NASA Technical Memorandum 4167

Estimates of Galactic Cosmic Ray Shielding Requirements During Solar Minimum

Lawrence W. Townsend, John E. Nealy,
John W. Wilson, and Lisa C. Simonsen

FEBRUARY 1990

NASA Technical Memorandum 4167

Estimates of Galactic Cosmic Ray Shielding Requirements During Solar Minimum

Lawrence W. Townsend, John E. Nealy,
John W. Wilson, and Lisa C. Simonsen
Langley Research Center
Hampton, Virginia

National Aeronautics and
Space Administration
Office of Management
Scientific and Technical
Information Division
1990

Introduction

As the 20th century draws to a close, there is an ever-increasing interest in manned interplanetary travel. In particular, attention is focused on manned missions to the Earth's Moon and to the planet Mars and its satellites. A major concern to interplanetary mission planners is exposure of the crew to highly penetrating and damaging space radiations. The two major sources of these radiations are solar particle events (SPE) and galactic cosmic rays (GCR). Estimates of radiation exposures from energetic solar proton events (flares) are presented in references 1 and 2. In addition, preliminary calculations of GCR exposures through aluminum were presented previously (ref. 3). These latter estimates were of limited usefulness, however, because of the restriction to nonhydrogenous targets imposed by the missing nucleon-hydrogen cross section data bases in the transport code. To rectify that limitation in the code, the HZE (high-energy heavy ion) component of the GCR transport code (ref. 4) was coupled to a modified version of the Langley Research Center nucleon transport code BRYNTRN (ref. 5). This coupling of the two deterministic transport codes produced a single complete code for use in GCR shielding and dosimetry studies (ref. 6). This code, however, is considered to be interim in that it does not treat meson contributions, neglects target fragments produced by propagating protons and heavy ions, uses accurate but somewhat simplified input cross sections, and has not been optimized for computational efficiency. The neglect of target fragment contributions from the incident GCR protons can be corrected for in the calculations by separately computing the contribution with BRYNTRN (ref. 5) and adding the results to the proton dose and dose equivalent predictions, as done in reference 6. Nevertheless, the interim computer code is useful for initial exposure and shield requirement estimates, as long as the limitations are understood by the user.

In this report, estimates of integral fluxes (particles/cm^2/year), doses (centigrays/year), and dose equivalents (centisieverts/year or sieverts/year) in tissue, behind various thicknesses of aluminum, water, and liquid hydrogen shielding, are presented according to particle composition (protons, neutrons, alphas, and HZE). These target materials were chosen because of their applicability to spacecraft design and radiobiological applications. The calculations for solar minimum periods (which are most limiting for exposure considerations) use as the input spectrum the analytical model of the GCR environment promulgated by the Naval Research Laboratory (ref. 7). Because of a minor computational error in the earlier preliminary results for aluminum and water (ref. 6), the results presented herein should be used for exposure and shielding estimates instead of the earlier incorrect values.

Calculation Methods

The incident galactic cosmic ray spectrum (ref. 7) for free space is propagated through the target material using the accurate analytical/numerical solutions to the transport equation described in references 4 and 5. These highly accurate solution methods have been verified (to within 2 percent accuracy) by comparison with exact, analytical benchmark solutions to the ion transport equation (refs. 8 and 9).

These transport calculations include

1. Linear Energy Transfer (LET) dependent quality factors from ICRP-26 (ref. 10).
2. Dose contributions from propagating neutrons, protons, alpha particles, and heavy ions (HZE particles).
3. Dose contributions resulting from target nuclear fragments produced by all neutrons and primary protons and their secondaries.
4. Dose contributions due to nuclear recoil in tissue.

Major shortcomings of the calculations are

1. Except for tissue targets, mass number 2 and 3 fragment contributions are neglected.
2. Target fragmentation contributions from HZE particles and their charged secondaries are neglected (although they are included for nucleons).
3. All secondary particles from HZE interactions are presently assumed to be produced with a velocity equal to that of the incident particle. For neutrons produced in HZE particle fragmentations, this is conservative.
4. A quality factor of 20 is assigned to all multiply charged target fragments from the incident protons. To improve this approximation, one needs to calculate target fragment spectra correctly.
5. Meson contributions to the propagating radiation fields are neglected.
6. Nucleus-nucleus cross sections are not fully energy dependent (nucleon-nucleus cross sections are fully energy dependent).

