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Comparison of Martian Meteorites and Martian Regolith as Shield Materials for Galactic Cosmic Rays

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Abstract

Theoretical calculations of radiation attenuation due to energetic galactic cosmic rays behind Martian rock and Martian regolith material have been made to compare their utilization as shields for advanced manned missions to Mars because the detailed chemical signature of Mars is distinctly different from Earth. The modified radiation fields behind the Martian rocks and the soil model were generated by solving the Boltzmann equation using a HZETRN system with the 1977 Solar Minimum environmental model. For the comparison of the attenuation characteristics, dose and dose equivalent are calculated for the five different subgroups of Martian rocks and the Martian regolith. The results indicate that changes in composition of subgroups of Martian rocks have negligible effects on the overall shielding properties because of the similarity of their constituents. The differences for dose and dose equivalent of these materials relative to those of Martian regolith are within 0.5 and 1 percent, respectively. Therefore, the analysis of Martian habitat construction options using in situ materials according to the Martian regolith model composition is reasonably accurate. Adding an epoxy to Martian regolith, which changes the major constituents of the material, enhances shielding properties because of the added hydrogenous constituents.

Introduction

The primary galactic cosmic rays (GCR) consist mostly of protons and alpha particles with a small but significant component of heavier particles. Figure 1 illustrates the spectra at 1 astronomical unit (AU) for primary GCR ions up to nickel by using the 1977 solar minimum GCR environmental model (ref. 1), which represents a maximum in intensity of the GCR. Humans on a manned mission to Mars will require more protection from the GCR than has been used heretofore on shorter missions (ref. 2).

For habitats on the surface of Mars, the regolith of a particular locale is a convenient candidate for bulk shielding without excessive launch weight requirements from Earth. The Martian regolith model composition, which is based on Viking lander data (ref. 3), has been used in the Martian regolith shielding studies (ref. 4). Over the years, Martian meteorites have been found, and vast literature exists about them. These meteorites are investigated for the radiation attenuation characteristics and their shielding ability. The compositions of the meteorites are obtained from the *Mars Meteorite Compendium—1996* compiled by Meyer (ref. 5).

Although the detailed effect of the Martian atmospheric shield is not a concern in this study, the transmitted GCR environment at the 1977 solar minimum behind various materials is calculated for the complex radiation environmental components as a function of shield composition and thickness to compare the shield effectiveness of these materials. The radiation attenuation characteristics behind each material are assessed in terms of conventional dosimetry by using quality factors (ref. 6). The dose and dose equivalent are compared for different Martian meteorites as candidate habitats from space radiation in deep space missions for human protection. To see the accuracy of the previous analysis of Martian habitat, these results are compared with that from Martian regolith model composition, in which only 5 of the more abundant elements occurring in samples were chosen although up to 11 constituent atoms are in each meteorite. Shielding ability of materials with varying composition and constituents is analyzed by comparing dose and dose equivalent behind various materials with various thicknesses.

Chemical Analyses of Martian Meteorites, Martian Regolith, and Composites

Martian meteorites are considered as random soil samples from Mars for space construction. Chemical analyses of 11 Martian meteorites are found from the *Mars Meteorite Compendium* (ref. 5). These igneous rocks are grouped into five subgroups according to their own distinct chemical signatures. The first group of Basalt includes some Martian meteorites such as QUE94201, Shergotty, Zagami, and EETA79001. Martian meteorites named LEW88516 and ALHA77005 are in the second group called Lherzolite; Martian meteorites named Governador Valadares, Nahkla, and Lafayette are in the next group called Clinopyroxenite; ALH84001 is in the Orthopyroxenite group; and Chassigny is in the Dunite group. These groupings are apparent in the patterns of chemical analyses of the five most abundant chemical components of each meteorite as shown in figure 2. The average weight percentage of chemical analyses of these groups also shows their own distinct variation of compositions in figure 3. Therefore, the attenuation characteristics are examined by using the average compositions within these groups. Average atomic constituents of each group are given in table 1 as atomic parameters for the transport code.

In assessing the radiation protection for future manned exploration and habitation of Mars, the Martian regolith model composition (ref. 3) has been used. (See ref. 4.) A representative sampling of Martian regolith (ref. 3) was reported to have a density of 1.4 g/cm^3 and to contain almost exclusively only five elements: O (62.5 mol-percent), Si (21.77), Fe (6.73), Mg (6.06), and Ca (2.92). The representative atomic parameters are given in table 2.

