Estimates of GCR Radiation Exposures on Mars for Female Crews in Hemispherical Habitats

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Abstract—Radiation exposure estimates for female crew members within simple hemispherical habitats constructed of aluminum on the surface of Mars are made for a representative radiation environment consisting of the current galactic cosmic ray environment. Females, because of their generally smaller physical stature, have less body self-shielding and are expected to receive larger doses than males for the same incident environments. In this work we use the HZETRN radiation transport code, originally developed at NASA Langley Research Center, and the Computerized Anatomical Female human geometry model to carry out the study. Comparisons of the predicted organ exposures with current NASA Permissible Exposure Limits are presented.

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1. INTRODUCTION

Future space exploration will likely include human crews traveling to and living on Mars for extended periods of time. A major concern in planning for such missions is exposure of crews to harmful space radiation environments consisting of the ever present galactic cosmic ray (GCR) background, and sporadic, large solar energetic particle events (SPEs). Although the highest radiation exposures are likely to occur during the transits from Earth to Mars [1], significant exposures will also be received during lengthy stays on the Martian surface, although the exposure rates are likely to be lower there due to the shielding provided by the overlying Martian atmosphere [2]. In this work we focus on estimating the radiation exposures from the current galactic cosmic ray (GCR) environment, which is one of the most intense of the space era.

Previous work, carried out some time ago [2], [3] suggested that the blood forming organ (BFO) dose from a combined solar minimum galactic cosmic ray (GCR) environment and a large solar particle event (SPE), for an astronaut at the mean elevation of Mars, would not exceed the 30-day radiation exposure limit of 25 rem (25 cSv in modern units) recommended at that time by the National Council on Radiation Protection and Measurements (NCRP) [4] for the BFO. Those calculations used an older GCR environmental model [5], a earlier version of the HZETRN space radiation transport code [6], and substituted a simple 5-cm water depth approximation for the actual bone marrow or BFO body self-shielding distribution, rather than using a realistic human geometry model, such as the computerized anatomical man (CAM) [7] or female (CAF) [8] models. However, the variation in Mars atmospheric shield thickness with the variation in arrival angle of the particles relative to the local zenith was accounted for, as was the 2π shadow shielding provided by the planet’s mass. Radiation exposure estimates were made for both Mars CO2 atmosphere density models, the warm low density model (16 g cm−2) and the cold high density model (22 g cm−2) areal densities [9].

In this work we revisit the issue of radiation exposures on the surface of Mars. The present, improved calculations use the latest GCR environmental model of Badhwar and O’Neill [10], which is the current NASA standard. The transport of the incident radiation spectra through the CO2 atmosphere is carried out using the much more recent and improved version of HZETRN [11]. Also, a realistic body self shielding distribution is used to estimate organ doses and dose equivalents, which are in turn used to calculate the effective dose, which is the relevant radiation protection quantity for comparing to the present limits, as specified in the NASA Permissible Exposure Limits (PELs) [12]. These newer calculations also employ the quality factors

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2 IEEEAC paper #1215, Version 2, Updated November 17, 2009
specified in Publication 60 of the International Commission on Radiological Protection (ICRP) [13], which replaced the previously-used values from ICRP Publication 26 [14].

The outline of the paper is as follows. In section 2, the scenarios to be analyzed are described. Section 3 presents details of the methods used to obtain the radiation exposure estimates for these scenarios for comparison with the appropriate radiation limits. Section 4 presents the calculated results and discusses them. Finally, section 5 summarizes the work and provides concluding remarks.

2. MARS SURFACE SCENARIOS

It is assumed that a female crewmember is located at ground level in the center of a hemispherical structure composed of aluminum, located at the mean elevation of the surface of Mars. The ground level center location inside the hemisphere was selected because it is the location within the structure where the radiation exposures are the highest. A female human geometry was selected for the study, rather than a male geometry, because females generally have a smaller physical stature resulting in less body self-shielding and are therefore expected to receive larger doses than males for the same incident environments and habitat shielding. In addition, radiation limits for females are slightly lower than for males of the same age, due to the increased radiosensitivity of some organs [12].

Three different areal densities for the aluminum hemisphere are assumed: (1) 0.3 g cm\(^{-2}\), which is comparable to the protection provided by a spacesuit; (2) 5 g cm\(^{-2}\), which is comparable to protection provided by a surface lander; and (3) 40 g cm\(^{-2}\), which is comparable to that provided by a permanent habitat.

For the Mars atmosphere, the composition is assumed to be pure CO\(_2\). Both low-density (16 g cm\(^{-2}\)) and high-density (22 g cm\(^{-2}\)) models were used. These areal densities are for a direction vertically through the Mars atmosphere starting from the mean surface elevation, and represent the thinnest shielding provided by the atmosphere. Since incoming GCR and SPE radiation arrives isotropically, the atmosphere shielding thicknesses (path lengths) are greater for particles arriving at angles greater than zero, with respect to the local zenith. The results presented herein account for this by averaging the dose for all arrival angles from 0 to 80 degrees. At an arrival angle of 80 degrees from the zenith (10 degrees above the local horizon) the atmosphere areal densities are ~120 g cm\(^{-2}\) for the high-density model and ~90 g cm\(^{-2}\) for the low-density model. As the arrival angle approaches the horizon, the areal densities increase dramatically, exceeding 160 g cm\(^{-2}\) for the low-density model, and 210 g cm\(^{-2}\) for the high-density model. At these depths, contributions to the organ exposures used to calculate effective dose are minimal and can be ignored.