For these shortcomings, items 3 and 4 are conservative. The remaining items, however, are not and probably alone result in a 15- to 30-percent underestimate of the exposure. As discussed elsewhere (ref. 11), the main sources of uncertainty are the input nuclear fragmentation model and the incident

GCR spectrum. Taken together, they could easily impose a factor of 2 or more uncertainty in the exposure predictions.

Results

Figure 1 displays dose equivalent (in units of sieverts/year) as a function of water shield thickness (in units of areal density, g/cm^2, or thickness, cm). Curves are displayed for solar minimum and solar maximum periods. The numerical values used in this figure are listed in table I. Also listed in this table are values for the absorbed dose in centigrays/year (cGy/yr) as a function of water shield thickness. For all thicknesses considered, the dose and dose equivalent during solar maximum are less than half of the dose and dose equivalent during solar minimum. Therefore, we will restrict the present analysis to solar minimum periods, since they are the most limiting for GCR exposures. This is not meant to imply, however, that exposures during solar maximum periods are not important. On the contrary, the cumulative exposures resulting from combined GCR and increased solar flare activity during solar maximum could potentially be significant. Analyses of these hazards are in progress and will be reported separately.

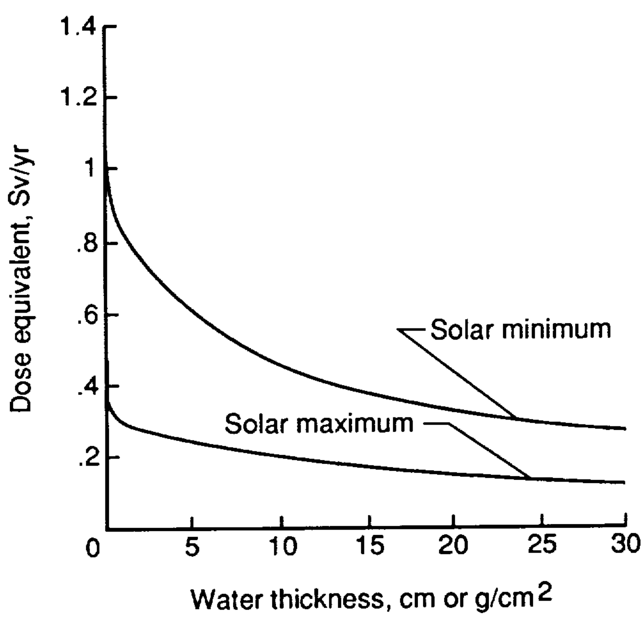

Figure 1. Dose equivalent in water, as a function of shield thickness, resulting from galactic cosmic rays.

The actual compositions of the calculated radiation fields are displayed in tables II–IV, where values for dose equivalent, dose, and particle flux are listed by particle type (neutrons, protons, etc.) and as a function of water thickness. The target fragment dose and dose equivalent contributions for incident protons and their secondaries, computed using BRYNTRN (ref. 5), are displayed separately in these tables.

From table I (or fig. 1), estimates of the thicknesses of water shielding required to protect astronauts from GCR particles can be obtained. At present there are no recommended exposure limits for deep-space exploratory missions. Therefore, we will use the currently proposed annual limits for Space Station Freedom (ref. 12) as guidelines. These are 3 Sv to the skin (0.01 cm depth), 2 Sv to the eye (0.3 cm depth), and 0.5 Sv to the blood-forming organs—BFO—(5 cm depth). Clearly, from table I, none of these limits are exceeded during periods of solar maximum activity, as the unshielded (0 cm depth) dose equivalent is estimated to be less than 0.5 Sv. Similarly, during solar minimum periods, the estimated unshielded dose equivalent of 1.2 Sv does not exceed either the skin or the eye exposure limits. The dose equivalent at 5 cm depth, which yields an estimate of the unshielded BFO exposure, is 0.61 Sv, which exceeds the 0.5 Sv limit by 22 percent. To reduce this estimated exposure below 0.5 Sv requires approximately 3.5 g/cm^2 (3.5 cm) of water shielding in addition to the body self-shielding of 5 g/cm^2 (5 cm).

