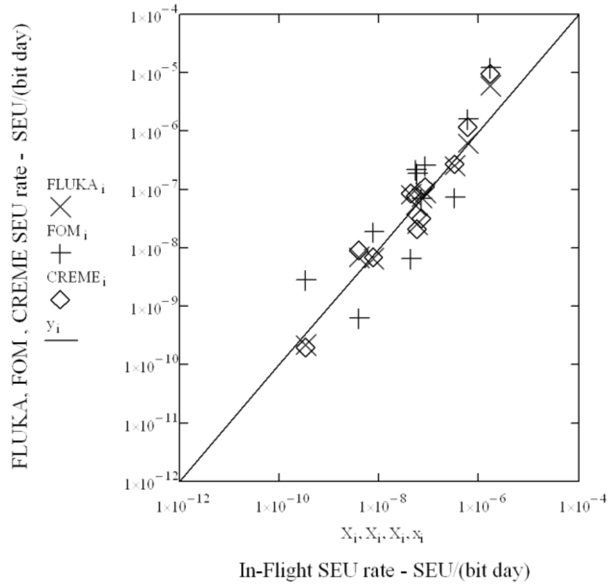

FIGURE 5. A simple regression plot comparing in-flight SEE rates with those calculated using FLUKA based methods, CREME-96 tools, and the Petersen FOM

$$\sum_i \left[\frac{\left(X_i - \mathrm{FLUKA}_i\right)^2}{\left(X_i\right)^2}\right]^{0.5} = 5.7 \qquad \sum_i \left[\frac{\left(X_i - \mathrm{CREME}_i\right)^2}{\left(X_i\right)^2}\right]^{0.5} = 10.6 \qquad \sum_i \left[\frac{\left(X_i - \mathrm{FOM}_i\right)^2}{\left(X_i\right)^2}\right]^{0.5} = 26.8 \tag{1}$$

surface range from less that 0.22 centi-Sieverts (cSv) to nearly 1.0 cSv per year, depending on geographic location, with cosmic ray contributions contributing on the order of 10% of the natural environment total (18). The Earth's atmosphere provides about 1000 g/cm^2 of passive shielding mass at sea level and provides the bulk of the GCR and solar particle event (SPE) shielding. The geomagnetic field contributes to cosmic ray shielding at low to mid latitudes but contributes little at high latitude and even less near the geomagnetic poles (19). SPEs can dramatically increase air crew dose rates at high latitude (20).

Increasing altitude and latitude means moving into a less shielded environment so that commercial and military air crews can receive between 0.5 and 25 equivalent microsieverts per hour depending on altitude, latitude, and the state of the 11 year solar cycle which modulates galactic cosmic rays in the inner solar system (24). SPEs can increase dose rates to air crews flying high latitude/altitude routes dramatically up to values on the order of 30 to 50 micro-Sieverts (μSv) per hour (25). A typical dose rate on ISS is 20 μSv per hour. The increase in annual dose, above natural background, for air crews flying mid-latitude routes is 0.5 cSv per year and increases again to 0.9 cSv per year for air crews flying high latitude routes (23).

The Federal Aviation Agency Office of Aerospace Medical and Human Factors Research, Radiobiology Research Team has developed and validated the CARI-6 cosmic ray nuclear reaction and transport model to estimate air crew and traveler radiation doses (19) and provides an on-line flight radiation dose calculation tool (21).

As altitude increases to include low-Earth orbit environments and beyond, flight crew dose rates continues to increase. Some examples of space flight mission radiation exposures as shown in Table 2.

TABLE 2. Spaceflight Crew Radiation Dose Examples: as calculated using the HZETRN nuclear reaction and transport code combined with in-flight dosimeter data and assuming 20 to 50 g/cm^2 Al shielding and not including secondary particle shower effects internal to the human body which can increase effective dose (relative to measured dose) by about 50%

Mission	Dose
Space Shuttle Mission 41-C (8-days, 460 km, 28.5 degrees)	0.56 E cSv
Apollo 14 (9-day mission to the Moon)	1.14 E cSv
Skylab 4(87days, 473 km, 21 degrees)	17.8 E cSv
Estimated Mars mission (3 years)	120.0 E cSv

NASA space flight crew ionizing radiation exposure limits are derived from a not-to-exceed limit of 3% radiation-exposure-induced death (REID), from cancer, with a 95 % confidence level (Code of Federal Regulations), where the cancer fatality can occur many years after the space flight exposure. However, there is considerable uncertainty in the dose-REID relationship for space radiation exposures because nearly all dose-REID data is based on historical epidemiology and the biophysics of space radiation is very different from that of radiation we are typically exposed to on Earth (1). In addition, the dose-REID relationship varies substantially with age and gender with older men having the lowest cancer susceptibility and young women the highest cancer susceptibility (1). Finally, in-flight crew ionizing radiation dose isn't measured directly but is, rather, calculated using the HZETRN nuclear reaction and transport code (1) with input from calibrated in-flight dosimeters and LET spectrometer measurements. Including the contribution of secondary particle occurring inside the human body is an important aspect of calculating flight crew accurate dose numbers (1, 22).

An important consequence of secondary particle showers in the human body is the realization that much early work on the benefits of low atomic number high hydrogen content materials for spacecraft shielding against galactic cosmic rays has been invalidated (22) as is shown in Figure 6.

The new Crew Exploration Vehicle (CEV or Orion) design objective is 15.0 cSv per year, down from the historical 50.0 cSv per year as driven by uncertainty in the dose-REID relationship in the primary galactic cosmic ray (GCR) dominated space radiation environment. AS shown in Table 2, historical spacecraft designs are unable meet a 15.0 E cSv annual limit even in relatively benign low-Earth orbit environments.