Because hydrogen-containing compounds are efficient as potential space structural components (refs. 7 and 8), an epoxy, ICI Fiberite 934, which is an aerospace-qualified resin, is considered as a possible binder for the Martian regolith. The potential benefits of introducing epoxy into Martian regolith are compared by varying weight fraction of epoxy from 10, 20, and 30 percent. Their atomic parameters are given in table 3.

GCR Transport and Conventional Risk Assessment

The primary mechanism for loss of energy by energetic particles is by means of coulombic interactions with electrons in the target, such as atomic and molecular stopping cross sections (ionization). Additional energy is lost through coulombic interactions and collisions with target nuclei (projectile and target fragmentations). Although nuclear reactions are far less numerous, their effects are magnified because of the large momentum transferred to the nuclear particles and the impacted nucleus itself. Many secondary particles of nuclear reactions are sufficiently energetic to promote similar nuclear reactions and thus cause a buildup of secondary radiation.

The propagation and interactions of high-energy ions up to atomic number 28 in Martian meteorites and Martian regolith model are simulated by using the transport code HZETRN (ref. 9). This code solves the fundamental Boltzmann transport equation and applies the straight-ahead approximation for nucleon, light ions, and high-charge, high-energy (HZE) nuclei with velocity-conserving fragmentation interactions for HZE nuclei colliding with shield materials. The interactions of HZE nuclei have been carefully investigated because of their unusually high specific ionization and their enormous energy range (ref. 9). The nuclear reactions of light ions (proton, neutron, ^{2}H, ^{3}H, ^{3}He, and ^{4}He) have been added into this code because they are abundant in primary GCR and build up with increasing shield thickness due to longer ranges and greater multiplicities in inelastic events (ref. 10).

The level of biological injury from the transmitted GCR environment behind a material is assessed in terms of conventional dosimetry, which is a measure of the response of living tissue behind a shield. The conventional method of extrapolating the human radiation risk database to high LET exposures is introduced by the dose equivalent H given by the following equation:

$$H = QD \tag{1}$$

where Q is the LET-dependent quality factor defined by ICRP (ref. 6) to represent trends of measured relative biological effectiveness (RBE) in cell culture, plant, and animal experiments and D is the absorbed dose due to energy deposition at a given location by all particles. Although the absolute human risk is not known because of biological uncertainty, the dose equivalent is a measure of the response of living tissue behind a material. The dose and dose equivalent as a function of slab thickness represent the radiation risk behind the material in tables 4 and 5.

Comparison of Dose and Dose Equivalent From Galactic Cosmic Rays

For the comparison of the shield effectiveness of the materials, the free-space fluences are used without modification of the spectra by the carbon dioxide atmosphere of Mars. The absorbed dose at solar minimum from an annual GCR exposure behind Martian rocks and Martian regolith model is in table 4, and the dose equivalent with radiation quality factor is in table 5. The dose and the dose equivalent among the five subgroups are changed within 1 and 2 percent, respectively. This illustrates that changes in composition of these subgroups with similarity of constituents in table 1 have negligible effects on the overall shielding properties. These values of five subgroups are compared with those of the Martian regolith model, which is comprised of only five representative constituents in table 2. Dose and dose equivalent for the thicknesses up to 50 g/cm^2 vary only within 0.5 and 1 percent, respectively. These small differences in the shielding capability of the materials at moderate to large depths indicate that the relative differences of the compounds are comparable with these results when the attenuation of the Martian atmosphere is present. Therefore, the Martian regolith model adequately represents Martian in situ material, and previous analyses for Martian habitats (ref. 4) are assumed reasonably accurate.

The effects of changing constituents of a candidate material, such as Martian regolith, by introducing hydrogen-containing epoxy are examined by varying its weight fractions. These are shown in figures 4 and 5 for the thicknesses up to 50 g/cm^2. Adding an epoxy to Martian regolith to bind it into a composite enhances its shielding properties for GCR; the thicker the shield, the better is its shielding characteristics. For a composite of Martian regolith with 30-percent epoxy by weight, dose and dose equivalent at 50 g/cm^2 are decreased by 4 and 13 percent relative to those for Martian regolith. These results illustrate that changing constituents with lighter atoms is much more effective than changing composition alone for developing shield materials against GCR. A material with a high density of hydrogen, which is a composite of Martian regolith with 30 percent epoxy by weight, provides the most effective shielding at all thicknesses because of its greater efficiency in attenuating the heavier ions that are most destructive to living tissue (ref. 11).

