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Estimation of the Astronaut's Doses inside the Spacecraft Habitable Module in Deep Space

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Abstract—The estimation of the dose rates of astronauts inside the spacecraft habitable module with dimensions ∅6 m and length 12 m with an aluminum shell thickness of 15 g/cm^2 at the minimum and maximum of solar activity during flights in deep space has been presented. The estimation was based on the FLUKA calculations of the spectral characteristics of all components of the internal radiation field in the module from protons, deuterons, ^{3}He, and nuclei with $2 \leq Z \leq 28$ of Galactic Cosmic Radiation. To estimate the dose, the fluence-to-effective dose equivalent conversion coefficients for the male astronauts (cohort of never smoking males aged 30–60 years) have been used.

Keywords: Galaxy Cosmic Radiation, spacecraft, long-term interplanetary flights, radiation field, astronaut exposure, the dose of radiation

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1. INTRODUCTION

The space radiation represents a major limiting factor for long-duration human interplanetary missions. The current knowledge of radiation exposure at the deep space is exclusively based on calculations applying radiation transport codes in combination with Galactic Cosmic Radiation (GCR) simulation and spacecraft models. The energies of solar corpuscular radiation are so low (for a proton to a few keV), that the particles are completely stopped within the material of the spacecraft shell. In extremely intense solar proton events large currents with energies up to several GeV can escape into the interplanetary space, but the probability of such dangerous event is small. Currently, there are no reliable ways to predict their occurrence, but similar big events are rare in history. In principle, their occurrence has a lower probability at the solar activity minimum, but due to solar activity (SA) and GCR are anticorrelated, the maximum of the GC particle intensity occurs during SA minimum.

The exact date of the man's first mission to Mars has not yet been clearly determined. SpaceX plans to launch the first crewed mission in 2024. The NASA still states its aim of sending human explorers to Mars in the 2030s (the next low-energy launch window for Earth/Mars trips occurs in 2033). Another possible date for NASA can be 2037. Most likely that the certain dates in which the crewed mission will be launched will be chosen from the reason of beneficial astronomical position of Earth and Mars, but not SA reason. This is owing to the crew dose can be even lower with a lower SA due to the reduction of the mission duration.

Now NASA is considering three scenarios of Mars manned mission: Short-Stay Mission, Long-Stay Mission and Fast Transit Long-Stay Mission [1]. The lowest energy transfer to Mars is the Long-Stay Mission (~460 days flight, ~460 days stay). The mission times are the following: summary flight time is ~260 days, ~620 days stay. It is clear that it is important for both radiation safety and the achievement of the mission scientific goal to minimize the transit time of the mission and to maximize Martian surface operation time. Therefore, despite the increases in propulsive energy, the fast transit mission is preferred. Based on the foregoing, it can be assumed that the duration of the flight to Mars will be anyway no more 500 days, and the duration of the stay on Mars will be to 600 days regardless of SA.

The energetic particle radiation was measured by the Radiation Assessment Detector (RAD) on the board of Mars Science Laboratory while traveling from the Earth to Mars in 2011–2012. The average dose rate on the surface of Mars was about 210 μGy/day for the first 300 sols) (except for the only one weak solar proton event at which the dose rate increased to 260 μGy/day) with average quality factor in tissue ~3 for the whole 2π sr radiation field [2]. It corresponds to the mean dose equivalent rate on the Martian surface near 0.60–0.67 mSv/d. The mean

Table 1. GCR fluences at solar activity minimum and maximum

GCR particle	$W = 0$	$W = 190$
	fluence, $cm^{-2} s^{-1}$	Fluence, $cm^{-2} s^{-1}$
Protons	4.499	0.566
Alphas	0.415	0.085
Deuterons	0.083	0.017
^{3}He	0.058	0.013
Nuclei $Z > 2$	4.04×10^{-2}	6.65×10^{-3}

daily dose equivalent rate during the flight was estimated near 1.75 mSv/day [3]. Monthly averaged Wolf number (W) during 2011–2013 was in limits 80–85 [4]. It should be noted that the RAD had minimum shielding against radiation (smaller than 10 g/cm^2) and threshold of energy for protons of ~120–150 MeV.