Figure 1 displays the atmosphere path lengths as a function of arrival angle, as measured from the local zenith.

The incident radiation environment is assumed to be a GCR solar minimum spectrum comparable to that observed in the current solar minimum period. The GCR intensity is anticorrelated with solar activity. Hence, the most intense GCR environments occur during periods of solar minimum activity. Radiation exposure estimates for female crew members on the surface of Mars from large SPEs will be addressed elsewhere and are not included in this work.

Figure 1- Mars atmosphere areal density (path length) as a function of arrival angle for both low-density (16 g cm\(^{-2}\)) and high-density (22 g cm\(^{-2}\)) atmosphere models

3. CALCULATIONAL METHODS

The incident radiation spectrum for the current GCR solar minimum, obtained from the model of Badhwar and O’Neill [10] is transported through the Mars atmosphere (16 to 200 g cm\(^{-2}\)), then through the appropriate hemispherical aluminum shielding, and finally through the body self-shielding for the CAF organ of interest, using the HZETRN space radiation transport code developed at NASA Langley research Center. For the body composition, water is commonly used as a substitute for soft tissue, and is used herein for that purpose. The incident spectrum includes all elements from hydrogen through iron, which are the main ones contributing to human exposures in space.

The HZETRN code transports all incident ions and their nuclear reaction secondary products, including secondary neutrons. The database of secondary nuclear reaction products is calculated for the code using an in nuclear fragmentation model, NUCFRG2, developed for that purpose at NASA Langley Research Center [15]. The transport code also includes stopping powers to account for energy loss due to excitation and ionization by the charged particles traversing the medium resulting from collisions with the orbital electrons of the atoms and molecules in the target medium. The CAF model body self-shielding distributions in combination with the HZETRN results are then used to calculate the dose and dose equivalent estimates to critical organs. The body organ self-shielding
distributions are obtained using 968 rays, which cover the entire $4\pi$ solid angle surrounding a particular organ site. Doses and organ dose equivalents are calculated for the bone marrow, bladder, breast, colon, esophagus, heart, kidney, eye lens, liver, lung, ovary, pancreas, skin, stomach, and thyroid. For organs such as the skin and bone marrow, which are distributed throughout the body, doses and dose equivalents are obtained by averaging over more than 33 anatomical locations for each organ. For large organs, such as the bladder, breast, kidney, etc., at least 10 sites in the organ are averaged over. For localized organs, such as the eye lens, only one site is used. Note that organ doses (D) are given in units of centiGray (cGy), where 1cGy = 0.01 Gy = 1 rad and 1 Gy = 1 J/kg. Organ dose equivalents (H) are in units of centiSievert (cSv) where 1cSv = 0.01 Sv = 1 rem and 1Sv = 1 J/kg. The units on effective dose (E) are also cSv.

**Effective Dose Calculation**

The organ doses are calculated by folding the body self-shielding distribution for the organ of interest with the dose as a function of depth in water (tissue surrogate) obtained from the HZETRN transport code using

$$D(x) = \sum_j \int_0^\infty S_j(E) \Phi_j(x, E) \, dE$$

(1)

where $D(x)$ is the dose at depth $x$ in the tissue surrogate (water) due to all particles, $S_j(E)$ is the stopping power of particles of type $j$ with energy $E$, and $\Phi_j(x, E)$ is the flux of particles of type $j$ at $x$ with energy $E$.

The organ dose equivalents are also calculated by folding the body self-shielding distribution for the organ of interest with the dose equivalent as a function of depth in water obtained from HZETRN using

$$H(x) = \sum_j \int_0^\infty Q_j(E) S_j(E) \Phi_j(x, E) \, dE$$

(2)

where $Q$ is a quality factor that accounts for the fact that different particle types do differing amounts of biological damage for the same absorbed dose.

Once the organ dose equivalents are calculated for each organ, the effective dose is obtained from

$$E = \sum_T w_T H_T$$

(3)

where the tissue weighting factors $w_T$ are the proportionate detriment of the organ denoted by $T$ when the whole body is irradiated [16]. The values used herein are listed in Table 5.1 in reference [16].

The calculated effective dose values for female crew members, as a function of path length through the CO$_2$ atmosphere of Mars are displayed in Figure 2 for each of the three different hemispherical habitats. The final effective dose values, presented in the next section, are obtained by averaging the effective doses over all arrival angles from the zenith (0 degrees) to 80 degrees (near the local horizon) in increments of 5 degrees.