For comparison purposes, calculations of skin (0 cm depth) and BFO (5 cm depth) exposures behind various thicknesses of aluminum and liquid hydrogen shielding were made. The results are presented in tables V–XII. For aluminum, 6.5 g/cm^2 (2.4 cm) of shielding thickness is required to reduce the BFO dose equivalent below the annual limit (see table VII). For liquid hydrogen, 1 g/cm^2 (14 cm) of shielding is required. For relative comparison purposes, the BFO dose equivalent as a function of shield thickness (areal density) is plotted in figure 2 for these three materials. Clearly, shielding effectiveness per unit mass increases as the composition of the shield changes from heavier to lighter mass elements. For liquid hydrogen, an added advantage is the reduced neutron fluence due to the absence of neutrons in the target composition and the lack of target fragment contributions because of the elementary nature of hydrogen. From these results, for an allowed BFO exposure of 0.25 Sv/year, which corresponds to a factor of 2 uncertainty in a 0.5 Sv/year estimate, the mass ratios for the shielding are approximately 1:5:11 for LH_2:H_2O:Al. Obviously, for GCR shielding, the materials of choice are those composed of low atomic mass number constituents with significant hydrogen content.

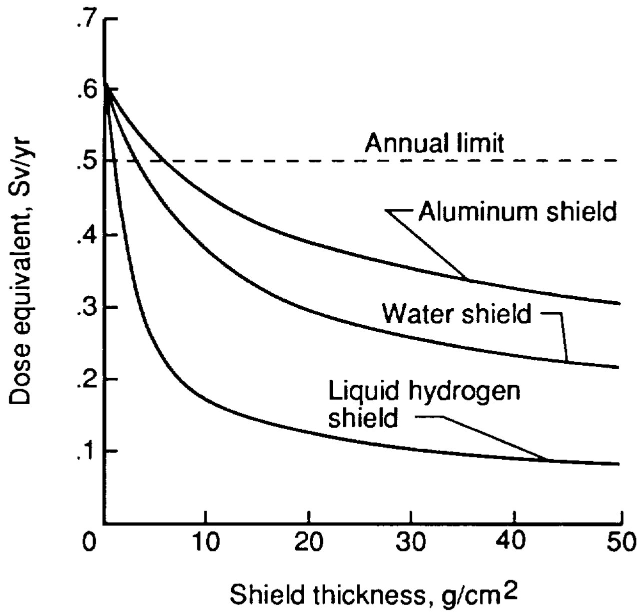

Figure 2. Blood-forming organ dose equivalent as a function of shield type and thickness.

Although the calculations are useful for estimating relative shield effectiveness for the purpose of comparing different materials, quantitatively they should be considered as preliminary estimates of actual shield mass requirements. Aside from the previously mentioned shortcomings related to neglecting meson production and target fragment contributions from interactions of HZE particles and the target medium, it is apparent from figure 2 that the dose equivalent is a slowly decreasing function of shield thickness. This is a result of secondary particle production processes whereby the heavier GCR nuclei are broken up into nucleons and lighter nuclear fragments by nuclear and coulombic interactions with the shield material. This slow decrease in dose equivalent with increasing shield thickness means that relatively small uncertainties in predicted doses arising from nuclear fragmentation model inaccuracies may yield large uncertainties in estimated shield thicknesses. A preliminary analysis of the nonlinear relationship between exposure uncertainty and the resulting shield mass uncertainty was presented in reference 11. The most startling finding was that a factor of 2 uncertainty in exposure amplified into an order of magnitude uncertainty in shield mass requirements. To further illustrate this, water shield mass increase (in percent) as a function of BFO exposure uncertainty (in percent) is listed in table XIII. For the latter quantity, the calculated exposure is assumed to be smaller than the actual exposure by the percentage indicated, i.e., the exposure is underestimated.