The other GCR dosimeter Liulin-MO is now on the board of ExoMars mission. During the transit to Mars for the period, April–September/ 2016, the mean dose equivalent rate from GCR for the same time period was about 2 ± 0.3 mSv/d [5]. The average shielding of Liulin-MO detectors was also about 10 g/cm^2. This dose rate is in good agreement with the RAD data since the average W value for the ExoMars flight period was about 40.

2. SIMULATION PROCEDURE

2.1. The Geometry of the Spacecraft Habitable Module

In our previous works [6, 7], we considered the spacecraft habitable module with a diameter of 6 and a length of 12 m ($V = 339.3$ m^3), protected by the conventional aluminum shell with 15 g/cm^2 thickness. For example, the shell of the ISS, in its most heavily shielded areas, also has achieved 15 g/cm^2. This Al thickness is able to stop all protons at energies below 100–200 MeV, and is therefore efficient for trapped radiation and most solar proton events. Other protection materials (water, polyethylene, Kevlar, etc.) were not considered due to insufficient engineering development of projects and high-cost such shielding which is not compensated by a slight increase in the effectiveness of protection of the same thickness in g/cm^2.

2.2. Calculation of the Inner Radiation Field

In [7], a detailed calculation of the radiation field inside the habitable module at the minimum and maximum SA was done with the FLUKA-2011 code. As initial radiation the following GC particles were considered in the energy range 10 MeV/n–500 GeV/n: protons, deuterons, ^{3}He and nuclei with $2 \leq Z \leq 28$. GC particle fluences were calculated by the algorithm [8] for mean Wolf numbers W 0 and 190 (corresponding to the accepted minimum and maximum solar activity). The fluences of GCR at 0 and 190 in the above mentioned energy range are shown in Table 1.

The energy spectra for the next components of the inner field were presented in [7]: protons, $\pi^{\pm}$ and $\mu^{\pm}$-mesons, deuterons, tritons, ^{3}He, nuclei with $2 \leq Z \leq 58$ in the energy ranges from 10 MeV/n to 100 GeV/n, gamma-rays and neutrons from 1 MeV to 100 GeV. These energy spectra are averaged in the whole volume of the module. The energy threshold for neutrons is due to the neutron spectrum below 1 MeV depends stronger on the filling of the module with hydrogen-containing materials than on the external space particle spectrum. The calculated field of gamma-rays does not contain gamma-rays from the induced activity and from the reaction of radiation capture of slow neutrons. Therefore, the total fluences of gamma-rays and neutrons were underestimated.

2.3. Fluence-to-Effective Dose Equivalent Conversion Coefficients for the Astronaut Cohort

Knowledge of the energy spectra of all components of the internal field allows one to determine the effective dose of an astronaut from each component by convolving the spectra with the energy dependence of the specific effective dose (conversion coefficient fluence-to-effective dose). Fairly reliable dose estimation for each component can be made on the basis of the fluence-to-effective dose equivalent conversion coefficients [9] for the cohort of persons as close as possible to the astronaut cohort (never-smoking male aged 30–60 years). The coefficients for protons, deuterons, tritons, ^{3}He, alpha-particles, and heavy nuclei were calculated on the basis of relationships between quality factor Q and linear energy transfer L, linear energy y and NASA parameter Z^{*2}/β^2 [10]. These coefficients are similar, especially in the high-energy region. The total dose of the astronaut is then obtained by summing the contributions of all component doses.

3. RESULTS OF SIMULATION

In Tables 2 and 3 the effective doses equivalent rates for all components of the inner field, calculated with the conversion coefficients on basis of $Q(L)$- and $Q(Z^{*2}/\beta^2)$-relationships for isotropic geometry of human irradiation are presented for SA minimum and maximum.

In the tables, there are highlighted by bold type cases when the fluencees of the internal particles exceed the fluences of the primary GC particles. The inner particle fluences involve also the part of initial GC particles crossing the module shell without nuclear interactions.

