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RADIATION PROTECTION GUIDELINES FOR SPACE MISSIONS

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ABSTRACT

The National Aeronautics and Space Administration's (NASA) current radiation protection guidelines were recommended in 1970. The career limit was set at 400 rem. Today, using the same approach as in 1970, but with the current risk estimates, a considerably lower career limit would obtain. Also, there is considerably more information about the radiation environments that will be experienced in different missions than previously. Since 1970 women have joined their ranks. For these and other reasons it was considered necessary to reexamine the radiation protection guidelines. This task has been undertaken by the National Council on Radiation Protection and Measurements Scientific Committee 75 (NCRP SC 75).

Below the magnetosphere the radiation environment varies with altitude and inclination of the orbit. In outer space missions galactic cosmic rays, with the small but important heavy ion component, determine the radiation environment.

The new recommendations for career dose limits, based on lifetime excess risk of cancer mortality, take into account age at first exposure and sex. The career limits range from 100 rem (1.0 Sv) for a 24 year old female to 400 rem (4.0 Sv) for a 55 year old male compared to the previous single limit of 400 rem (4.0 Sv). The career limit for the lens of the eye has been reduced from 600 rem (6.0 Sv) to 400 rem (4.0 Sv).

Key Words: Radiation Protection, Space, Radiation Environment, Solar Particle Event, Protons, HZE Particles

DISCLAIMER

INTRODUCTION

The role of space in the history of humans is yet to be determined. Nevertheless, there can be little doubt that there will be an increasing human presence in space in the 21st century. No longer is space the realm of a very few highly selected, highly trained male pilots that enjoyed and earned the proud title of astronauts. Space has already been penetrated by the politicians, and space workers are contemplated. In short, consideration of radiation protection in space must now take into account that the space workers of the future will be demographically more like the terrestrial counterpart. The time has come to re-examine the original recommendations (Casarett and Lett, 1983; Sinclair, 1983). The task of reassessment of radiation protection in space has been undertaken by NCRP SC-75.(a)

The subject of radiation protection standards for space workers is timely and appropriate for a symposium that emphasizes looking forward to the future of radiation protection. Herb Parker would have appreciated the challenge and would have had pertinent and incisive advice.

Radiation Environments

The radiation environments fall into four main categories: 1) below the partially distinct regions called trapped radiation or Van Allen belts, 2) within the inner zone, 3) within the outer belt, and 4) outside the

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(a) J. D. Boice, V. P. Bond, S. Curtis, R. J. M. Fry, Chairman, D. Grahn, W. K. Sinclair, J. B. Storer, P. Todd, Ex Officio - D. S. Nachtwey; Advisors: E. V. Benton and B. Worgul; Consultants: E. J. Ainsworth, E. L. Alpen, J. Lett, E. G. Stassinopoulos and C. A. Tobias.

magnetosphere. There are three sources of the radiation, namely, trapped particle radiation in the Van Allen belts, galactic cosmic radiation and solar particle radiation. Protons are the predominant radiation in the inner trapped radiation belt. Whereas, in the outer belt or zone, it is electrons that are most important. The spectrum of electron intensities in the outer belt extend to higher energies and the total intensity is about an order of magnitude greater than in the inner zone. For any of the missions planned in the near future the trapped protons of the inner zone are the most important radiation. The most intense region of the inner zone is the so-called South Atlantic Anomaly between Africa and South America where the spiraling protons reach closer to the earth in their orbits than in other regions. The energy spectra of the protons is remarkable in its breadth.

Galactic cosmic rays consist mainly of protons, with smaller contributions of helium ions, and heavier ions. The presence of ions heavier than helium, especially iron, raises interesting radiobiological questions.

Radiation Dosimetry on Manned Spacecraft

The dosimetry on U.S. and Soviet manned space missions has been reviewed recently (Benton, 1986). To date, the radiation exposures that astronauts and cosmonauts have experienced have been low for a number of reasons. Most missions have been relatively short and those of longer duration have in general, been at low altitudes and favorable orbital inclinations.

In Table 1, the details for three space shuttle flights are given that illustrate the influence of altitude and orbital inclination. The lowest dose rate encountered in these three missions was on STS-2 with a low altitude and 38° inclination. In the case of STS 41B, at a similar height the 28.5° orbital inclination resulted in a greater radiation exposure. The marked effect of altitude is evident from the increase in dose rate experienced by the crew on Flight 51J. Duration is, of course, important and on the case of Skylab 4 a mission of 90 days at 435 km altitude and 50° inclination the average total surface dose was about 7.7 rad (Bailey, 1977).

Table 1

Radiation Dose Rates on Space Shuttle Flights(a)

Spacecraft	Altitude (km)	Inclination (°)	Average Crew Dose Rate mrad/day
Columbia STS 2	254	38	3.6
Challenger STS 41B	297	28.5	6.5
Atlantis 51J	510 max.	28.5	107.8

(a)Data taken from review by Benton, 1986.

