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MANNED MARS MISSION RADIATION ENVIRONMENT AND RADIOBIOLOGY

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ABSTRACT

This paper discusses potential radiation hazards to crew members on manned Mars missions. It deals briefly with radiation sources and environments likely to be encountered during various phases of such missions, providing quantitative estimates of these environments.

This paper also provides quantitative data and discussion on the implications of such radiation on the human body. Various sorts of protective measures are suggested. Recent re-evaluation of allowable dose limits by the National Council of Radiation Protection is discussed, and potential implications from such activity are assessed.

DISCUSSION

The crewmembers of a manned mission to Mars (MMM) will be unavoidably exposed to ionizing radiation as they pass through the inner trapped proton belt, the outer trapped electron belt, and through the galactic cosmic ray (GCR) flux of interplanetary space. Moreover, outside of the Earth's magnetosphere, there is the possibility for exposure to proton radiation from solar particle events (SPE). On the surface of Mars, the GCR and SPE fluxes will be less than half that of free space because of the 2-pi shielding by the planetary mass and the shielding provided by the thin Martian atmosphere. Some representative dose equivalents in these regions are shown in Table 1.

It should be emphasized that the listed dose equivalents are approximate. In the future, as planning for MMMs matures, the depth-dose-equivalent projections must be refined. These dose projections are complex functions of the particle fluence, the charge and energy (velocity) of the particles, the interaction of the primary particulate radiation with the spacecraft material, the production of secondary particles, body self-shielding, the ionization density or linear energy transfer (LET) of the particle in tissue, relative biological effectiveness (RBE) of different particles, and other factors. For many of these factors, the uncertainties are large. The factor which is, perhaps, the most uncertain is the RBE upon which is based the quality factor (Q) to be applied for radiological health risk assessment. Recent experimental data indicate that high LET radiation such as in GCR may be 50 or so times as effective as low LET radiation such as the gamma and X-rays to which the Japanese A-bomb survivors were exposed. Moreover, the application of conventional radiological health practices to GCR is likely not warranted. Before a Manned Mars Mission is attempted, the radiological health risks must be refined and uncertainties reduced.

The implications of the approximate dose equivalents listed in Table 1 can still be considered in relationship to general radiological health impacts. In Table 2, note that the doses to achieve a certain biological end point must be given in a short time (hours) to be effective in eliciting the response. If the dose is protracted over several days, 2.5 times the dose is required to elicit the response. If the exposure is protracted over a very long time, the dose-response relationships shown in the table are replaced by entirely different types of dose responses resulting from hematological depression. With this in mind, a comparison of the doses in Table 2 with those in Table 1 indicates that only in the case of an anomalously large SPE (ALSPE) need we be concerned with the potential for an immediate mission impact. Although such ALSPE are rare events, having occurred only once or twice per 11-year solar cycle during the past 3 solar cycles for which measurements are available, their potentially serious effects dictate that they be protected against. Moreover, it has been estimated that the dose rate for the August of '72 event could have been 10 times higher if it had occurred 4 days later when the Sun's rotation would have placed the flare zone in a more damaging location relative to the near-Earth vicinity.

Various possible means for the management of ALSPE risks during travel in free space are as follows: (1) Schedule mission for period around solar minimum--there is about a 6-year period during which SPE's are not expected to occur; (2) Shield spacecraft with nonfunctional mass against the known worst-case event (August 1972) times a safety factor to reflect the facts that (a) the August 1972 event would have been worse if it had originated in the optimum region of the Sun, and (b) it is not known how large an ALSPE can be; (3) Arrange stowage, water tanks, and waste tanks to provide shielding as above using parasitic shield mass only to fill the gaps; (4) Provide a storm cellar--a

TABLE 1

APPROXIMATE BLOOD FORMING ORGAN DOSE EQUIVALENTS AND
RADIATION HEALTH RISK FOR A MANNED MARS MISSION DURING SOLAR MINIMUM