The third column of the tables shows the dose rates from primary GC particles evaluated using $Q(L)$-relationship for male astronauts in open space [9], and in columns 5 and 6—doses rate from internal particles estimated using $Q(L)$- and $Q(Z^{*2}/\beta^2)$-relationships for male astronauts [9] within the habitable module. Unfortunately, for light particles (pions, muons, kaons, electrons) and gamma-rays there is not enough information to calculate conversion coefficients on basis of $Q(L)$- and $Q(Z^{*2}/\beta^2)$-relationships for the astronaut cohort. But the contribution of these components to the total dose is very small; therefore, to complete the picture, the tables give slightly overestimated doses for these components, obtained on the basis of available literature data. In the tables are showed the values of doses for pions and muons, obtained using the $Q(L)$-relationship for the entire population cohort [11] in accordance with ICRP Pub.103, value of dose for kaons obtained on basis of ICRP Pub. 74 [12] and values of effective doses for electrons and gamma-rays [13]. Instead of the doses for d, t, ^{3}He calculated by $Q(Z^{*2}/\beta^2)$-relationship, the tables show the values calculated by $Q(L)$-relationship for astronauts due to lack of data (these values are proximately equal). In general, these substitutions have virtually no effect on the total dose rate values.

4. DISCUSSION

In open space, nuclei with $Z > 2$ create up to 54–60% of the total dose of astronauts. The contribution of iron nuclei is especially great (more than alpha particles). Of course, a small part of the nuclei with the minimum energy will be stopped in the spacesuit, but even the iron nuclei with an energy of tens of MeV/n will punch it. As a result, the selected lower energy threshold for the GC particles will not actually affect the specified value.

The presence of a spacecraft shell with a thickness of 15 g/cm^2 of aluminum leads to a significant increase of particle fluence in the internal field of the module, but the cosmonaut's total dose is weakened slightly. This means that a decrease in the values of the specific effective dose of particles with the dissipation of their energy and charge decreasing in nuclear interactions as they pass through the shell is almost offset by an increase in the number of secondary particles. In the internal radiation field, the role of nuclei with $Z > 2$ decreases and their contribution to the total dose is about only 20–23%. There are also practically no differences in the contributions to the total dose of heavy nuclei at different values of W. The contribution of secondary fast and ultrafast neutrons to the total dose inside the module is relatively small—about 14% on average.

Fluence and dose variability in the internal field with a change in solar activity is less pronounced in comparison with fluence and dose of GCR variability. Thus, during the Fast Transit Long-Stay Mission (260 days) the minimal accumulated flight dose can be near 0.24 Sv at $W = 0$ and near 0.062 Sv at $W = 190$. The same dose values for the Long-Stay Mission (460 days) will be about 0.43 and 0.11 Sv respectively. Of course, these values are lower estimates of the astronaut dose, since they do not take into account electrons and gamma-rays in the GCR, underestimate the dose from secondary low-energy neutrons and gamma rays inside the module and do not include the dose from possible proton events on the Sun. However, these unaccounted factors (except the last) can lead to an underestimation of the obtained dose values by no more than 10–15%. But the main result is that our calculations give dose estimations smaller than those obtained by calculations using the NASA program HZETRN or RAD data. HZETRN is a deterministic transport code based on a numerical one-dimensional solution of the Boltzmann transport equation and anthropomorphic phantom. The code uses a straight-ahead approximation and is not applicable to the calculation of radiation fields in complex geometries. 3-D code FLUKA is a better tool to understand the full radiation environment produced within the spacecraft. The RAD measured the GCR absorbed dose rate in silicon and then used the resulting spectrum, after conversion of the deposited energy in silicon to linear energy transfer in water, to obtain the average quality factor Q, which was found to be 3.82 ± 0.25 [14]. This method is a rough approximation to estimate the equivalent dose of the whole body, but this is not an effective dose that takes into account the radiosensitivity of different organs and tissues, as well as a cohort of exposed persons. The results of dose calculations in this article should be considered as a fairly correct estimation of the low threshold of the crew radiation exposure in future flights to Mars.