Again we note that if the exposure is underestimated by a factor of 2 (the 50-percent entry), then the resultant shield mass must be increased by an order of magnitude (1000 percent). To account for the $\approx$15-percent uncertainty resulting from neglect of meson production and the incomplete treatment of target fragmentation, the shield mass must be doubled (increased by 100 percent). Similarly, possible inaccuracies in the input fragmentation cross sections could underestimate the exposures by as much as 20 to 30 percent (ref. 13) and result in potential shield mass increases by up to a factor of 4 (over 400 percent increase). Clearly the *complete* development of an accurate and comprehensive transport code is needed, and uncertainties in the actual GCR environmental model and in the input nuclear fragmentation models need to be resolved through additional theoretical and experimental research. Finally, we note that radiation exposure is cumulative and therefore requires consideration of contributions from all sources including onboard nuclear power sources, solar particle events, and galactic cosmic rays. Exposure to onboard sources will reduce the allowed exposures from solar flares and cosmic rays and thereby increase required shield thicknesses necessary to stay below the exposure limits.

Concluding Remarks

Preliminary estimates of radiation exposures resulting from galactic cosmic rays are presented for interplanetary missions. Particle flux, dose, and dose equivalent values are presented, for solar minimum periods, as a function of water, aluminum, and liquid hydrogen shield thickness. The main contributions to the radiation doses arise from high-energy heavy ion (HZE) particles. As the incident radiations attenuate in the shield material, there is a significant buildup of secondary particles resulting from nuclear fragmentation and coulomb dissociation processes. A substantial fraction of these secondaries are energetic protons and neutrons. During solar minimum periods, at least 1 g/cm^2 of liquid hydrogen shielding, 3.5 g/cm^2 of water shielding, or 6.5 g/cm^2 of aluminum shielding will be needed to keep the estimated risk to the blood-forming organs below the current annual Space Station Freedom limit of 0.5 Sv/year. The preferred materials of choice for galactic cosmic ray shielding are materials with low atomic mass number constituents and significant hydrogen content. Significant uncertainties in the input cosmic ray spectra, and in the input nuclear fragmentation cross sections, could radically alter these estimates, however, by requiring substantial quantities of additional shielding to compensate for their uncertainties.

References

1. Townsend, Lawrence W.; Nealy, John E.; and Wilson, John W.: *Preliminary Estimates of Radiation Exposures for Manned Interplanetary Missions From Anomalously Large Solar Flare Events.* NASA TM-100620, 1988.
2. Townsend, Lawrence W.; Nealy, John E.; Wilson, John W.; and Atwell, William: Large Solar Flare Radiation Shielding Requirements for Manned Interplanetary Mission. *J. Spacecr. & Rockets*, vol. 26, no. 2, Mar./Apr. 1989, pp. 126–128.
3. Wilson, John W.; Townsend, Lawrence W.; and Atwell, William: *Preliminary Estimates of Galactic Cosmic Ray Exposures for Manned Interplanetary Missions.* NASA TM-100519, 1987.
4. Wilson, J. W.; Townsend, L. W.; and Badavi, F. F.: Galactic HZE Propagation Through the Earth's Atmosphere. *Radiat. Res.*, vol. 109, no. 2, Feb. 1987, pp. 173–183.
5. Wilson, John W.; Townsend, Lawrence W.; Nealy, John E.; Chun, Sang Y.; Hong, B. S.; Buck, Warren W.; Lamkin, S. L.; Ganapol, Barry D.; Khan, Ferdous; and Cucinotta, Francis A.: *BRYNTRN: A Baryon Transport Model.* NASA TP-2887, 1989.
6. Townsend, Lawrence W.; Wilson, John W.; and Nealy, John E.: *Preliminary Estimates of Galactic Cosmic Ray Shielding Requirements for Manned Interplanetary Missions.* NASA TM-101516, 1988.
7. Adams, James H., Jr.: *Cosmic Ray Effects on Microelectronics, Part IV.* NRL Memo. Rep. 5901 (Revised), Naval Research Lab., Dec. 31, 1987.
8. Wilson, John W.; and Townsend, L. W.: A Benchmark for Galactic Cosmic Ray Transport Codes. *Radiat. Res.*, vol. 114, no. 2, May 1988, pp. 201–206.
9. Wilson, John W.; Townsend, Lawrence W.; Ganapol, Barry; Chun, Sang Y.; and Buck, Warren W.: Charged-Particle Transport in One Dimension. *Nucl. Sci. & Eng.*, vol. 99, no. 3, July 1988, pp. 285–287.
10. *Recommendations of the International Commission on Radiological Protection.* ICRP Publ. 26, Pergamon Press, Jan. 17, 1977.
11. Townsend, Lawrence W.; Wilson, John W.; and Nealy, John E.: Space Radiation Shielding Strategies and Requirements for Deep Space Missions. SAE Tech. Paper Ser. 891433, July 1989.
12. National Council on Radiation Protection and Measurements: *Guidance on Radiation Received in Space Activities.* NCRP Rep. No. 98, July 31, 1989.
13. Townsend, L. W.; and Wilson, J. W.: An Evaluation of Energy-Independent Heavy Ion Transport Coefficient Approximations. *Health Phys.*, vol. 54, no. 4, Apr. 1988, pp. 409–412.