Slow accumulation of whole body dose from GCR presently limits the duration of manned space operations outside Earth's magnetosphere to times on the order of 180 days, assuming historically typical spacecraft shielding mass of 20 to 30 g/cm^2. Uncertainties in the dose-REID relationship and the required 95 % confidence level have driven the baseline spaceflight crew dose limit from 100.0 E cSv to 15.0 E cSv.

GCRs have higher kinetic energy than solar particle event cosmic rays or trapped radiation (1, 22) so that substantially thicker shielding is needed to mitigate space crew GCR dose during long duration missions. As implied by the data shown in Figure 6, the overall programmatic cost of the available passive shielding needed to extend the 180 day limit to 3 years are very likely prohibitive at this time. Even a small cylindrical pressurized living space for a crew of four (D = 4.5 meters, L = 4.5 meters) has a surface area of 8.5 x 10^5 square centimeters, and with a shielding thickness on the order of 400 g/cm^2 to meet the 15 cSv career limit, the resulting shielding mass is 340 metric tons (about 10 x the unshielded spacecraft mass) for the three year flight.

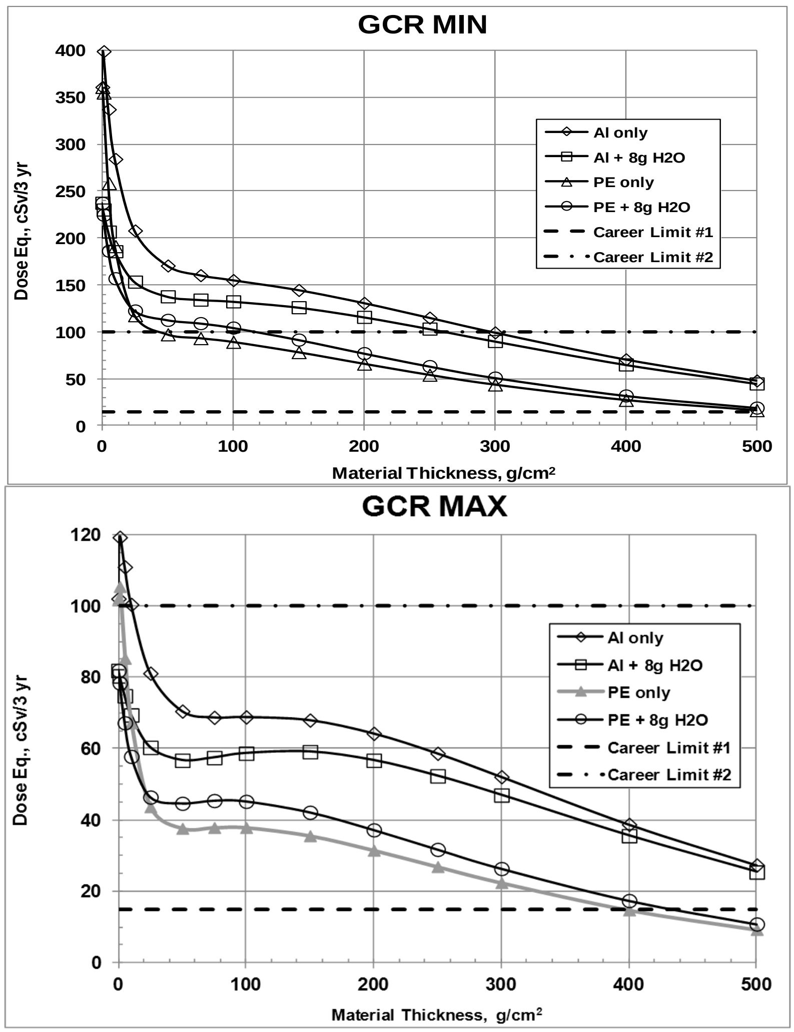

FIGURE 6. Passive radiation shielding mass requirements for a 3 year interplanetary flight (Earth-Mars-Earth) implied by 100 E cSv and 15 E cSv career dose limits with and without inclusion of secondary particle showers in the human body. The in-body secondary particle shower effects are included by placing 8 g/cm^2 of water between the shield and the dose measurement point in the HZETRN calculations. GCR MAX and GCR MIN refer to the interplanetary GCR environment during maximum and minimum of the 11 year solar cycle respectively.

SUMMARY AND CONCLUSIONS

The effects of energetic cosmic ray charged particles on contemporary electronic systems as well as human health and safety depend primarily on the ability of both primary CR and secondary shower charged particles to produce tracks of ionization and excitation in the target material.

Cosmic ray secondary particle shower species, especially neutrons and protons, can dominate effects on electronic systems and human health in high shielding mass environments such as: 1) Earth surface environments, 2) high altitude aircraft environments, and 3) heavily shielded manned spacecraft. In massive targets, like the human body, where secondary particle showers can contribute on the order of 50% of the total body dose expressed in Equivalent or Effective Sieverts (E Sv).

SEE effects on electronic systems can be managed by: 1) selection of resistant parts, 2) EDAC and FDIR functions, and 3) robust/highly redundant system architectures. Shielding mass can mitigate electronic system TID and SEE effects from SPE and trapped radiation but is largely ineffective against GCR.

Slow accumulation of whole body dose (expressed in E Sv) from GCR presently limits the duration of manned space operations outside earth's magnetosphere to times on the order of 180 days. The overall programmatic cost of the available passive shielding needed to extend that limit may be prohibitive at this time.

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