Radiation Source	Skin Dose Eq.	Deep Organ (5 cm) Dose Eq.	Excess Lifetime Cancer Incidence in a 30-Year Old Male*
CHRONIC EXPOSURE TO GCR			
FREE SPACE			
behind 4 g/cm^2 Al	36 rem/yr	27 rem/yr	1~%/yr of exposure
ON MARS			
behind 4/cm^2 habitat shielding and 10 g/cm^2 CO_2 atmosphere	12 rem/yr	10 rem/yr	<0.5%/yr of exposure
ACUTE EXPOSURE TO ALSPE (a' la August '72)			
FREE SPACE			
behind 2 g/cm^2 Al	1106 rem	105 rem	~6%
behind 15 g/cm^2 Al	27 rem	7 rem	<0.5%
ON MARS			
behind 10 g/cm^2 CO_2	83 rem	17 rem	<1%
behind 10 g/cm^2 CO_2 +	~0 rem	~0 rem	Negligible

*The % increased cancer incidence for a 30-year old female is roughly twice that for a 30-year old male.

Note: Low Earth Orbit Phase and Van Allen Belt Passage Phase together contribute <4 rem. The % increase in cancer for a typical Mars Mission is obtained by multiplying the yearly % by the number of years of exposure.

TABLE 2

EARLY EFFECTS OF ACUTE (LESS THAN 1 DAY) RADIATION (IN RAD AT >5 CM)

	1ST DAY				20-60 DAYS
	ANOREXIA	NAUSEA	VOMITING	DIARRHEA	LETHALITY
ED_{10}*	40	50	60	90	220
ED_{50}	100	170	215	240	285
ED_{90}	240	320	380	390	350

EARLY EFFECTS OF RADIATION GIVEN AT LOW RATE (4-6 DAYS)

AS ABOVE X 2.5	ABOVE X2

*EFFECTIVE DOSE FOR 10, 50, OR 90 % OF A POPULATION OF NORMAL PEOPLE.

TABLE 3

RADIATION EXPOSURE LIMITS

CONSTRAINTS IN REM	SKIN (0.1 MM)		EYE (3 MM)		BONE (5 CM)	
	NAS[A]	NCRP[B]	NAS	NCRP	NAS	NCRP
1 YR AVERAGE DAILY RATE	0.5	-	0.3	-	0.2	-
30-DAY MAXIMUM	75	150	37	100	25	25
QUARTERLY MAXIMUM	105	-	52	-	35	-
YEARLY MAXIMUM	225	300	112	200	75	50
CAREER LIMIT	1200	600	600	400	400	100-400[C]

[A]NAS = NATIONAL ACADEMY OF SCIENCES, 1970, CURRENT OFFICIAL LIMITS.

[B]NCRP = NATIONAL COUNCIL ON RADIATION PROTECTION AND MEASUREMENTS, 1986, RECOMMENDED BY SCIENTIFIC COMMITTEE 75. NOT YET OFFICIAL.

[C]VARIABLE DEPENDING ON AGE AT START OF EXPOSURE AND ON SEX. THE CAREER LIMITS CAN BE APPROXIMATED BY 200 + 7.5 (AGE-30) FOR MALES AND 200 + 7.5 (AGE-38) FOR FEMALES.

smaller region of the spacecraft which utilizes shielding from stowage, tankage, and parasitic mass; and (5) Provide a group partial body shield consisting of a cylinder inflatable up to a wall thickness of about 20 cm with stored water. The cylinder in operation would surround the torsos of the crewmen huddled back-to-back to improve shielding of the blood forming organs (BFO) in the spine. [During the August 1972 event, most of the dose (60%) was received in a 6-hour period. Conceivably a 12-hour stay in the "water bed" shield would be tolerable.] This crew shield concept could take different forms with a variety of tradeoffs.

On the surface of Mars, one could shield against an ALSPE by using only 10 cm (4 inches) of Martian soil, which, with a density of 3.5 g/cm^3, would provide excellent shielding and reduce the skin dose from an August 1972 event to below 1 rad. Conceivably an astronaut could cover himself with soil as one does with sand at the beach or an astronaut could insert an inflatable storm cellar into a crater on Mars and cover it with soil by means of explosive charges.

In the case of an ALSPE occuring either in flight or on the Martian surface, adequate warning will be required. The Earth-based optical network currently used to warn STS astronauts of potential SPE will not be able to view the region of the Sun which poses the greatest threat to a Mars-bound spacecraft. A system comparable to NOAA's proposed Solar X-ray Imager (SXI) will be required. Also, active, alarmed dosimeters will be required to alert the crew of the arrival of the first particles.