Table I. Galactic Cosmic Ray Dose and Dose Equivalent in Tissue as a Function of Water Shield Thickness

[All values are rounded to nearest 0.1]

Thickness, cm or g/cm^2	Solar maximum period		Solar minimum period	
	Dose, cGy/yr	Dose equivalent, cSv/yr	Dose, cGy/yr	Dose equivalent, cSv/yr
0	6.4	45.1	17.1	120.6
1	5.4	29.0	14.9	82.6
2	5.4	27.6	14.6	76.1
3	5.4	26.3	14.4	70.3
4	5.4	25.1	14.2	65.4
5	5.4	24.0	14.0	61.1
6	5.4	23.0	13.8	57.4
7	5.3	22.0	13.7	54.1
8	5.3	21.2	13.5	51.1
9	5.3	20.4	13.4	48.6
10	5.3	19.6	13.3	46.3
11	5.3	19.0	13.2	44.2
12	5.3	18.4	13.1	42.4
13	5.3	17.8	13.0	40.7
14	5.2	17.3	12.9	39.3
15	5.2	16.8	12.8	37.9
16	5.2	16.3	12.7	36.7
17	5.2	15.9	12.6	35.6
18	5.2	15.6	12.6	34.6
19	5.2	15.2	12.5	33.7
20	5.2	14.9	12.4	32.8
25	5.1	13.6	12.1	29.6
30	5.1	12.7	11.9	27.3
40	5.0	11.6	11.4	24.6
50	4.9	11.0	10.9	22.9

Table II. Solar Minimum Galactic Cosmic Ray Dose Equivalent in Tissue as a Function of Particle Type and Water Shield Thickness

[All values are rounded to nearest 0.1]

Thickness, cm or g/cm^2	Dose equivalent, cSv/yr, from—				
	Neutrons	Protons	Target fragments	Alphas	HZE
0	0	9.7	0	7.0	102.5
1	.3	6.6	5.9	3.4	66.4
2	.6	7.0	5.9	3.2	59.3
3	.9	7.4	5.8	3.1	53.1
4	1.2	7.7	5.8	3.0	47.7
5	1.4	8.0	5.8	2.9	43.0
6	1.7	8.2	5.8	2.8	38.9
8	2.1	8.6	5.7	2.6	32.1
10	2.6	9.0	5.6	2.4	26.7
15	3.5	9.6	5.4	2.0	17.4
20	4.3	10.0	5.2	1.6	11.7
25	4.9	10.2	5.0	1.3	8.0
30	5.4	10.4	4.8	1.0	5.2
40	6.2	10.4	4.4	.7	2.8
50	6.6	10.2	4.0	.5	1.4

Table III. Solar Minimum Galactic Cosmic Ray Dose in Tissue as a Function of Particle Type and Water Shield Thickness

[All values are rounded to nearest 0.1]

Thickness, cm or g/cm^2	Dose, cGy/yr, from—				
	Neutrons	Protons	Target fragments	Alphas	HZE
0	0	6.2	0	3.0	7.8
1	.1	6.0	.3	2.7	5.8
2	.1	6.4	.3	2.6	5.3
3	.2	6.6	.3	2.5	4.9
4	.2	6.8	.3	2.4	4.5
5	.3	7.1	.3	2.3	4.1
6	.4	7.2	.3	2.2	3.8
8	.5	7.5	.3	2.0	3.2
10	.5	7.8	.3	1.9	2.8
15	.7	8.3	.3	1.6	1.9
20	.9	8.6	.3	1.3	1.4
25	1.1	8.7	.3	1.1	1.0
30	1.2	8.8	.2	.9	.8
40	1.3	8.8	.2	6	.4
50	1.4	8.6	.2	.4	.2

