Crew Radiation Exposure Estimates from GCR and SPE Environments During a Hypothetical Mars Mission

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Some recent analyses of potential radiation exposures to crews on the surface of Mars focused solely on exposures from extremely large solar particle events (SPE). These analyses estimated radiation doses to critical organs, as well as effective doses, and compared them to crew permissible exposure limits. Contributions to crew exposures from galactic cosmic rays (GCR) were not addressed. In this work we present results for crew exposure estimates from GCR particles, as well as SPE protons. We assume a 200-day transit between Earth and Mars, a 500-day stay on the surface of Mars, and a 200-day transit from Mars back to Earth. For the transit phases of the mission we assume that the crew is protected by a spacecraft having 20 g/cm^2 aluminum or 40 g/cm^2 aluminum shielding. For the stay on the surface of Mars, we assume a habitat shielded by 40 g/cm^2 aluminum within the Martian atmosphere at altitudes of 25 km, 0 km, and -7 km, corresponding to the summit of Olympus Mons, the mean surface elevation, and the depth of the Hellas Impact Basin. The mission is assumed to begin 450 days prior to solar maximum and to end 450 days after solar maximum. The maximum for solar cycle 23 is used and assumed to have occurred on August 5, 2000. Radiation exposure estimates are obtained utilizing HZETRN 2010, the deterministic space radiation transport code developed at NASA Langley Research Center.

Nomenclature

E	=	proton energy
m	=	proton mass
E_D	=	effective dose
H_T	=	dose equivalent
w_T	=	tissue weighting factor
D	=	absorbed dose
Q	=	quality factor

I. Introduction

IN the future, astronauts participating in long-duration missions to Mars will face chronic exposure from galactic cosmic rays (GCR) as well as possible acute exposure to transient solar particle events (SPE). Past works have made comparisons between NASA's permissible exposure limits (PELs) and calculated organ doses and effective doses from several historical SPE.[1-5] The transient nature and large variability of particle intensity and energy means it can be difficult to accurately predict SPE exposures. In certain scenarios, crews may experience SPE exposures high enough to surpass the PELs.

In order to more correctly model the radiation environment experienced by an astronaut on a long-duration mission to Mars, similar calculations need to be performed to determine GCR exposure. Due to their high energies and prevalent nature, it is difficult to fully shield an astronaut from GCR. Additionally, annual doses from a GCR

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environment are not likely to exceed 200 mGy, indicating that the primary health concern arises from stochastic effects like cancer formation or neurological damage.[6-9] Similar to exposures received from SPE, the highest GCR exposures will most likely occur during transit to or from Mars, where the only shielding is that inherent to the spacecraft.[3, 7, 10] Exposures on the Martian surface will most likely be lower due to the presence of a CO_2-based atmosphere and the planet's bulk.[2] In this work, we first calculate the total effective dose received by both male and female crew members from chronic GCR exposures over a 900-day mission to Mars. Afterwards, we calculate the total effective dose received by both male and female crew members from one acute SPE exposure. Due to the unpredictable nature of SPE, we assumed the crew experienced a single event during the 900-day mission. Thus, effective doses for the total mission are presented for two scenarios: one in which a SPE occurred in transit and one in which it occurred on the Martian surface.

The next section includes details on the various mission scenarios modeled in this work, followed by a brief description of the computational methods used to calculate the organ doses, organ dose equivalents, and total effective doses for female and male crew members from both GCR and SPE exposures. Additionally, NASA's permissible exposure limits (PELs) for short-term effects and NASA's career radiation exposure limits are presented here. Finally, the results for all mission scenarios are displayed, followed by concluding remarks.

