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RADIATION EFFECTS IN SPACE

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INTRODUCTION

In 1492 Columbus set off from Europe to discover the New World. Ninety men set off into uncharted seas in 3 vessels with only compasses and crude quadrants. Their success vindicated the vision of their Admiral and the support of their young Queen. In 1961, less than 500 years later, Yuri Gagarin journeyed into space. One year later Neil Armstrong and Edwin Aldrin were walking on the Sea of Tranquility on the moon as Michael Collins orbited above in Columbia. Man had pierced the magnetosphere and despite the heart-breaking loss of lives since then, a future for interplanetary missions was ensured.

Space travel within the magnetosphere will soon be routine. Originally, space was the realm of an elite group of experienced pilots. Now, crews consist of men and women who are experts in various fields and even U.S. politicians have traveled into space.

Sitting on a rocket as it hurtles into the sky will never be without risk. However, as more people spend more time in space, and the return to the moon and exploratory missions are considered, the other risks require continuing examination. The effects of microgravity and radiation are two potential risks in space. These risks increase with increasing mission duration. This paper considers the risk of radiation effects in space workers and explorers.

Radiation Environments

In 1958, Van Allen and his colleagues were surprised when their instruments on Explorer I indicated an abrupt decrease in cosmic ray measurements above about 900 km. They deduced, correctly, that their instruments had been

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saturated by an enormous and unexpected flux of charged particles. The particles were protons. The zone of trapped particles stretches from about 1,000 km to 76,000 km above the earth at the equator. As the outer part of this zone consists of electrons and the inner part of protons they are described for convenience as the inner and outer radiation or Van Allen belts. The inner belt dips down to 400 km above the region between South America and Africa to form what is known as the South Atlantic Anomaly.

Galactic cosmic rays and solar particle radiation complete the celestial radiations.

I have chosen two types of space mission to illustrate the range of radiation environments that exist in space (Curtis et al., 1987). First, a so-called low-earth orbit within the magnetosphere and second a Mars mission, beyond the magnetosphere.

In low-earth orbits the radiation environment is determined by the altitude and the orbital inclination. In Table 1 are shown the doses that might be expected in the proposed orbit for the U.S. Space Station. With the proposed orbit and altitude the space station will traverse the South Atlantic Anomaly region of the inner radiation belt. Therefore, the radiation will be protons. The total dose that the crew of the space station may incur depends on the duration of the mission and the shielding. Based on the assumptions shown in Table 1 the total dose equivalent could reach about 100 mSv in a 100-day mission. If the assumption of a radiobiological effectiveness (RBE) of 1.0-1.2 for protons is correct the prediction of radiation effects is relatively simple.

Table 1. Space Station*

	Radiation	Dose to Bone Marrow (mGy/day)+
Orbital Inclination 28.5°	Protons	0.81
Altitude 450 km	Galactic Cosmic Rays	0.045
	Total daily dose equivalent:	0.97 mSv

*Assumptions: Shielding 1g/cm^2 Aluminum, Solar Minimum
+Source: NCRP, 1987.

Estimates of the radiation doses that might be experienced on long duration mission to Mars are shown in Table 2.

Table 2. Mission to Mars*

Radiation	Source	Dose Equivalent Bone Marrow (mSv)+
Protons and Electrons	Radiation Belts	~40
Galactic Cosmic Rays	Journey & Sojourn	~ 1.0 mSv

Solar particle events would add to radiation dose.

*Assumptions 1) 2 g/cm^2 Al shielding, Duration of mission: 3 yr.
+Source: NCRP, 1987.

The worrisome unknown in missions beyond the magnetosphere is the occurrence of large solar particle events (Rust, 1982). These events result in a shower of high energy protons; dose rates can rise rapidly and skin doses reach levels that could cause acute effects (Fig. 1).

Beyond the magnetosphere the heavy ion component of the galactic cosmic rays, while small, becomes important. The RBE values for ^{56}Fe ions compared to low-LET radiations for various endpoints is shown in Table 3 (Grahn, 1973; Todd, 1983).

Table 3. RBE values for plateau beam Iron-56
600 MeV/n 190 keV/μm

Test System	Endpoint	RBE+
DNA	Double strand breaks	<1.0
Human kidney T-1 cells	D_{10}	2.6
Mouse CFU-s	D_{10}	2.2
Mouse Testes	D_0	1.5
Mouse C3H T101/2 cells	Malignant transformation	~3
Lens of the Eye	Opacities	
Rabbit		~5
Mouse		5-20
Mouse: Harderian Gland	Tumors	~30
Mouse: Life Span	Days	<1.0

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The heavy ion track is long with a core of dense ionizations and a wide penumbra of delta rays. As many cells are traversed by one continuous track the radiation-induced damage is different from that caused by other radiations. The question is whether groups of cells in vital centers of the CNS or in the fovea could be irrevocably damaged by the fluences of heavy ions encountered in long missions beyond the magnetosphere. An unequivocal answer is needed.

Recently the National Council on Radiation Protection and Measurements (NCRP) (1987) has made recommendations about radiation protection in space. Cancer is considered the most important risk. NCRP decided that career exposure limits should be set so that the risk did not exceed a 3% lifetime risk of excess mortality for cancer. The safest terrestrial occupations have a lifetime risk of less than 3% and the least safe occupations a lifetime risk greater than 3% (Sinclair, 1987).

NCRP used the risk estimates developed by the NIH ad hoc committee in its preparation of the radioepidemiological tables (NIH, 1985). Age at the start of exposure and sex have been taken into account for the first time in radiation protection standards. The recommendations for career dose equivalent limits for both cancer and other lesions are shown in Tables 4 and 5. It can be seen from Table 5 that NCRP has recommended lower career limits than the National Academy of Sciences did in 1970. It is hoped that these recommended limits will protect the space worker and be sufficiently flexible for planning of missions. The recommended radiation limits are only a guide for exploratory missions, such as to Mars.

Table 4. Recommended Dose Equivalent Career Limit (Sv) Based on 3% Excess Lifetime Cancer Mortality

	Age at First Exposure			
	25	35	45	55
Male	1.5	2.5	3.25	4.0
Female	1.0	1.75	2.5	3.0

Table 5. Recommended Dose Equivalent Career Limits (Sv)

	Bone Marrow	Skin	Lens of the Eye
NAS 1970	4.0	12.0	6.0
NCRP 1987	1.0-4.0*	6.0	4.0

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FIGURE LEGEND

Fig. 1. Estimated skin dose equivalents as a function of time after the solar particle event in 1972. The estimated maximum dose equivalent to the lens of the eye is about 16 Sv. The plot is based on data from J. W. Wilson, in Workshop on the Radiation Environment of the Satellite Power System LBL-8581-UC-41 CONF-7809164, 1978, and A. Hardy, R. Beever, D. S. Nachtwey, personal communication, 1987.