Radiation Effects and Protection for Moon and Mars Missions

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Abstract

Manned and robotic missions to the Earth's moon and Mars are exposed to a continuous flux of Galactic Cosmic Rays (GCR) and occasional, but intense, fluxes of Solar Energetic Particles (SEP). These natural radiations impose hazards to manned exploration, but also present some constraints to the design of robotic missions. The hazards to interplanetary flight crews and their uncertainties have been studied recently by a National Research Council Committee (Space Studies Board 1996). Considering the present uncertainty estimates, thick spacecraft shielding would be needed for manned missions, some of which could be accomplished with onboard equipment and expendables. For manned and robotic missions, the effects of radiation on electronics, sensors, and controls require special consideration in spacecraft design. This paper describes the GCR and SEP particle fluxes, secondary particles behind shielding, uncertainties in radiobiological effects and their impact on manned spacecraft design, as well as the major effects on spacecraft equipment. The principal calculational tools and considerations to mitigate the radiation effects are discussed, and work in progress to reduce uncertainties is included.

Introduction

For space flight beyond the Earth's magnetosphere both men and spacecraft equipment face a significant hazard from the natural ionizing radiation environment (NCRP 1989; Space Studies Board 1996; Wilson 1995; Shielding Strategies for Human Space Exploration: A Workshop 1997; Adams 1992). The primary sources of this environment are energetic protons and heavy ions during Solar Energetic Particle (SEP) events (Shea 1990; Sauer 1990) with energies up to a few 100 MeV, and Galactic Cosmic Rays (GCR) (Badhwar 1996; Wiebel 1994; Nymmik 1992), which consist of protons and

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heavy ions with energies in the GeV range. For some transportation scenarios the Earth's proton belts may also be a factor. These particle environments produce a variety of effects, both for man and for equipment, which significantly impact design for interplanetary missions.

Particle Sources

Galactic Cosmic Rays (GCR) consist of atomic nuclei with about 85% protons, 14% alpha particles, and 1% heavier nuclei (Wiebel 1994). The effects of heavy nuclei far outweigh their number because their energy deposition is proportional to atomic charge squared. Figure 1 (a, b) shows the energy spectra of selected GCR nuclei both for solar maximum and solar minimum (Badhwar 1996). The low energy part (below ~1 GeV) of the GRC is modulated by about a factor of two as the solar wind and magnetic field increases and decreases over the solar cycle. There has been a continuing effort over many years to measure and model GCR fluxes. Current models (Badhwar 1996; Wiebel 1994; Tylka 1997) are believed to have accuracies of about 25 percent.

Solar Energetic Particle (SEP) events consist primarily of protons and alpha particles, with a heavy ion component which varies from event to event (Shea 1990; Sauer 1990). The source region is believed to be near active regions on the Sun's surface, with possible secondary acceleration associated with coronal mass ejections (Kahler 1992). Since SEP events are associated with active regions on the Sun, they are more frequent near solar maximum and a single active region may produce a few SEP events over a period of weeks. Figure 2 (Shea 1993) shows SEP occurrences over the last few solar cycles. While the average particle energy for SEP events is lower than for GCR, the flux is much higher. Figure 3 (Shea 1990; Sauer 1990) compares the spectra of several of the largest events. Individual events last from a few hours to several days with most of the fluence in the first day, which allows "storm shelters" to be considered for flight crews. Figure 4 (Shea 1990; Sauer 1990) shows the time profile of a large SEP. Although SEP events are correlated with solar activity, no current model is available for prediction of individual events. Models (Feynman 1993) are available for assigning a probability that a given mission fluence will be exceeded, and for worst-case assessments (Tylka 1997).

Biological Effects

Radiation safety is a key consideration designing manned planetary missions. In 1989 the National Council on Radiation Protection (NCRP) (NCRP 1989) recommended a career limit on radiation exposure to flight crews of 2 Sieverts (200 rem), for males at age 30, based upon risk considerations for the low-Earth orbit environment (principally electrons below a few MeV and protons below a few hundred Mev). An increase of 3% for death by cancer was the risk criterion. (See Table 1.)