In addition to the increased radiation safety factor, incorporating the epoxy into unconsolidated Martian regolith for manufacturing of structural blocks assures many other advantages. It provides more durable structures with significantly less material and more versatility in design and utility of structures. Furthermore, there may be a great advantage in the use of unconsolidated Martian regolith in construction compared with the use of rocks. For manufacturing structural blocks, the distribution of fragment size affects the making of a good consolidated void-free composite. Rocks need to be processed first into fragments, whereas Martian regolith is merely gathered. The different rock fragmentation methods require a different amount of energy to fragment a unit volume of rock, the specific energy. To make smaller fragment sizes to minimize voids requires higher specific energy (ref. 12). Using hard rocks requires high energy and provides no advantage in shielding effectiveness. The benefits of an epoxy-regolith composite must be traded in the context of a complete design reference mission scenario which takes into account total mass of shielding, additives, processing equipment, EVA (extra vehicular activity) time, and other things relative to crew exposure risks (ref. 13).

Concluding Remarks

A theoretical investigation of the interaction and alteration of space radiations by various Martian meteorites shows that Martian meteorite subgroups having up to 11 constituents have negligible effects on the overall shielding properties. These subgroups are compared to the Martian regolith model, which has only five representative constituents. The radiation attenuation characteristics in terms of dosimetry among these materials vary only about 0.5 percent for dose and about 1 percent for dose equivalent for the thicknesses up to 50 g/cm^2. This result illustrates that the Martian regolith model adequately represents Martian in situ material. The use of rocks to build structural components requires large energy inputs and is not viable.

The effects of hydrogen-containing composites of epoxy/Martian regolith as potential Martian habitat are examined. Adding 30 percent epoxy by weight to Martian regolith enhances shielding properties in which dose and dose equivalent are decreased by 4 and 13 percent at 50 g/cm^2, respectively. The composite that has the highest density of hydrogen among those considered in this study gives the most effective shielding properties at all thicknesses. Thus, for developing shield materials against galactic cosmic rays, making a composite with lighter atoms, which changes the major constituents of a material, is much more effective than varying the composition of similar heavier constituents.

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Table 1. Atomic Parameters for Each Group of Martian Meteorites

Element	Atomic number, *Z*	Atomic weight, *A*	Atomic density, atoms/g, for—				
			Basalt	Lherzolite	Clinopyroxenite	Orthopyroxenite	Dunite
O	8	16	1.60×10^{22}	1.58×10^{22}	1.54×10^{22}	1.65×10^{22}	1.51×10^{22}
Na	11	23	2.35×10^{20}	9.15×10^{19}	1.13×10^{20}	2.66×10^{19}	2.51×10^{19}
Mg	12	24	1.61×10^{21}	4.07×10^{21}	1.79×10^{21}	3.77×10^{21}	4.81×10^{21}
Al	13	27	8.50×10^{20}	3.34×10^{20}	1.94×10^{20}	1.45×10^{20}	8.23×10^{19}
Si	14	28	5.01×10^{21}	4.50×10^{21}	4.88×10^{21}	5.38×10^{21}	3.87×10^{21}
P	15	31	5.60×10^{19}	2.00×10^{19}	3.76×10^{18}	0.00×10^{00}	6.41×10^{18}
K	19	39	1.23×10^{19}	3.31×10^{18}	2.93×10^{19}	1.95×10^{18}	5.31×10^{18}
Ca	20	40	1.06×10^{21}	4.04×10^{20}	1.56×10^{21}	1.98×10^{20}	6.52×10^{19}
Ti	22	48	8.21×10^{19}	3.28×10^{19}	2.59×10^{19}	1.53×10^{19}	7.60×10^{18}
Mn	25	55	4.42×10^{19}	3.91×10^{19}	5.69×10^{19}	4.04×10^{19}	4.51×10^{19}
Fe	26	56	1.58×10^{21}	1.67×10^{21}	1.79×10^{21}	1.46×10^{21}	2.29×10^{21}

Table 2. Atomic Parameters of Representative Martian Regolith

Element	Atomic number, *Z*	Atomic weight, *A*	Atomic density, atoms/g
O	8	16	1.67×10^{22}
Mg	12	24	1.62×10^{21}
Si	14	28	5.83×10^{21}
Ca	20	40	7.81×10^{20}
Fe	26	56	1.80×10^{21}