Future Space Missions and Radiation Exposures

Over the years a considerable knowledge has accumulated about the radiation environments in space. NCRP SC-75 has used dose estimates developed recently by NASA and Curtis (Curtis et al., 1986) for a number of possible and, hopefully illustrative missions. The dose estimates of the low earth orbit (LEO) missions are shown in Table 2. In Table 3 are shown estimates that are more speculative for what we have considered exploratory missions that will involve small numbers of specially selected crew members.

For a number of reasons the dose estimates for missions in LEO can be made with greater confidence than in GEO. For example, there are marked temporal variations in the intensities of the trapped electrons that are the major factor in the radiation environment in GEO.

It can be seen from Table 2 that the bone marrow dose to the crew of the proposed space station for one tour of 90 days could be about 9 rems. Increased shielding can, of course, reduce the dose. The amount of shielding will depend, in part, on the time that the space crews will have to spend on any one tour.

Table 2

Dose Estimates for Space Missions in Low Earth Orbit

(1.0 gm/cm^2 Al Shielding)

Mission	Radiation Source	Duration (Days)	Dose (Rem)	
			"Bone Marrow"	Skin
LEO Space Station 450 km 28-1/2° orbit	South Atlantic Anomaly Galactic Cosmic Rays	90	9	16
LEO Medium Inclination 450 km 57° orbit	Galactic Cosmic Ray South Atlantic Anomaly	90	7	14
LEO Polar Orbit 450 km 90°	Galactic Cosmic Rays South Atlantic Anomaly	90	7	12

Table 3

Dose Estimates for Space Missions Beyond the Magnetosphere

Mission	Radiation Source	Duration (Days)	Dose (Rem) "Bone Marrow"
Sortie to GEO 35790 km 0°, parking Longitude 160°W 2 gm/cm^2 Al	Van Allen Belts Galactic Cosmic Rays	15	6
Lunar Mission 4 gm/cm^2 Al	Van Allen Belts Galactic Cosmic Rays	90	7
Mars Mission	Galactic Cosmic Rays Van Allen Belts ?SPE and Power Sources	1095	~100

Solar Particle Events

The sun is as restless as an active volcano. With some solar flares there is a large emission of protons and some helium and heavier ions that are known as solar particle events (SPEs) (Rust, 1983). SPEs are classified into two types (King, 1974), ordinary or anomalously large (Al). The solar particle event in August, 1972 was the largest that has been recorded and is used as a benchmark.

Fortunately, the very large SPEs that might threaten missons outside the shielding of the magnetosphere are infrequent. However, planning of such missions must take into account the possibility of Al SPEs. Unfortunately, predictions of SPEs while improving (Stassinopoulos, 1975; Stauber et al., 1983; Heckman et al., 1984) remains uncertain.

The impact of an Al SPE on the radiation environment of various missions is shown in Table 4. It can be seen that the space station, with the proposed 28-1/2° orbital inclination will enjoy the full protection of the radiation belts. On the other hand, an Al SPE during a misson in GEO is of considerable concern.

Table 4

Dose Equivalents (rem) from SPE (Al)

Orbital Inclination	Altitude (km)	Shielding (gm/cm^2 Al)	Blood-Forming Organs	Skin	Lens
285°	450	1.0	-	-	-
57°	450	1.0	4	40	31
90°	450	1.0	29	420	310
Geosynchronous 160°W	35790	2.0	105	1100	900

Biological Effects of Space Radiation

Protons of various energies are the radiation that will be experienced in all missions. Values for Q of 1.14 to 1.3 have been used in the estimates of dose equivalents for the space station depending on the orbital inclination. The average Qs were calculated from the individual differential energy spectra of the particles using the relationship of Q as a function of LET_∞ defined by ICRP (1977).

There are no data for human experience of exposures to this radiation quality that are helpful in the estimation of RBEs for early or late effects. Experimental animal data suggest that the RBE for protons for non tumor effects and for cancer induction compared to ^{60}Co gamma radiation range from 1.0 to about 1.2 (Urano et al., 1984). Earlier studies also suggested that the RBE of protons for a number of effects was about 1 (Clapp et al., 1974).

In the 1960s an ambitious program was initiated to study both acute and late effects of irradiation with protons ranging in energy from 32-3200 MeV on monkeys (Dalrymple et al., 1966). This study was designed to provide information about the effects of radiations that would be encountered in space. Despite the difficulties of carrying out such a study especially with the regular and incontrovertible changes in staff that occurs in the armed forces the study has been continued with care for over two decades (Yochmowitz et al., 1985). The study does provide support for the contention that the effectiveness of protons in the induction of cancer is similar to low-LET radiations (Wood et al., 1986). The continuing surveillance of the surviving animals will provide invaluable data for cataractogenesis and other late effects.