Table IV. Solar Minimum Galactic Cosmic Ray Flux as a Function of Particle Type and Water Shield Thickness

[All values are rounded to nearest 0.1]

Thickness, cm or g/cm^2	Flux, particles/cm^2/yr, from—			
	Neutrons	Protons	Alphas	HZE
0	0×10^7	1.3×10^8	1.2×10^7	1.4×10^6
1	.4	1.3	1.2	1.3
2	.8	1.3	1.2	1.2
3	1.2	1.3	1.1	1.2
4	1.6	1.4	1.1	1.1
5	1.9	1.4	1.0	1.1
6	2.2	1.4	1.0	1.0
8	2.9	1.4	.9	.9
10	3.5	1.4	.9	.8
15	4.7	1.4	.7	.6
20	5.8	1.4	.6	.5
25	6.7	1.4	.5	.4
30	7.4	1.4	.4	.3
40	8.4	1.3	.3	.2
50	9.0	1.3	.2	.1

Table V. Solar Minimum Galactic Cosmic Ray 0-cm-Depth Dose Equivalent in Tissue as a Function of Particle Type and Aluminum Shield Thickness

[All values are rounded to nearest 0.1]

Thickness,[a] g/cm^2	0-cm-depth dose equivalent, cSv/yr, from—					
	Neutrons	Protons	Target fragments	Alphas	HZE	Total dose equivalent
1	0.4	7.5	5.9	3.5	69.4	86.8
2	.8	8.2	5.9	3.4	64.5	82.8
3	1.2	8.6	5.9	3.3	59.9	79.0
4	1.6	9.0	5.9	3.2	55.7	75.4
5	2.0	9.4	5.9	3.2	51.9	72.2
6	2.4	9.7	5.8	3.1	48.4	69.4
8	3.1	10.2	5.8	2.9	42.4	64.4
10	3.8	10.6	5.8	2.8	37.4	60.3
15	5.3	11.5	5.7	2.4	27.9	52.7
20	6.6	12.0	5.5	2.1	21.3	47.6
30	8.7	12.7	5.3	1.6	13.1	41.3

[a]1 g/cm^2 of aluminum is equivalent to 0.37 cm thickness.

Table VI. Solar Minimum Galactic Cosmic Ray 0-cm-Depth Dose in Tissue as a Function of Particle Type and Aluminum Shield Thickness

[All values are rounded to nearest 0.1]

Thickness,[a] g/cm^2	0-cm-depth dose equivalent, cGy/yr, from—					
	Neutrons	Protons	Target fragments	Alphas	HZE	Total dose
1	0.1	6.3	0.3	2.7	6.1	15.5
2	.2	6.8	.3	2.6	5.7	15.5
3	.2	7.1	.3	2.6	5.3	15.5
4	.3	7.4	.3	2.5	5.0	15.5
5	.4	7.6	.3	2.4	4.9	15.5
6	.5	7.8	.3	2.4	4.5	15.4
8	.6	8.2	.3	2.3	4.0	15.4
10	.7	8.5	.3	2.2	3.6	15.3
15	1.0	9.1	.3	1.9	2.8	15.1
20	1.3	9.5	.3	1.7	2.3	15.0
30	1.7	10.0	.3	1.3	1.5	14.7

[a]1 g/cm^2 of aluminum is equivalent to 0.37 cm thickness.