Table 3. Atomic Parameters of Various Weight Fraction of Epoxy/Martian Regolith Composites

Element	Atomic number, *Z*	Atomic weight, *A*	Atomic density, atoms/g, for—		
			10% epoxy/90% regolith with Density = 1.39	20% epoxy/80% regolith with Density = 1.38	30% epoxy/70% regolith with Density = 1.37
H	1	1	3.77×10^{21}	7.55×10^{21}	1.13×10^{22}
C	6	12	3.33×10^{21}	6.65×10^{21}	9.98×10^{21}
N	7	14	3.60×10^{20}	7.19×10^{20}	1.08×10^{21}
O	8	16	1.56×10^{22}	1.45×10^{22}	1.33×10^{22}
Mg	12	24	1.46×10^{21}	1.30×10^{21}	1.14×10^{21}
Si	14	28	5.25×10^{21}	4.66×10^{21}	4.08×10^{21}
S	16	32	8.99×10^{19}	1.80×10^{20}	2.70×10^{20}
Ca	20	40	7.03×10^{20}	6.25×10^{20}	5.47×10^{20}
Fe	26	56	1.62×10^{21}	1.44×10^{21}	1.26×10^{21}

Table 4. Annual Dose Behind Martian Rock Groups and Martian Regolith

	Annual absorbed dose. cGy/yr, behind—					
Thickness, g/cm^2	Basalt	Lherzolite	Clinopyroxenite	Orthopyroxenite	Dunite	Martian regolith
0	19.44	19.44	19.44	19.44	19.44	19.44
0.5	21.56	21.55	21.58	21.54	21.58	21.56
1	21.95	21.93	21.97	21.91	21.96	21.94
3	22.30	22.27	22.33	22.24	22.32	22.29
5	22.28	22.25	22.31	22.21	22.31	22.27
10	21.97	21.94	22.02	21.89	22.01	21.96
20	21.29	21.25	21.33	21.19	21.34	21.27
30	20.65	20.62	20.70	20.56	20.71	20.64
50	19.48	19.44	19.53	19.39	19.54	19.47

Table 5. Annual Dose Equivalent Behind Martian Rock Groups and Martian Regolith

	Annual dose equivalent. cSv/yr, behind—					
Thickness, g/cm^2	Basalt	Lherzolite	Clinopyroxenite	Orthopyroxenite	Dunite	Martian regolith
0	120.13	120.13	120.13	120.13	120.13	120.13
0.5	134.46	134.44	134.47	134.37	134.55	134.45
1	132.31	132.26	132.38	132.15	132.44	132.30
3	121.17	121.07	121.36	120.83	121.40	121.15
5	111.51	111.37	111.78	111.06	111.79	111.48
10	93.96	93.75	94.33	93.35	94.29	93.91
20	74.54	74.28	74.95	73.84	74.88	74.48
30	64.84	64.58	65.24	64.17	65.16	64.80
50	56.48	56.23	56.80	55.89	56.76	56.47