A 1996 study (Space Studies Board 1996) considered flights beyond the shielding effect of the Earth's magnetic field and predicted interplanetary mission doses (Wilson 1995; Shielding Strategies for Human Space Exploration: A Workshop 1997) approaching or exceeding the recommended annual limit of 50 rem (NCRP 1989). That report considered the significant differences between the ambient and induced environments in low-Earth orbit and those dominated by GCR (and occasional SEP's), which contain a significant flux of heavy nuclei and a wide range of secondary constituents produced by high energy interactions in shielding (see Figure 5, Adams 1992). The uncertainties in both the cosmic ray flux and the secondary particles from interactions were discussed. Also stressed was the greater biological risk from highly ionizing heavy nuclei and the larger uncertainties in the present knowledge of this risk. In addition to energy deposition proportional to the square of the atomic number, the heavy nuclei have a higher "relative biological effectiveness" for carcinogenisis. This effect has traditionally been included in predictions using "quality factors" ranging up to ~20, depending on the particle and its energy. Recent research includes calculational approaches that emphasize microscopic details of the energy deposition (Rossi 1997; Wilson 1995).

The 1996 report, (Space Studies Board 1996) entitled "Radiation Hazards to Crews of Interplanetary Missions," concluded that the uncertainty in estimates of carcinogenic risk from the GCR and SEP events range from a factor of 4 to 15. In the worst case of that estimate the excess carcinogenic risk would increase to 45% for a "career dose." The major uncertainty is in knowledge of the biological response to particles of various atomic numbers and energies. There is also a factor of ~2 uncertainty associated with the prediction of all secondary particles and their spectra behind shielding.

Effects on Equipment

The ionizing radiation environments affect electronic devices in variety of ways (Pickel 1980; Bendel 1983; Smith 1987; Summers 1987; Stapor 1990; Petersen 1992; Smith 1994; Petersen 1995; Croley 1995; Tylka 1996; Pickel 1996). For semiconductor microelectronics, the electric charge induced when a heavy ion passes through the part, or when a proton has a nuclear interaction in the part, is often comparable with the charge moving in device circuits. Thus, the device's state can be changed. This can result in various types of transient or permanent single event effects (SEE) such as upset, latchup or burnout of the device. Particle interactions can also displace atoms from the crystalline lattice producing cumulative degradation of the part characteristics. Solar panels use semiconductor solar cells whose power output is significantly impacted by large SEP's. Ionizing particle can induce spurious background noise in sensors and optical detectors. These effects can be mitigated in a number of ways. Parts "hardened" to dose and SEE can be selected; error correction and redundant circuit design can be used. Also, local or "spot" shielding can reduce SEP effects, but is not effective for GCR particles. Solar panels are oversized to compensate for radiation degradation over the mission life.

Generally, radiation doses encountered on interplanetary missions are not so high as to affect the mechanical properties of materials, but optical darkening and surface thermal property changes can occur, and there is some evidence of synergistic effects between radiation, UV, thermal cycling, and vacuum.

While there are uncertainties in the environments (especially SEP events), the biggest hurdle to defining the effects of the environments on equipment is usually the lack of data defining how the device or material degrades or fails when exposed to energetic particles. This is compounded by the fact that exposing one lot of devices manufactured together to radiation in ground tests is no guarantee that the next lot will respond in an identical fashion. Ideally, for critical applications, flight parts and test parts are drawn from the same manufactured lot. Still, ground tests at particle accelerators leave a much be desired in terms of simulating the exposure rates, particle energies, and particle types encountered in space.

Radiation Shielding

Shielding material slows charged particles through interactions with many atomic electrons (ionization energy loss). However, the GCR and SEP event protons and heavy nuclei occasionally interact with the shield atomic nuclei and, depending upon the primary particle and its energy, the result will be a variety of secondary particles, including protons and neutrons, lighter fragments of primary and target heavy nuclei, and gamma rays. At higher primary energies "showers" of mesons may be produced along with subsequent electron and gamma ray showers. These secondary fluxes often exceed the primary flux (see Figure 6, Armstrong 1991). The complexity of accurately predicting these particles folded with the larger uncertainties of biological response to each species and energy, produce most of the uncertainties cited in the recent NRC/SSB report.