II. Mission Scenarios

The 900-day mission was centered between the August solar maximum peaks for cycle 23. This mission length was chosen in accordance with NASA's criteria for a long-duration expedition as defined in the *Human Exploration of Mars Design Reference Architecture*.[11] The 200-day transit from Earth to Mars occurred between May 13, 1999 and November 29, 1999, the 500-day stay on the Martian surface occurred between November 29, 1999 and April 12, 2001, and the 200-day transit from Mars to Earth occurred between April 12, 2001 and October 29, 2001. Transit was assumed to occur outside of Earth's magnetosphere in free space at 1 astronomical unit. During transit, male or female crew members were placed in the center of a spherical spacecraft composed of 20 or 40 g/cm^2 aluminum. On the Martian surface, male or female crew members were located at ground level in the center of a hemispherical shelter composed of 40 g/cm^2 aluminum. Aluminum served as a substitute for Martian regolith because aluminum's molecular composition is similar to the average molecular composition of regolith. The shelter was placed at 25 km, 0 km, and -7 km elevation, which corresponded to the highest surface elevation on the summit of Olympus Mons, the mean surface elevation, and the lowest surface elevation in the Hellas Impact Basin, respectively. The outside of the habitat was exposed to up to 300 g/cm^2 of the Martian atmosphere, which consisted of primarily CO_2 with trace amounts of nitrogen and argon. This composition was based upon measurements from the Viking Lander missions.[12] Organ exposures at atmospheric thicknesses above 300 g/cm^2 are negligibly small and are not considered in these calculations.

III. Computational Methods

A. Particle Transport

In this work, GCR and SPE transport calculations were performed using NASA's HZETRN 2010 (High Z and Energy TRaNsport) deterministic space radiation transport code.[13, 14] HZETRN 2010 transports the incident spectra from GCR or SPE and the resulting secondary particles formed during nuclear collisions with target materials. Secondary particles considered by HZETRN 2010 include neutrons, protons, deuterons, tritons, helium-3, and helium-4. In regards to both charged and neutral particle transport, HZETRN 2010 incorporates the one-dimensional Boltzmann equation with the straight ahead and continuous slowing down approximations, where the straight ahead approximation assumes all secondaries move in the same direction as the incident ion.[15] Body points of importance were identified in the Computerized Anatomical Man (CAM) and Computerized Anatomical Female (CAF) body self-shielding human geometry models to calculate the whole body effective dose.[16-18] HZETRN 2010 code outputs included the organ doses and dose equivalents for the eye lens, skin, blood-forming organs (BFO), heart, and the central nervous system (CNS), as well as total effective doses. After organ dose equivalents and effective doses for a series of shielding thicknesses in free space and on the Martian surface were calculated, the values were compared to NASA's PELs and career radiation exposure limits, respectively.

B. Incident GCR Spectra

The 2010 Badhwar and O'Neill GCR environmental model for the specified dates in solar cycle 23 were used as the incident spectra for all mission scenarios and were generated using the Online Tool for the Assessment of Radiation in Space (OLTARIS) computational tool developed at NASA Langley Research Center.[19, 20] During the transit periods, the GCR spectra were transported through free space, the appropriate spherical aluminum shielding (20 or 40 g/cm^2), and the CAM and CAF body self-shielding human geometry models. For the stay on the Martian surface, the GCR spectrum was transported in sequence through free space, the Martian atmosphere (up to 300 g/cm^2), the aluminum habitat (40 g/cm^2), and the CAM or CAF human geometry models. After transport, the organ-specific dose equivalents and the total effective doses were calculated.

C. Incident SPE Spectra

The October 1989 incident SPE spectrum were modeled using the default differential spectrum[20] provided in equation 1. Units for the differential SPE spectrum are in protons/(cm^2 – AMeV – event). The October 1989 event was used at the suggestion of the National Research Council.[21] When compared to the August 1972 event, NASA's adopted proton spectrum for SPE shielding calculations, the October 1989 integrated proton fluences below 100 MeV is within a factor of two of the August 1972 event, but it has a harder spectrum above 100 MeV. *E* is proton energy in MeV and *m* is the proton mass of 938 MeV.

$$\Phi(\mathrm{E}) = 6.104 \text{ x } 10^8 \left[\frac{E+m}{\sqrt{E\,(E+2m)}}\right] exp\left[\frac{-\sqrt{E\,(E+2m)}}{92.469}\right] \quad (1)$$

Similar to the GCR calculations, the incident SPE spectrum was transported through free space, the appropriate spherical aluminum shielding (20 or 40 g/cm^2), and the CAM or CAF body self-shielding human geometry models during the transit periods. For the stay on the Martian surface, the chosen SPE spectrum was transported in sequence through free space, the Martian atmosphere (up to 300 g/cm^2), the aluminum habitat (40 g/cm^2), and the CAM or CAF human geometry models. Once again, organ-specific dose equivalents and the total effective doses were calculated.