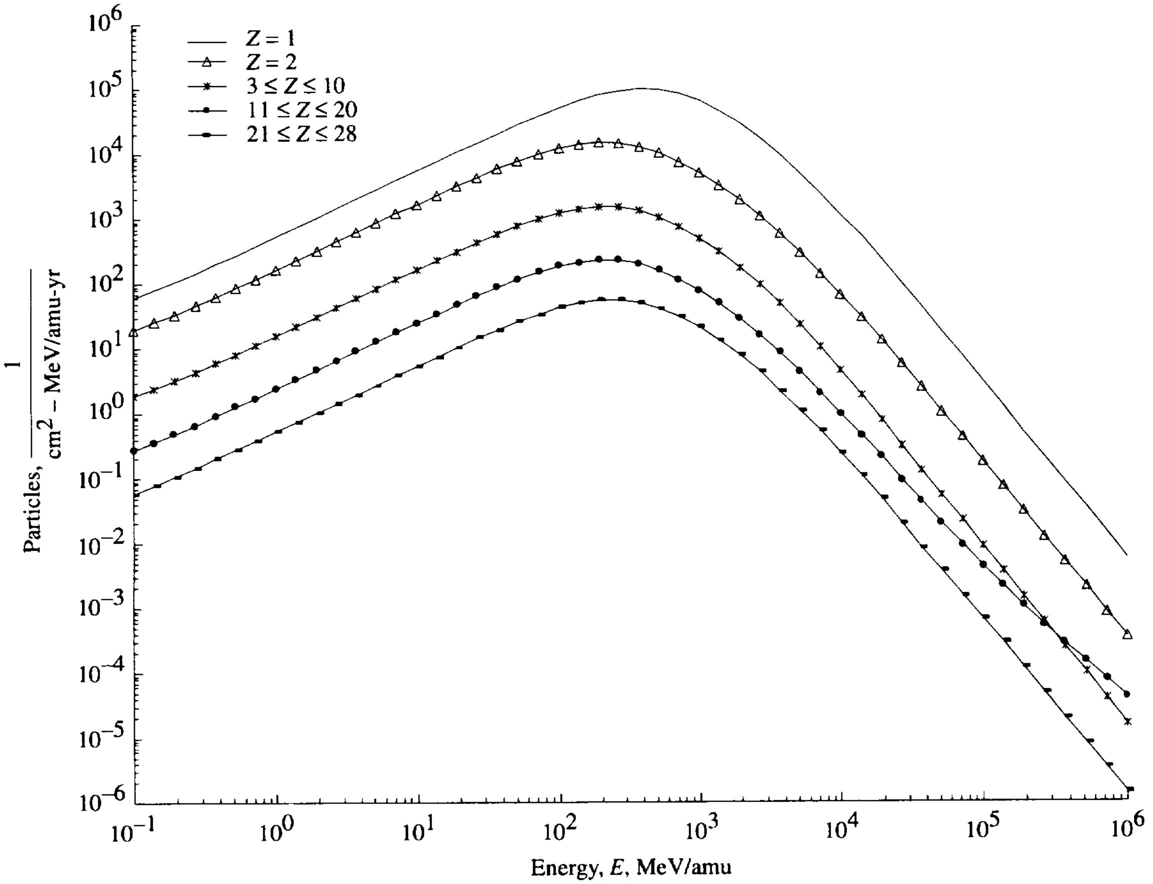

Figure 1. Primary galactic cosmic ray spectra for 1977 solar minimum.