Perhaps the particles in space of most radiobiological interest are the High Z- and Energy-Particles (HZE) that are a small component of the galactic cosmic rays. These particles are of concern in planning the exploratory missions of long duration beyond the magnetosphere. The HZE particles that are of particular concern are those with energies greater than about 100 keV/μm and iron is, perhaps the most important of the ions. The combination of the length of the particle track, the density of the ionizations in the track and the penumbra of delta rays distinguish these particles from other radiations. The concern is whether on long missions the fluence of HZE particles could reach a level that resulted in damage to critical centers in the CNS or the fovea of the retina. We do not know enough about the relationship of traversal of cells by HZE particles and the los or retention of function in the neurones of the CNS to predict the risk with precision.

HZE particles are a small component of the galactic cosmic rays but we do need an accurate value for Q to obtain dose equivalents. The RBEs for acute effects and late effects, such as cancer and cataract induction, are still under study (Ainsworth, 1986). The results of one study on one tissue suggest that RBE for cancer induction is about 30 (Fry et al., 1985).

Risk Estimates and Career Limits

The risk estimates that NCRP SC-75 has used are those derived by the NIH ad hoc committee in the development of the radioepidemiological tables (Rall et al., 1985). In the derivation of probabilities of causation both age and sex are determinants of cancer risk. NCRP SC-75 has taken advantage of this stratification and set separate career limits for males and females as a function of age at first exposure. Thus eight career limits have been derived that range from 100 rem (1.0 Sv) to 400 rem (4.0 Sv) as shown in Table 5.

The career limits have been based on a lifetime excess risk of cancer of 3×10^{-2}. Such a lifetime risk is comparable to the risks in occupations such as construction and agriculture but is greater than terrestrial radiation exposed workers. The risks of space travel are considerable and it will be important to estimate the total lifetime risk for workers on the space station. All things considered a 3% lifetime excess risk of death from cancer seems reasonable, especially as most cancers occur late in life and cause less life shortening than accidental deaths in many other occupations.

Table 5

Career Limit (rem)[(a),(b)]

Lifetime Excess Risk of Fatal Cancer	Age at first exposure	25	35	45	55
	Male	150	250	325	400
3×10^{-2}	Female	100	175	250	300

[a] Divide by 100 for dose equivalents in Sv.

[b] Based on a 10y exposure duration.

A simple relationship of career limits to the age of first exposure has been derived and is shown in Figure 1. The career dose equivalent is approximately $200 + 7.5\,(\text{age} - 38)$ rem for females up to 300 rem and $200 + 7.5\,(\text{age} - 30)$ rem for males up to 400 rem.

Terrestrial radiation protection standards are set in the hope of preventing so-called nonstochastic effects. The career and shorter duration limits were chosen to protect the blood forming tissues. The recommended limits for the lens of the eye and the skin are shown in Table 6. The proposed limits should provide the desired protection and some flexibility for planning missions.

Table 6

Recommended Dose Equivalent Limits (rem)(a)

	Bone Marrow	Eye	Skin
Career	see Table 5	400	600
Annual	50	200	300
30 Days	25	100	150

(a)Divide by 100 for dose equivalents in Sv.

In Table 7 the recommendations made in 1970 are shown for comparison with the proposed limits shown in Tables 5 and 6. It can be seen that the new career limits have been reduced in general whereas the limits for shorter intervals are equal or slightly higher.

In conclusion it must be emphasized that the career and exposure accumulation rate constraints that are being suggested by NCRP SC-75 are not necessarily the final recommendations. The proposed new career limits are currently under review. Furthermore, when the revision of risk estimates, based on the atomic bomb survivors, becomes available it will be necessary to examine whether or not an adjustment in NCRP SC-75's recommendation is required.

Table 7

Exposure Limits and Exposure Accumulation Rate Constraints (NAS, 1970)

		Ancillary Reference Risks		
Constraint	Primary Reference Risk (rem[a] at 5 cm)	Bone Marrow (rem[a] at 5 cm)	Skin (rem[a] at 0.1 mm)	Ocular Lens (rem[a] at 3 mm)
1-year average daily rate		0.2	0.6	0.3
30 day maximum		25	75	37
Quarterly maximum[b]		35	105	52
Yearly maximum		75	225	112
Career limit	400	400	1200	600

(a) Divide by 100 for dose equivalent in Sv.

(b) May be allowed for two consecutive quarters followed by 6 months of restriction from further exposure to maintain yearly limit.

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FIGURE LEGEND

Fig. 1. Career depth-dose-equivalent as a function of the eye at first exposure: o---o Males, Δ --- Δ Females.