D. Radiation Exposure Quantities and Limits

Organ dose equivalents and total effective doses were compared to NASA's PELs (Table 1) and the career radiation exposure limits (Table 2), respectively.[22] Because PELs are based upon doses produced by gamma rays, it was necessary to convert the organ doses calculated in HZETRN 2010 from units of centigray (cGy) to centigray-equivalent (cGy-Eq) for comparison. This was accomplished by multiplying the organ doses in cGy by the Relative Biological Effectiveness (RBE) factor for protons. The recommended RBE for protons[23] with energy above 2 MeV is 1.5.

Effective doses (E_D) were calculated in HZETRN 2010 by multiplying the organ dose equivalent (H_T) by a dimensionless tissue weighting factor (w_T) and summing over all irradiated tissue (equation 2). Organ dose equivalent (H_T) takes the biological effectiveness of different radiation types into account, and is found by multiplying the absorbed dose in a given organ (D) by a LET-dependent quality factor (Q), as seen[24] in equation 3. Effective doses are expressed in units of centiSieverts (cSv) and can be directly compared to the career radiation exposure limits in Table . Note that these limits were selected such that a 3% risk of exposure-induced death from a fatal cancer, at a 95% confidence level, is not surpassed.[22]

$$E = \textstyle\sum_{\mathrm{T}} w_T \cdot H_T \quad (2)$$

$$H_T = Q \cdot D \quad (3)$$

Table 1. NASA PELs for short-term or career non-cancer effects.

Organ	30 days (cGy-Eq)	1 year (cGy-Eq)	Career (cGy-Eq)
Lens	100	200	400
Skin	150	300	400
BFO	25	50	NA
Heart	25	50	100
CNS	50	100	150
CNS ($Z \geq 10$)	-	10	25

Table 2. NASA career exposure limits for 1-year missions as a function of age of first exposure.

Age (years)	Effective Dose (cSv)	
	Female	Male
30	60	78
40	70	88
50	82	100
60	98	117

IV. Results

Effective dose results for the 200-day Earth-to-Mars transit, the 500-day Martian surface visit, and the 200-day Mars-to-Earth transit are presented below in Tables 3 and 4. Effective doses for the total mission are presented in Tables 5 and 6 for two scenarios: one in which a SPE occurred in transit and one in which it occurred on the Martian surface. While organ dose equivalents for the eye lens, skin, BFO, heart, and the CNS were calculated for both GCR and SPE exposures for all mission scenarios, none of the organ dose equivalents surpassed the NASA PELs for short-term or career non-cancer effects presented in Table 1. Because of this, organ dose equivalent results are not presented in this paper.

During the transit journeys, the GCR effective doses for both male (CAM) and female (CAF) crew members were lower during the Mars-to-Earth leg, which was product of utilizing realistic dates from solar cycle 23. Additionally, the effective doses were lower with 40 g/cm^2 aluminum shielding thickness compared to the same exposure scenario with 20 g/cm^2 aluminum shielding. This trend was also seen with the SPE effective doses, if the SPE occurred during one of the two transit periods. For the 20 g/cm^2 shielding scenario, the effective doses for male crew members were either slightly higher than or equal to the effective doses received by female crew members. When the shielding thickness was increased to 40 g/cm^2, the female crew members' effective doses were either slightly higher than or equal to the male effective doses. One reason female crew members might have higher effective doses stems from the fact that females have less body self-shielding than men, and are thus more likely to receive larger doses under the same radiation environment and shielding configurations.

Table 3. Calculated effective doses for female (CAF) and male (CAM) astronauts from GCR and SPE radiation during the Earth-to-Mars and Mars-to-Earth transits. Note that one calculation was made for SPE for both transit periods.

Effective dose (cSv)					
Radiation Event	**Human Geometry Model**	**20 g/cm^2 Al shielding**		**40 g/cm^2 Al shielding**	
		Earth-to-Mars	**Mars-to-Earth**	**Earth-to-Mars**	**Mars-to-Earth**
GCR	**CAM**	14.2	9.25	12.5	8.20
	CAF	14.2	9.25	12.5	8.21
SPE, Oct. 1989	**CAM**	14.4		6.60	
	CAF	14.2		6.63	

Table 4. Calculated effective doses for female (CAF) and male (CAM) crew members from GCR and SPE radiation as a function of elevation on the surface of Mars.