Table VII. Solar Minimum Galactic Cosmic Ray 5-cm-Depth Dose Equivalent in Tissue as a Function of Particle Type and Aluminum Shield Thickness

[All values are rounded to nearest 0.1]

Thickness,[a] g/cm^2	5-cm-depth dose equivalent, cSv/yr, from—					
	Neutrons	Protons	Target fragments	Alphas	HZE	Total dose equivalent
1	1.7	8.2	5.8	2.8	40.3	58.8
2	2.1	8.5	5.8	2.8	37.7	56.8
3	2.4	8.7	5.8	2.7	35.4	54.9
4	2.7	8.9	5.7	2.6	33.3	53.3
5	3.0	9.1	5.7	2.5	31.4	51.7
6	3.3	9.3	5.7	2.5	29.6	50.3
8	3.9	9.6	5.7	2.3	26.4	47.8
10	4.4	9.9	5.6	2.2	23.6	45.7
15	5.6	10.5	5.5	1.9	18.1	41.7
20	6.6	10.9	5.4	1.7	14.1	38.8
30	8.3	11.4	5.3	1.3	8.9	35.2
50	10.4	11.6	4.3	.8	3.8	30.9

[a]1 g/cm^2 of aluminum is equivalent to 0.37 cm thickness.

Table VIII. Solar Minimum Galactic Cosmic Ray 5-cm-Depth Dose in Tissue as a Function of Particle Type and Aluminum Shield Thickness

[All values are rounded to nearest 0.1]

Thickness,[a] g/cm^2	5-cm-depth dose, cGy/yr, from—					
	Neutrons	Protons	Target fragments	Alphas	HZE	Total dose
1	0.4	7.2	0.3	2.2	3.8	14.0
2	.4	7.4	.3	2.2	3.7	14.0
3	.5	7.6	.3	2.1	3.5	13.9
4	.6	7.7	.3	2.1	3.3	13.9
5	.6	7.8	.3	2.0	3.1	13.9
6	.7	8.0	.3	2.0	3.0	13.9
8	.8	8.2	.3	1.9	2.7	13.8
10	.9	8.4	.3	1.8	2.5	13.8
15	1.3	8.7	.3	1.6	2.0	13.8
20	1.3	9.0	.3	1.4	1.6	13.6
30	1.7	9.3	.3	1.1	1.1	13.3
50	2.1	9.3	.2	.7	.5	12.7

[a]1 g/cm^2 of aluminum is equivalent to 0.37 cm thickness.

Table IX. Solar Minimum Galactic Cosmic Ray Flux as a Function of Particle Type and Aluminum Shield Thickness

[All values are rounded to nearest 0.1]

Thickness,[a] g/cm^2	Flux, particles/cm^2/yr, from—			
	Neutrons	Protons	Alphas	HZE
0	0×10^7	1.3×10^8	1.2×10^7	1.4×10^6
1	.6	1.3	1.2	1.3
2	1.2	1.3	1.2	1.3
3	1.8	1.3	1.2	1.2
4	2.4	1.4	1.1	1.2
5	2.9	1.4	1.1	1.1
6	3.4	1.4	1.0	1.1
8	4.4	1.4	1.0	1.0
10	5.4	1.4	1.0	1.0
15	7.6	1.4	.9	.8
20	9.5	1.4	.8	.7
30	12.5	1.4	.6	.5
50	16.3	1.4	.4	.3

[a]1 g/cm^2 of aluminum is equivalent to 0.37 cm thickness.

Table X. Solar Minimum Galactic Cosmic Ray Depth Dose Equivalent in Tissue as a Function of Particle Type and Liquid Hydrogen Shield Thickness

[All values are rounded to nearest 0.1]

Thickness,[a] g/cm^2	Dose equivalent, cSv/yr, from—				
	Neutrons	Protons	Alphas	HZE	Total dose equivalent
Skin dose equivalent (0 cm depth)					
0	0	9.4	6.7	101.6	117.7
3	.2	6.6	2.7	31.8	41.3
10	.6	7.8	1.5	6.3	16.2
25	.8	8.1	.4	.4	9.7
50	.7	6.6	.1	<.1	7.4
75	.6	4.8	<.1	<.1	5.4
100	.4	3.3	<.1	<.1	3.8
BFO dose equivalent (5 cm depth)					
0	1.4	8.0	2.9	43.0	61.1
3	1.8	8.8	2.2	21.2	34.1
10	1.9	9.6	1.2	4.6	17.2
25	1.7	9.4	.4	.3	11.7
50	1.3	7.4	<.1	<.1	8.7
75	.9	5.3	<.1	<.1	6.2
100	.7	3.6	<.1	<.1	4.3

[a]1 g/cm^2 of LH_2 is equivalent to 14 cm thickness.