Table 2. GCR and internal particle fluence rates, effective dose equivalent rates from GCR and from internal particles within the habitable module at SA minimum ($W = 0$)

Particles	GCR fluence rate, $cm^{-2}\ s^{-1}$	$Q(L)$-based effective dose equivalent rate from GCR, μSv/h	Internal particle fluence rate, $cm^{-2}\ s^{-1}$	$Q(L)$-based effective dose equivalent rate, μSv/h	$Q(Z^{*2}/\beta^2)$-based effective dose equivalent rate, μSv/h
P	4.499	17.247	**4.695***	17.023	19.214
N	–	–	4.571	4.778	5.587
$\pi^{\pm}$	–	–	0.582	1.966	1.882
$\mu^{\pm}$	–	–	8.42×10^{-2}	0.113	0.113
$K^{\pm}$	–	–	0.0045	0.012	0.012
γ		–	4.349*	0.502	0.502
e^+, e^-		–	**0.507***	0.416	0.416
D	8.3×10^{-2}	0.571	$\mathbf{1.21 \times 10^{-1}}$	0.611	0.611
T	–	–	1.64×10^{-2}	0.140	0.140
^{3}He	5.77×10^{-2}	0.795	4.78×10^{-2}	0.659	0.659
^{4}He	0.415	5.631	0.246	3.361	3.728
Li	1.61×10^{-3}	0.048	$\mathbf{1.64 \times 10^{-3}}$	0.049	0.054
Be	8.91×10^{-4}	0.044	8.54×10^{-4}	0.040	0.038
B	3.23×10^{-3}	0.280	1.91×10^{-3}	0.153	0.182
C	1.15×10^{-2}	1.591	5.22×10^{-3}	0.663	0.734
N	3.02×10^{-3}	0.670	1.53×10^{-3}	0.310	0.316
O	1.06×10^{-2}	3.593	3.98×10^{-3}	1.258	1.148
F	2.48×10^{-4}	0.122	1.63×10^{-4}	0.075	0.063
Ne	1.85×10^{-3}	1.203	6.80×10^{-4}	0.432	0.346
Na	4.36×10^{-4}	0.396	2.08×10^{-4}	0.187	0.143
Mg	2.02×10^{-3}	2.395	6.90×10^{-4}	0.798	0.579
Al	4.08×10^{-4}	0.619	1.65×10^{-4}	0.251	0.176
Si	1.75×10^{-3}	3.075	4.78×10^{-4}	0.876	0.609
P	8.46×10^{-5}	0.199	4.34×10^{-5}	0.103	0.068
S	3.49×10^{-4}	0.922	1.03×10^{-4}	0.290	0.187
Cl	7.59×10^{-5}	0.243	3.65×10^{-5}	0.120	0.078
Ar	1.38×10^{-4}	0.540	4.96×10^{-5}	0.202	0.125
K	1.02×10^{-4}	0.440	3.61×10^{-5}	0.165	0.103
Ca	2.57×10^{-4}	1.065	6.26×10^{-5}	0.317	0.195
Sc	5.08×10^{-5}	0.252	2.29×10^{-5}	0.133	0.081
Ti	1.72×10^{-4}	0.915	4.80×10^{-5}	0.305	0.188
V	9.04×10^{-5}	0.488	2.94×10^{-5}	0.197	0.126
Cr	1.81×10^{-4}	0.983	4.62×10^{-5}	0.319	0.213
Mn	1.14×10^{-4}	0.698	3.88×10^{-5}	0.291	0.192
Fe	1.18×10^{-3}	6.951	1.97×10^{-4}	1.428	1.036
Co	9.28×10^{-6}	0.070	2.67×10^{-6}	0.022	0.015
Ni	5.45×10^{-5}	0.383	9.20×10^{-6}	0.076	0.053
Total	5.094	52.431	15.238	38.502	39.917

Table 3. GCR and internal particle fluence rates, effective dose equivalent rates from GCR and from internal particles within the habitable module at SA maximum ($W = 190$)