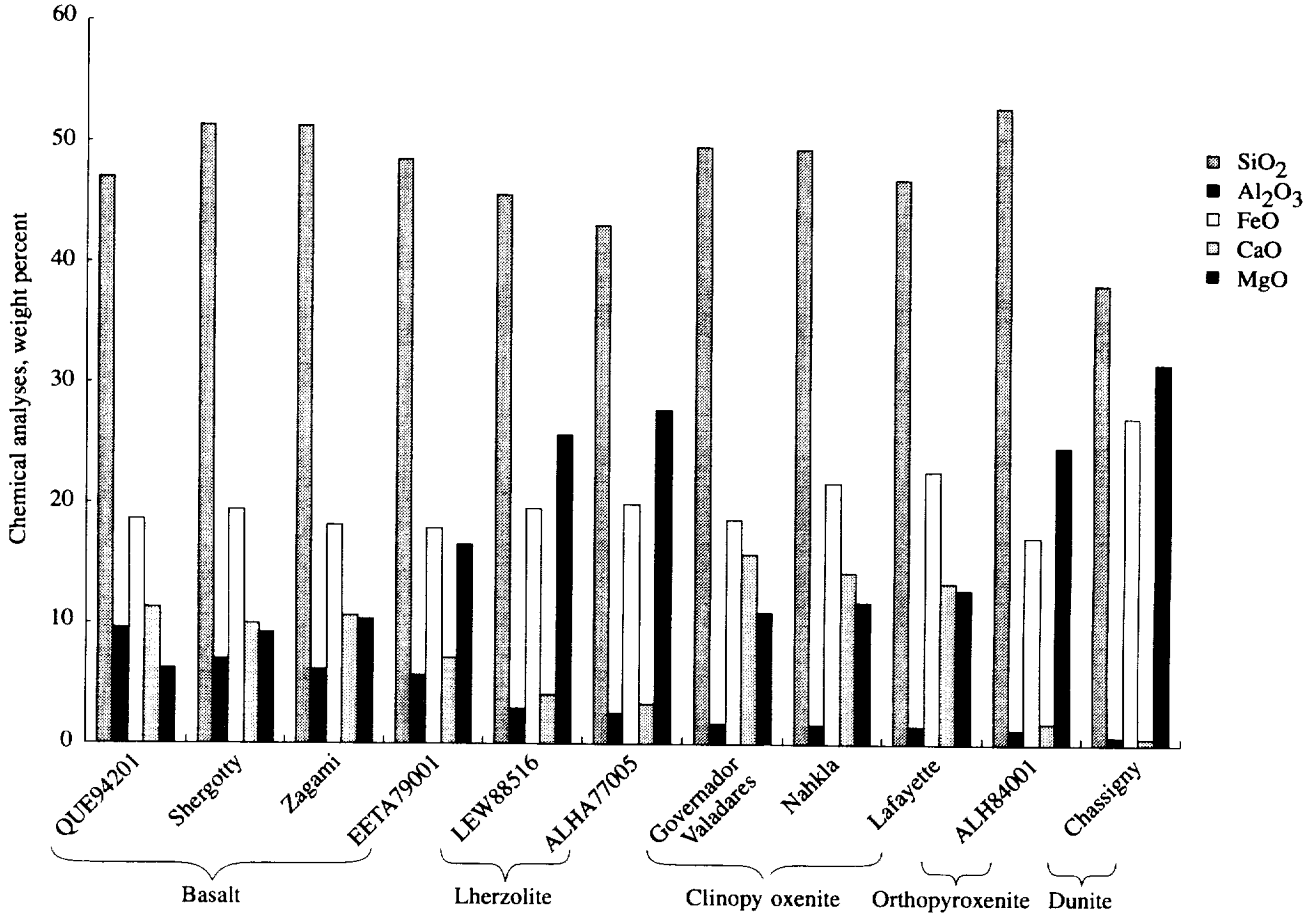

Figure 2. Chemical analyses of five most abundant chemical components of Martian meteorites.

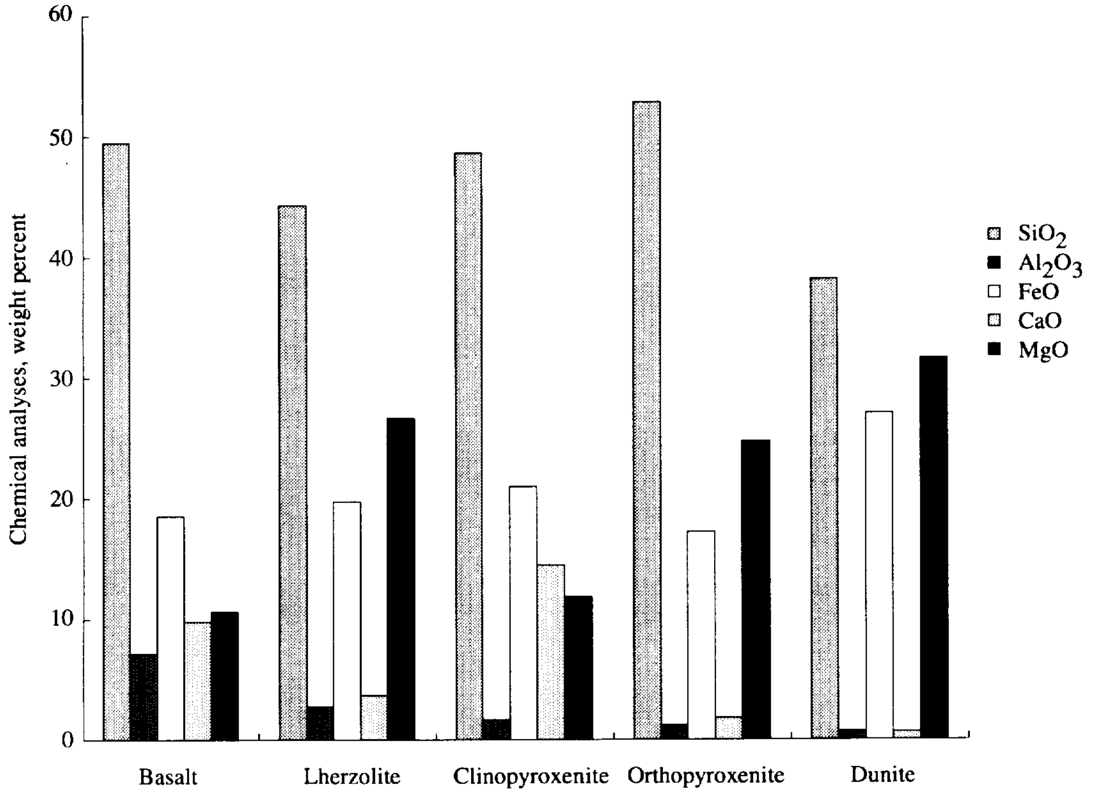

Figure 3. Average weight percent of chemical analyses of Martian meteorite groups.