Table XI. Solar Minimum Galactic Cosmic Ray Depth Dose in Tissue as a Function of Particle Type and Liquid Hydrogen Shield Thickness

[All values are rounded to nearest 0.1]

Thickness,[a] g/cm^2	Dose, cGy/yr, from—				
	Neutrons	Protons	Alphas	HZE	Total dose
Skin dose (0 cm depth)					
0	0	6.2	3.0	7.8	17.0
3	.1	6.4	2.2	3.2	11.9
10	.1	7.5	1.2	.9	9.7
25	.2	7.7	.4	.1	8.4
50	.2	6.2	<.1	<.1	6.5
75	.1	4.5	<.1	<.1	4.7
100	.1	3.1	<.1	<.1	3.2
BFO dose (5 cm depth)					
0	0.3	7.1	2.3	4.1	14.0
3	.4	7.8	1.8	2.3	12.3
10	.4	8.5	1.0	.7	10.6
25	.4	8.3	.3	.1	9.0
50	.3	6.5	<.1	<.1	6.8
75	.2	4.7	<.1	<.1	4.9
100	.1	3.2	<.1	<.1	3.3

[a]1 g/cm^2 of LH_2 is equivalent to 14 cm thickness.

Table XII. Solar Minimum Galactic Cosmic Ray Flux as a Function of Particle Type and Liquid Hydrogen Shield Thickness

Thickness,[a] g/cm^2	Flux, particles/cm^2/yr, from—			
	Neutrons	Protons	Alphas	HZE
0	0×10^6	1.3×10^8	12.4×10^6	138.9×10^4
3	2.8	1.4	9.9	94.9
10	6.8	1.4	5.8	42.4
25	9.6	1.3	1.8	8.1
50	8.9	1.0	.3	.5
75	7.0	.7	.04	.03
100	5.3	.5	.006	.002

[a]1 g/cm^2 of LH_2 is equivalent to 14 cm thickness.

Table XIII. Water Shield Mass Increase as a Function of Exposure Uncertainty

BFO exposure uncertainty,[a] percent	Water shield mass increase, percent
10	43
15	100
20	129
30	414
40	614
50	1000

[a]Exposures assumed to be *underestimated* by the indicated percent.

NASA National Aeronautics and Space Administration

Report Documentation Page

1. Report No. NASA TM-4167	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Estimates of Galactic Cosmic Ray Shielding Requirements During Solar Minimum		5. Report Date February 1990
		6. Performing Organization Code
7. Author(s) Lawrence W. Townsend, John E. Nealy, John W. Wilson, and Lisa C. Simonsen		8. Performing Organization Report No. L-16715
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665-5225		10. Work Unit No. 199-04-16-11
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546-0001		13. Type of Report and Period Covered Technical Memorandum
		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Estimates of radiation risk from galactic cosmic rays are presented for manned interplanetary missions. The calculations use the Naval Research Laboratory cosmic ray spectrum model as input into the Langley Research Center galactic cosmic ray transport code. This code, which transports both heavy ions and nucleons, can be used with any number of layers of target material, consisting of up to five arbitrary constituents per layer. Calculated galactic cosmic ray fluxes, doses, and dose equivalents behind various thicknesses of aluminum, water, and liquid hydrogen shielding are presented for the solar minimum period. Estimates of risk to the skin and blood-forming organs (BFO) are made using 0-cm- and 5-cm-depth dose and dose equivalent values, respectively, for water. These results indicate that at least 3.5 g/cm^2 (3.5 cm) of water, or 6.5 g/cm^2 (2.4 cm) of aluminum, or 1.0 g/cm^2 (14 cm) of liquid hydrogen shielding is required to reduce the annual exposure below the currently recommended BFO limit of 0.5 Sv. Because of large uncertainties in fragmentation parameters and the input cosmic ray spectrum, these exposure estimates may be uncertain by as much as a factor of 2 or more. The effects of these potential exposure uncertainties or shield thickness requirements are analyzed.

17. Key Words (Suggested by Authors(s)) Space radiation; Galactic cosmic rays; Radiation shielding	18. Distribution Statement Unclassified—Unlimited. Subject Category 93

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 13	22. Price A03

NASA FORM 1626 OCT 86

NASA-Langley, 1990