Adequate protection against ALSPE must be provided to preclude exceeding the official space radiation exposure limits: currently 25 rem to the blood forming organs, 37 rem to the lens of the eye, and 75 rem to the skin (Table 3). The 30-day limits are set to avoid immediate radiological health impacts on a mission involving nausea, vomiting, etc. After protection against immediate impacts, the remaining radiological health issue concerns radiogenic stochastic effects, primarily cancer induction.

Radiocarcinogenesis results from a combination of physical, chemical, and biological events occurring over the years and with low probability. The severity of cancer is independent of the dose received, but the probability that cancer will occur increases with dose.

Moreover, any radiation dose increases the risk. Therefore, limits are set based on an acceptable level of risk, not precluding any risk.

The current astronaut career radiation limits, which were published in 1970, were based primarily upon radio-epidemiological data from Hiroshima-Nagasaki A-bomb survivors. These data indicated that 400 rem doubled the natural cancer risk for males between 35 and 55, a group comparable to astronauts. The risk was deemed acceptable considering the other risks of space flight.

These limits are currently being reevaluated by Scientific Committee 75 of the National Council on Radiation Protection (NCARP) and measurements in light of the following considerations: (1) The appreciation of radiation-induced cancer risks has changed markedly since the earlier guidelines were developed prior to 1970; (2) HZE particle effects were not well known at that time and while they were deemed, in the early 1970's, to be unlikely to be limiting, the question needed reexamination as soon as real experimental evidence became available; (3) Philosophies relating to occupational risks, for example, comparisons with relative risks in chemical industries and with risks of fatal accidents in"safe" and "less than safe" industries; and (4) The numbers and the nature of the people, including sex, and the roles they are to perform and the time they are to spend in space have also appreciably changed.

Sinclair (1984), President of NCRP, has discussed these points in some detail. The basic thrust of the reevaluation is embodied in the following extended quote:

> "Among the considerations which the committee will no doubt discuss are the following. On Earth, we tend to compare the risks from occupational exposures of radiation workers to the accidental fatality rates of "safe" industries, which we consider to be 10^{-4}/year or less. . . Fatality rates for travel to and from work are in the same range. . . However, many industries described as 'less safe', but quite normal industries, are in the range up to 10^{-3}/year. . . and it may be justified to compare with them. Thus, it may be appropriate to consider a lifetime risk of say 50 years x 10^{-3} or 5%. This could be a limit which can be

received in a space worker's lifetime, or after a defined number of missions, if the dose or risk permission is known. At low doses, which applied to most space circumstance, 2 x 10^{-4}/rad might be used as the risk."

Sinclair's considerations imply a career dose limit of 205 rem to the organs susceptible to radiocarcinogenesis, which are essentially encompassed within the blood forming organs or 5 cm dose. Sinclair's risk factor of 2 x 10^{-4} cancer death/rad is admittedly rough. Susceptibility varies with age at time of irradiation and sex.

Since Sinclair's statement, NCRP Scientific Committee 75 has refined its' risk assessments and philosophy and is recommending to the Council as a whole the limits shown in Table 3. The tentative career limits for the deep organs are predicated on a 3% lifetime risk of cancer mortality. Because the risk per rem depends upon age at exposure and on sex, these factors are considered.

The 3% lifetime mortality is comparable to the accidental death risk incurred in careers in quite normal industries such as mining, transportation, and agriculture, and is therefore deemed an acceptable risk.

However, cancer incidence, in contrast to mortality, may be a more important endpoint in that quality of life is impacted by contracting cancer, even if cured. In short, risk factor estimates and considerations of acceptable risk can be refined further. However, if we accept a career dose of 200 rem, then the total estimated dose from Table 1 for a reasonable 3-year MMM scenario does not exceed the career limit for a 35-year old even with allowance for a number of previous low Earth orbit missions in, for example, Space Station, where up to about 10 rem/90-day tour could be accumulated.

In conclusion, radiation concerns will not prohibit MMMs but must be considered in the operation and the design of the spacecraft and the Mars base. Moreover, NASA is committed to the radiation protection principle of ALARA, that is, keeping doses As Low As Reasonably Achievable; therefore, every reasonable effort should be made to reduce the total dose-equivalent the crew will receive. Substantial effort will be required to reduce the dose uncertaintites and thus reduce unnecessary shielding mass to achieve optimum radiological health protection consistent with MMM goals.