Several "transport" calculational methods are available for the prediction of total dose and secondary fluxes behind shielding. NASA's life and materials science programs are in the process of improving and evaluating these methods (Nelson 1997; Parnell 1997). The interactions of the primary particles with the shield depend upon the atomic (electron) structure of the atoms and the structure of their nuclei. The lighter elements are more effective shields per unit weight (Figure 7, Wilson 1995). This has led to studies of composites as interplanetary spacecraft structures and shielding material. For long manned missions the structures and expendables required for the expedition may be configured to supply much, if not all, of the shielding required, although the worst case of the uncertainties (Space Studies Board 1996) would imply significant thicknesses (>20 centimeters of aluminum). The typical vector shielding for the assembled Space Station Hab/Lab is in the range 5 to 10 cm-Al (Colborn 1995).

Radiation Analysis Tools

To analyze the effects of ionizing radiation for a given manned or robotic mission a number of analysis tools are available, and input data flows into the models as shown in Figure 8. CREME96 (Adams 1984; Adams 1986; Tylka 1997), SpaceRadiation (Letaw), or CHIME (Chenette 1994) may be used, for example, to define environmental sources of GCR and large SEP's. The Feynman Flare Model (Feynman 1993) defines a probabilistic estimate of the total SEP proton fluence over a given mission length. The spacecraft shielding geometry can be described using a combinatorial geometry package, CADRays (Colborn 1995), or NOVICE (Jordan). The external fluxes are then transported through the shielding along with induced secondary particles. Particle transport codes commonly used are HETC(Armstrong 1972), HZETRN (Wilson 1994), BRYNTRN (Wilson 1994), Shieldose-2 (Seltzer 1994), or NOVICE. Effects modeling for SEE are available in CREME96, SpaceRadiation, and MACREE (Majewski 1995). For solar cell degradation the JPL code EQFLUX (Tada 1977) is applicable. NASA's Space Environment and Effects (SEE) program is funding some additions and improvements to the available environment models and calculational tools.

Conclusions

Recent work has reduced the uncertainties in cosmic ray environment models and incorporated continuous solar cycle modulation. The SEP models have also been improved (e.g., CREME96). There has recently been an increased effort to identify and reduce the uncertainties in biological response (Nelson 1997), particle flux predictions (Tylka,1997), and to improve particle transport methods (Parnell 1997), after a long period when few resources were dedicated to these problems. The biological uncertainties are the least tractable and may require much additional research for resolution. Because of the rapid introduction of new technology, device responses will probably remain the other area with big uncertainties as new effects and failure modes seem to arrive with each innovation. Early consideration of device effects and radiation shielding required for planetary missions, integral with other engineering design efforts, will reduce their impacts on mission development.

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TABLE 1: Table from NCRP No. 98, 1989

RECOMMENDED IONIZING RADIATION EXPOSURE LIMITS
FOR FLIGHT CREWS[4]
(Sieverts[5])

	BFO[6]	EYE	SKIN
DEPTH	(5 cm)	(0.3 cm)	(0.01 cm)
30 DAYS	0.25	1.0	1.5
ANNUAL	0.50	2.0	3.0
CAREER	1.0-4.0	4.0	6.0

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[4] The career depth dose-equivalent is based upon a maximum 3% lifetime risk of cancer mortality. The total dose-equivalent yielding this risk depends on sex and on age at the start of the exposure. The career dose-equivalent limit is nearly equal to:

2.0+ 0.075 (AGE - 30)Sv, for males, up to 4.0Sv

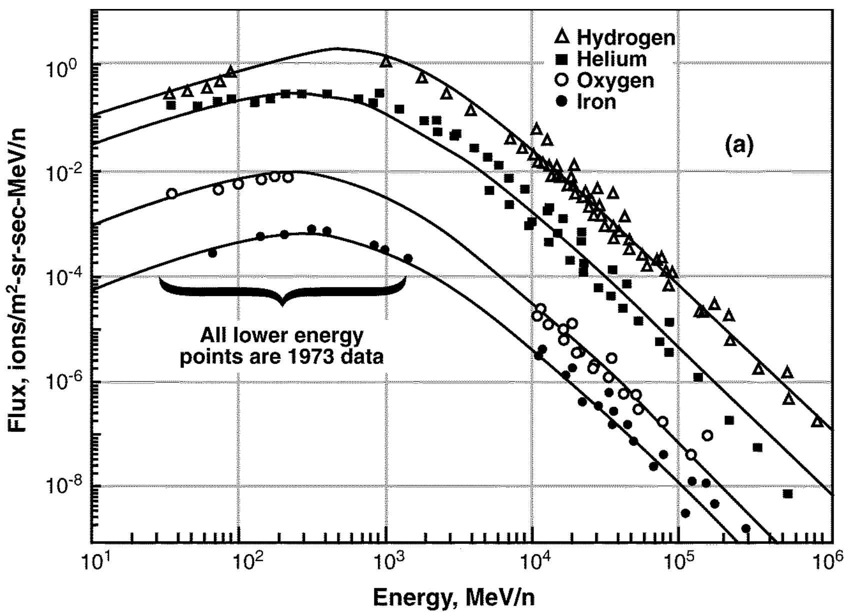
2.0+ 0.075 (AGE - 38)Sv, for females, up to 4.0Sv

Limits for 10 years exposure duration: "No specific limits are recommended for personnel involved in exploratory space missions, for example, to Mars" (NCRP No. 98, 1989, p. 163).

[5] Sievert-Equivalent dose determined by multiplying the absorbed dose at each energy desposition value (Linear Energy Transfer (LET)) by the corresponding quality factor for each ion and energy.

[6] BFO-Blood Forming Organs

Figures



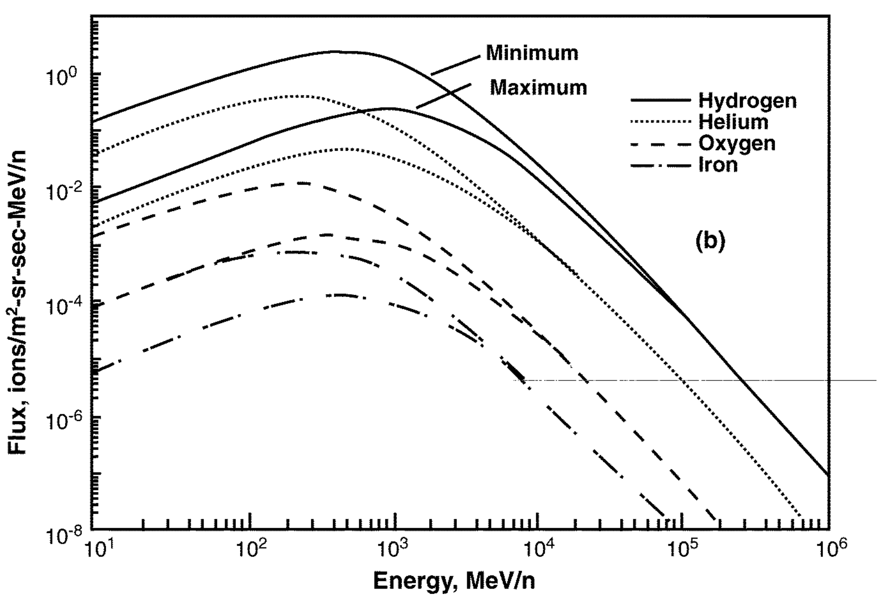


Figure 1. Galactic cosmic ray spectra at solar minimum (a), and for minimum and maximum
(b) (Badhwar 1996)