Particles	GCR fluence rate, $cm^{-2} s^{-1}$	Q(L)-based effective dose equivalent rate from GCR, μSv/h	Internal particle fluence rate, $cm^{-2} s^{-1}$	$Q(L)$-based effective dose equivalent rate, μSv/h	$Q(Z^{*2}/\beta^2)$-based effective dose equivalent rate, μSv/h
P	0.566	2.711	**0.802**	3.271	3.805
N	–	–	1.24	1.374	1.597
$\pi^{\pm}$	–	–	0.274	0.939	0.891
$\mu^{\pm}$	–	–	3.39×10^{-2}	0.046	0.046
$K^{\pm}$	–	–	3×10^{-3}	0.008	0.008
γ			1.66*	0.241	0.241
e^+, e^-			**0.245***	0.210	0.210
D	1.69×10^{-2}	0.145	$\mathbf{2.90 \times 10^{-2}}$	0.165	0.165
T	–	–	4.205×10^{-3}	0.044	0.044
^{3}He	1.27×10^{-2}	0.194	1.17×10^{-2}	0.177	0.177
^{4}He	8.46×10^{-2}	1.192	5.63×10^{-2}	0.793	0.907
Li	3.68×10^{-4}	0.011	$\mathbf{4.49 \times 10^{-4}}$	0.013	0.016
Be	2.00×10^{-4}	0.008	$\mathbf{2.35 \times 10^{-4}}$	0.009	0.010
B	7.02×10^{-4}	0.039	5.10×10^{-4}	0.029	0.036
C	2.39×10^{-3}	0.193	1.42×10^{-3}	0.119	0.138
N	6.34×10^{-4}	0.078	4.20×10^{-4}	0.054	0.058
O	2.29×10^{-3}	0.471	1.15×10^{-3}	0.243	0.220
F	5.95×10^{-5}	0.019	4.97×10^{-5}	0.016	0.013
Ne	3.82×10^{-4}	0.180	2.03×10^{-4}	0.097	0.072
Na	8.71×10^{-5}	0.063	6.41×10^{-5}	0.045	0.032
Mg	4.82×10^{-4}	0.447	2.23×10^{-4}	0.208	0.136
Al	9.11×10^{-5}	0.119	5.32×10^{-5}	0.069	0.044
Si	3.83×10^{-4}	0.615	1.56×10^{-4}	0.248	0.155
P	1.90×10^{-5}	0.042	1.45×10^{-5}	0.031	0.019
S	7.74×10^{-5}	0.205	3.46×10^{-5}	0.090	0.052
Cl	1.69×10^{-5}	0.055	1.24×10^{-5}	0.039	0.023
Ar	3.33×10^{-5}	0.136	1.74×10^{-5}	0.069	0.039
K	2.21×10^{-5}	0.106	1.22×10^{-5}	0.056	0.032
Ca	5.06×10^{-5}	0.273	2.17×10^{-5}	0.114	0.062
Sc	1.06×10^{-5}	0.067	8.21×10^{-6}	0.050	0.027
Ti	3.59×10^{-5}	0.254	1.72×10^{-5}	0.117	0.065
V	1.88×10^{-5}	0.139	1.09×10^{-5}	0.078	0.045
Cr	3.68×10^{-5}	0.283	1.71×10^{-5}	0.128	0.078
Mn	2.61×10^{-5}	0.216	1.51×10^{-5}	0.121	0.074
Fe	2.75×10^{-4}	2.182	7.71×10^{-5}	0.597	0.403
Co	2.65×10^{-6}	0.024	1.10×10^{-6}	0.009	0.006
Ni	1.37×10^{-5}	0.126	3.68×10^{-6}	0.033	0.022
Total	0.689	10.592	4.366	9.952	9.967

*Without the contribution of GCR gamma-rays or electrons.

SUMMARY

Considering the fact that the dose on the surface of Mars will be approximately twice lower than during the flight, it can be assumed that cancer risk limit (≤3% REID—Risk of Exposure Induced Death) will not be exceeded for the scenario of Fast Transit Long-Stay Mission if the contribution to the dose during the flight from Solar proton events will be at level of the Mars Science Laboratory flight (~5%).

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