Effective dose (cSv)				
Radiation Event	**Human Geometry Model**	**40 g/cm^2 Al shielding**		
		Elevation (km)		
		25	**0**	**-7**
GCR	**CAM**	13.8	12.1	11.1
	CAF	13.8	12.1	11.1
SPE, Oct. 1989	**CAM**	2.03	0.88	0.6
	CAF	2.05	0.89	0.6

During the 500-day stay on the Martian surface, the effective doses for both males and females exposed to a SPE and GCR decreased as the elevation decreased from 25 km to -7 km. Additionally, effective doses for males and females were the same in most scenarios. Effective doses for female crew members were slightly higher at the mean surface elevation (0 km) for an SPE exposure, for the same reason described above. Overall, GCR exposures were about 7 times higher than SPE exposures on the summit of Olympus Mons (25 km), about 14 times higher at the mean surface elevation (0 km), and approximately 18 times higher in the Hellas Impact Basin (-7 km).

As previously mentioned, a single SPE was assumed to have occurred during the 900-day mission. Because of this, effective doses for the total mission are presented for two scenarios: one in which a SPE occurred in transit and one in which it occurred on the Martian surface. In both cases, the NASA career limits (Table 2) are not surpassed for 20 g/cm^2 or 40 g/cm^2 of aluminum shielding in transit with 40 g/cm^2 shielding on the surface of Mars at all elevations, even for most the restrictive limits for a female with a first exposure at 30 years. Total mission effective doses were approximately equal for male and female crew members. As previously mentioned, effective doses decreased as the aluminum shielding increased from 20 to 40 g/cm^2 and as the elevation decreased from 25 km to -7 km.

Table 5. Calculated effective doses for female (CAF) and male (CAM) crew members for total mission where the SPE occurs during transit.

Effective dose (cSv)						
Human Geometry Model	**20 g/cm^2 Al shielding (transit) + 40 g/cm^2 Al shielding (habitat)**			**40 g/cm^2 Al shielding (transit + habitat)**		
	Elevation (km)			**Elevation (km)**		
	25	**0**	**-7**	**25**	**0**	**-7**
CAM	51.7	50.0	49.0	41.1	39.4	38.4
CAF	51.4	49.7	48.7	41.1	39.4	38.4

Table 6. Calculated effective doses for female (CAF) and male (CAM) crew members for total mission where the SPE occurs during the stay on the Martian surface.

Effective dose (cSv)						
Human Geometry Model	**20 g/cm^2 Al shielding (transit) + 40 g/cm^2 Al shielding (habitat)**			**40 g/cm^2 Al shielding (transit + habitat)**		
	Elevation (km)			**Elevation (km)**		
	25	**0**	**-7**	**25**	**0**	**-7**
CAM	39.3	36.4	35.2	36.5	33.6	32.4
CAF	39.3	36.4	35.1	36.5	33.7	32.4

V. Summary

A 900-day simulated mission to Mars was centered around the solar maximum for cycle 23. The 200-day journey from Earth to Mars occurred from May 13, 1999 to November 29, 1999, the 500-day stay on the Martian surface occurred between November 29, 2001 and April 12, 2001, and the 200-day journey from Mars to Earth occurred from April 12, 2001 to October 29, 2001. While crew members received chronic GCR exposures during the entire mission, it was assumed that a single SPE occurred over the 900-day period, either when the crew was in transit or on the Martian surface. HZETRN 2010 was used to transport radiation through a series of materials to determine organ doses, organ dose equivalents, and effective doses for male and female crew members. During transit, male and female crew members were shielded by 20 or 40 g/cm^2 aluminum. On the Martian surface, crew members were placed at 25, 0, and -7 km elevation and were shielded by a 40 g/cm^2 aluminum habitat, which served as a surrogate for a regolith habitat. Organ dose equivalents for the eye lens, skin, BFO, heart, and the CNS were calculated for both GCR and SPE exposures for all mission scenarios, but none of these values surpassed the NASA PELs. Additionally, effective doses for the total mission did not surpass the NASA career limits for the scenarios presented here. Overall, this paper presents potential radiation exposures to crews from both SPE and GCR during a realistic, long-term mission to Mars.

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