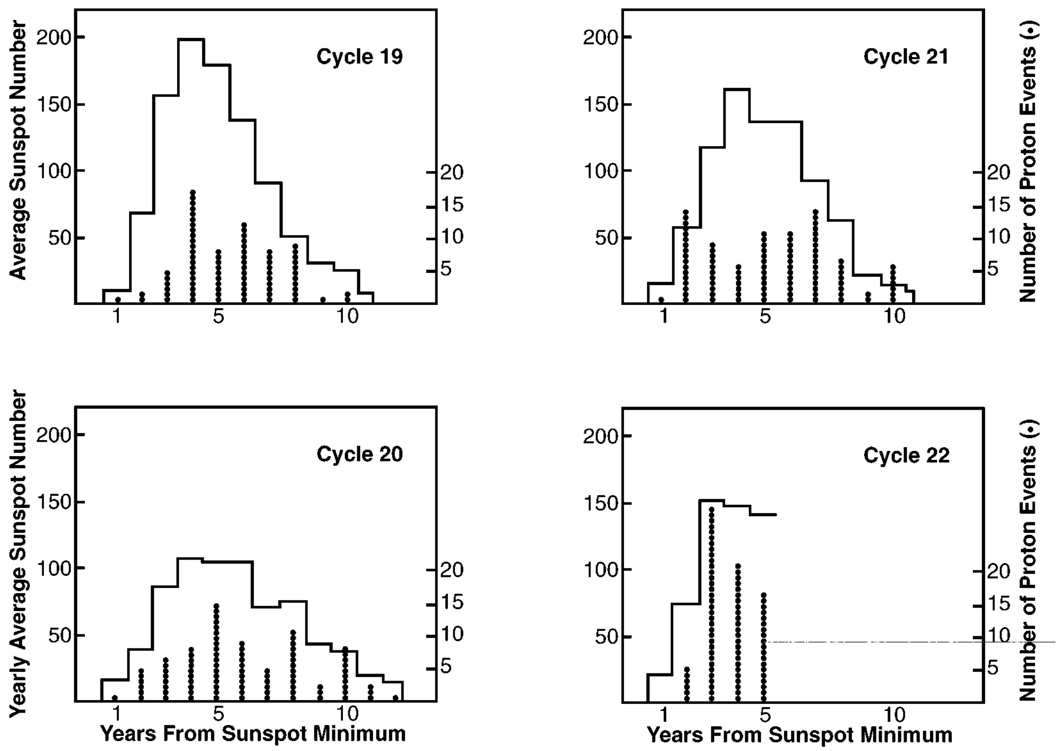


Figure 2. Significant solar particle events and sunspot numbers for solar cycles 19-22 (Shea 1993)