![Effective dose in units of cSv/day as a function of Mars atmosphere areal density (path length) for the three different hemispherical aluminum habitat thicknesses (0.3 g cm$^{-2}$, 5 g cm$^{-2}$, and 40 g cm$^{-2}$)](image)

**4. EFFECTIVE DOSE RESULTS**

Effective dose results are presented in Table 1 for the three hemispherical habitat configurations for both low-density and high-density atmospheres. Recall that the three configurations are representative of a space suit (0.3 g cm$^{-2}$), a surface lander (5 g cm$^{-2}$), and a permanent habitat (40 g cm$^{-2}$).

The daily effective dose values in the table can be multiplied by the length of stay for the mission on the surface of Mars in order to compare them to the career limits specified in the PELs. Therefore, for a six months mission on the surface, multiply the table results by 180, and by 365 for a one year mission.

**Table 1. Effective Dose (cSv/day) for Female Crew Members on the Surface of Mars**

<table>
<thead>
<tr>
<th>Aluminum Areal Density (g cm$^{-2}$)</th>
<th>High-Density Atmosphere</th>
<th>Low-Density Atmosphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>0.0686</td>
<td>0.0716</td>
</tr>
<tr>
<td>5</td>
<td>0.0681</td>
<td>0.0706</td>
</tr>
<tr>
<td>40</td>
<td>0.0664</td>
<td>0.0675</td>
</tr>
</tbody>
</table>
It is interesting to note from the table that the permanent habitat only reduces the effective dose by ~ 3% from the space suit value for the high-density atmosphere, and only by ~ 6% for the low-density atmosphere. Hence, the major source of protection from GCR particles for operations on the surface will be the Martian atmosphere. If the atmosphere were not present, such as the case for Earth’s moon, the effective dose for a female crew member in the assumed GCR environment on the surface would be 0.1039 cSv/day for the space suit shielding, 0.0945 cSv/day for the lander shielding, and 0.0722 cSv/day for the permanent habitat. Thus, the Mars atmosphere reduces the exposures by ~ 10% to ~ 35% over that provided by the aluminum shielding alone.

Comparison to Permissible Exposure Limits (PELs)

The NASA career exposure to radiation is limited to not exceed 3 percent risk of exposure induced death (REID) for fatal cancer. NASA uses a statistical assessment of uncertainties to ensure that this risk limit is not exceeded at a 95 percent confidence level. Table 2 lists the career permissible exposure limits for effective dose (in units of Sievert) for a female crewmember.

Table 2. Career Permissible Exposure Limits for Female Astronauts for a One Year Mission [12]

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>Effective Dose (cSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>37</td>
</tr>
<tr>
<td>30</td>
<td>47</td>
</tr>
<tr>
<td>35</td>
<td>55</td>
</tr>
<tr>
<td>40</td>
<td>62</td>
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<tr>
<td>45</td>
<td>75</td>
</tr>
<tr>
<td>50</td>
<td>92</td>
</tr>
<tr>
<td>55</td>
<td>112</td>
</tr>
</tbody>
</table>

These limits increase with increasing age due to the time lag required for solid tumor formation, which is on the order of 20 years. Also, since the probability of developing a fatal cancer, which is a stochastic process, increases with increasing dose, younger people are more at risk for developing a fatal cancer because they have a longer life expectancy than older people.

If one extrapolates the daily effective dose values in Table 1 out to a one year mission on the surface of Mars, the annual effective dose ranges from 26 cSv for the 0.3 g cm$^{-2}$ aluminum shield in the low-density atmosphere down to 24 cSv for the 40 g cm$^{-2}$ aluminum shield in the high-density atmosphere. Note that these effective doses are well below the limits in Table 2 for all crew member ages. If a very large SPE were to occur, it is possible that the limits could be exceeded for the thinner shield thicknesses. These exposure numbers, however, could be further reduced by placing the hemispherical habitat next to a cliff [2], which would reduce the exposure to half of those listed in Table 1, since the shadow shielding provided by the planet’s bulk would increase from $2\pi$ to $3\pi$.

5. Conclusions

Estimates of radiation exposures for female astronauts on the surface of Mars have been presented and compared with NASA permissible exposure limits. The calculations use the galactic cosmic radiation environmental model of Badhwar and O’Neill to provide the GCR spectrum that is input into the space radiation transport code HZETRN, developed at NASA Langley research Center. The GCR environment selected for analysis is the one appropriate for the current solar minimum condition, which represents the most intense GCR environment of the space era. The incident GCR spectrum is transported through the CO$_2$ atmosphere of Mars, both for high-density and low-density models, and then through hemispherical configurations of aluminum shielding representative of a space suit, surface lander, and a permanent habitat. Organ doses and dose equivalents for a female astronaut located at the highest dose point within the hemisphere are then calculated using the CAF human geometry model. The organ dose equivalents are then converted to effective doses for all six combinations of atmosphere models and hemispherical shielding configurations. The resulting effective doses are found to be well below NASA permissible exposure limits. It is also noted that the major contributor to exposure reduction is the shielding provided by the atmosphere of Mars. Only minor additional reductions are noted for the various aluminum shield thicknesses.

Future work will involve including exposures from large SPEs in the analyses. While the GCR environment alone does not exceed permissible exposure limits, including exposures from one or more large SPEs could cause limits to be approached or possibly exceeded.
REFERENCES


BIOGRAPHY

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