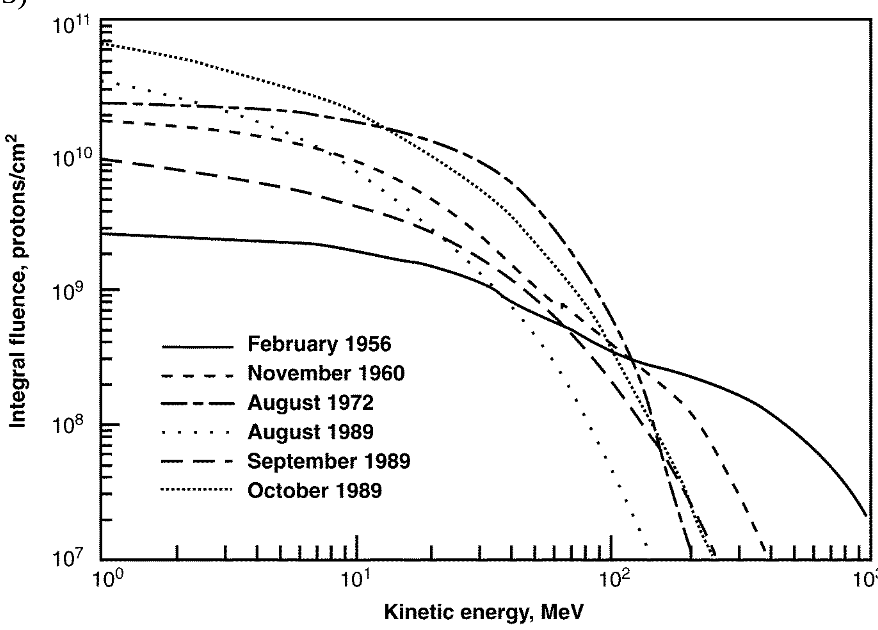


Figure 3. Spectra of larger solar particle events from 1956 to 1990 (Shea 1990; Sauer 1990)

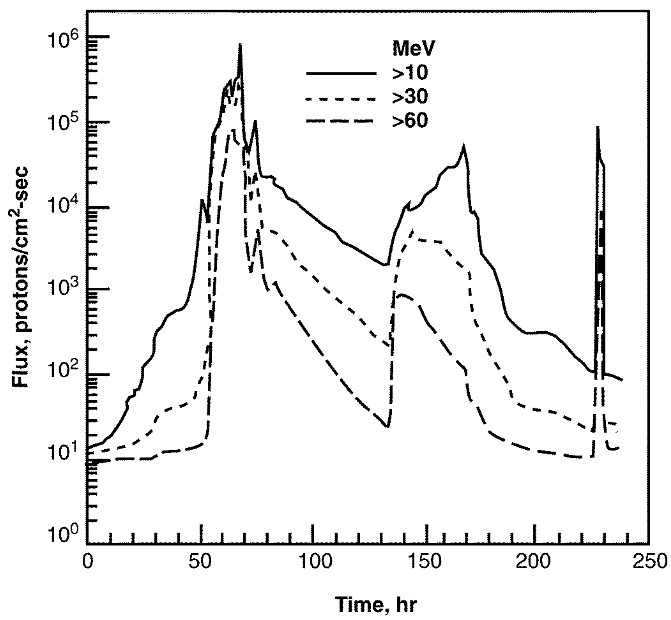


Figure 4. A solar flare time history (August 2-11, 1972) (Shea 1990; Sauer 1990)

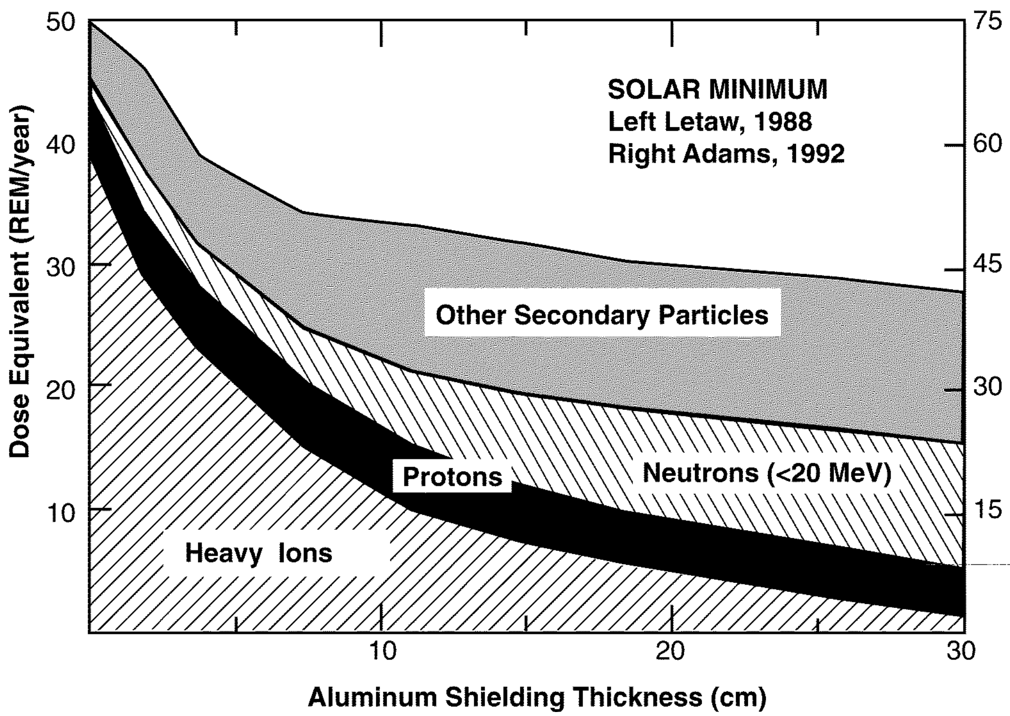


Figure 5. GCR dose equivalent versus shielding adapted from (Adams 1992; Letaw 1988). The left scale are dose values for nominal solar minimum (Letaw 1988) and the right scale are dose values for the 1977 solar minimum fluxes (Adams 1992).

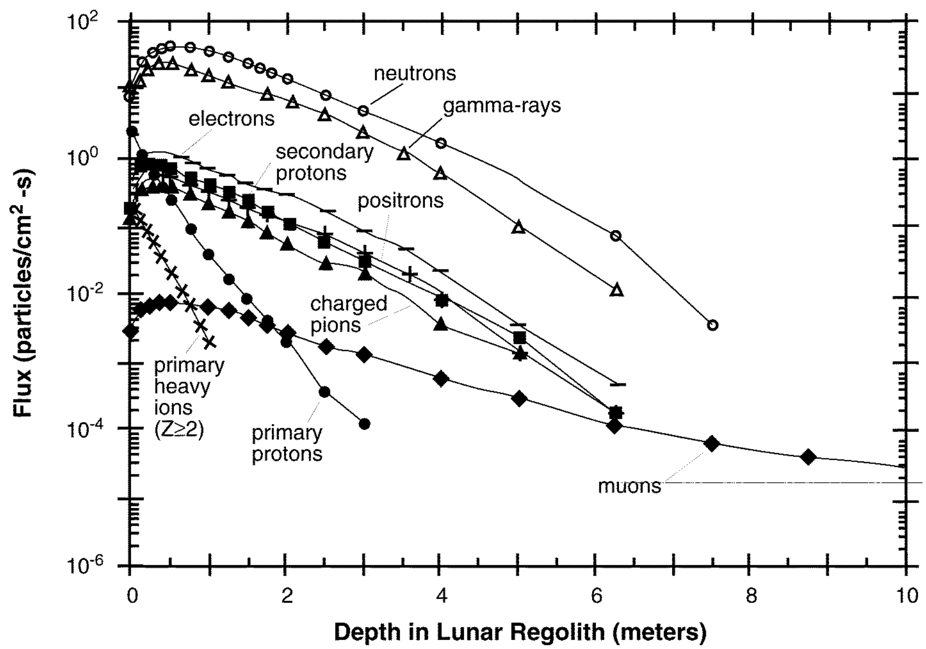


Figure 6. Radiation environment below the lunar surface due to GCR showing fluxes for primary and secondary components (Armstrong 1991)

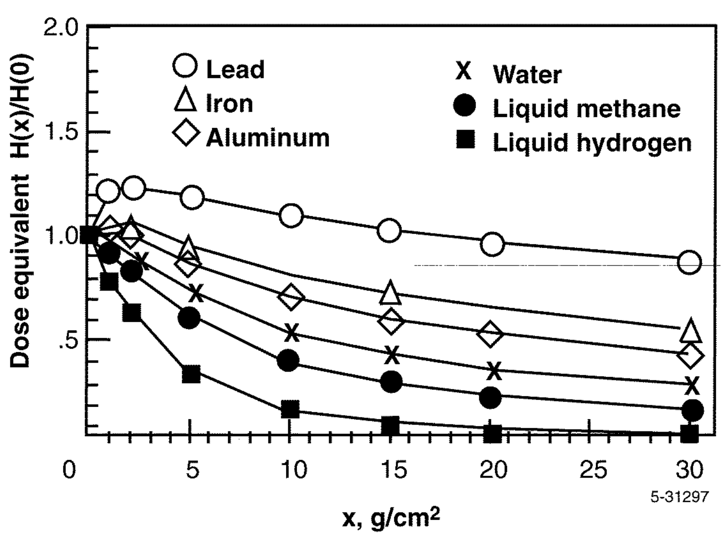


Figure 7. The relative GCR dose equivalent versus shielding thickness for various shielding

materials adapted from (Wilson 1995)

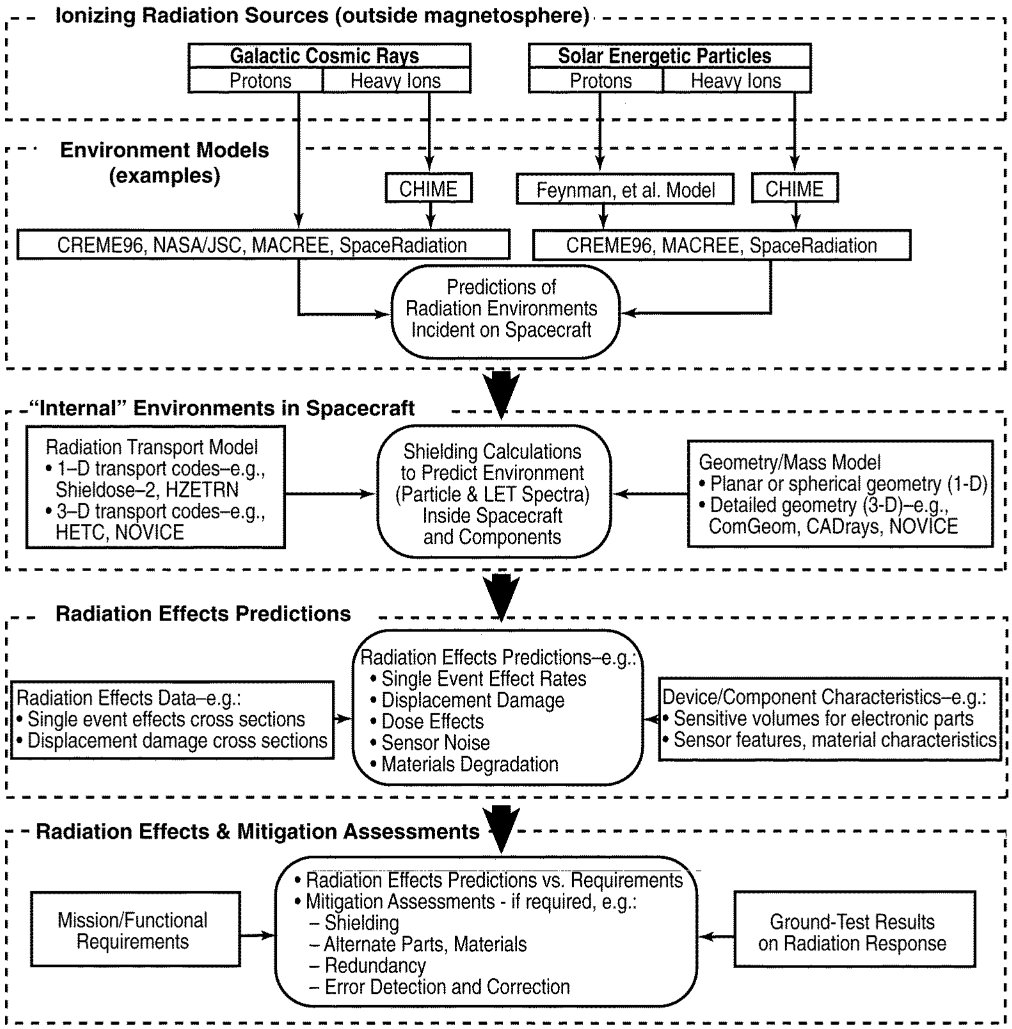


Figure 8. Ionizing Radiation Analysis Flow Chart

Key Words

Radiation
Dose
Flare
Cosmic Ray
Shielding
Space