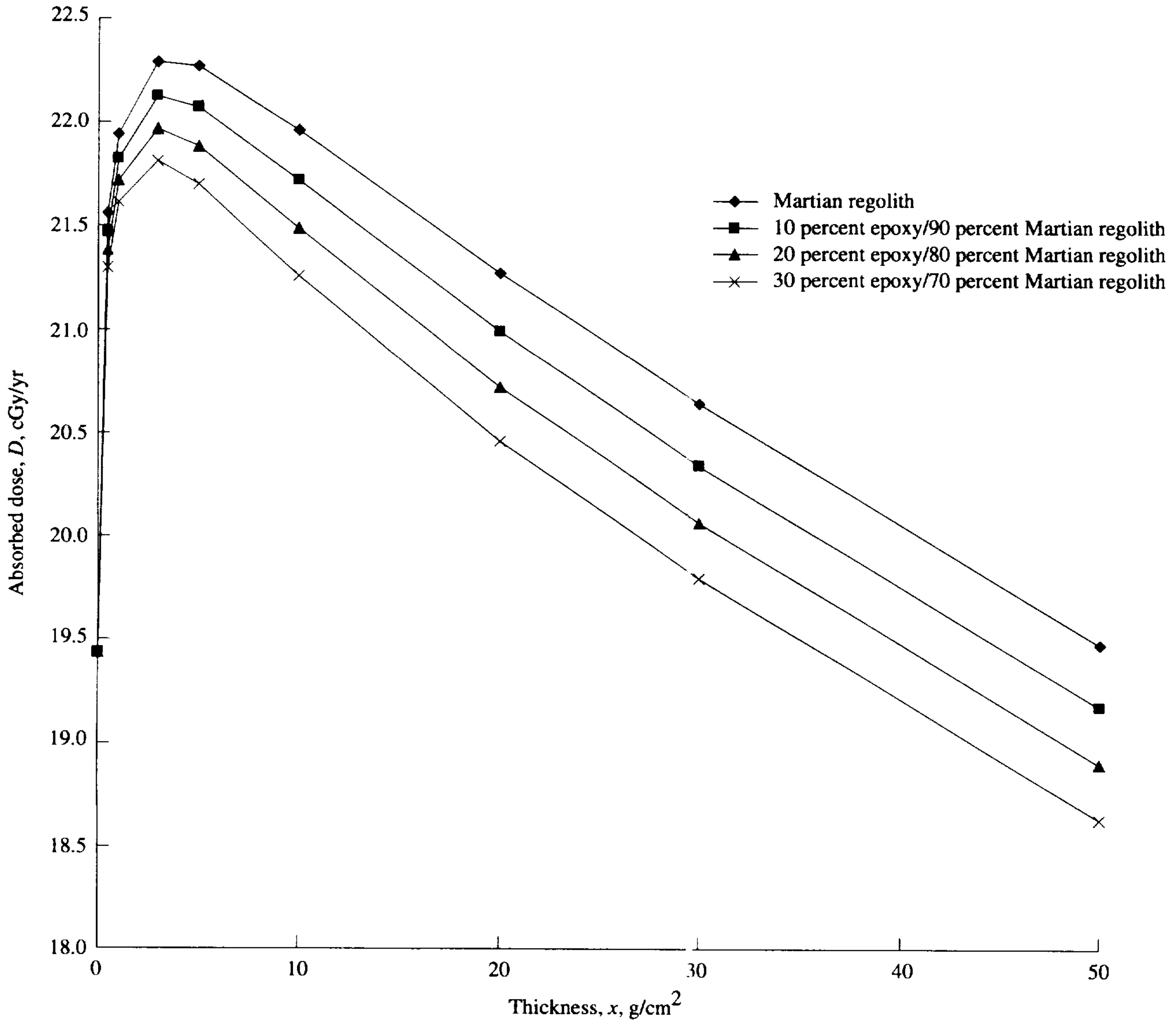

Figure 4. Annual dose behind Martian regolith and composites of Martian regolith by varying weight fractions of epoxy for thicknesses up to 50 g/cm^2.

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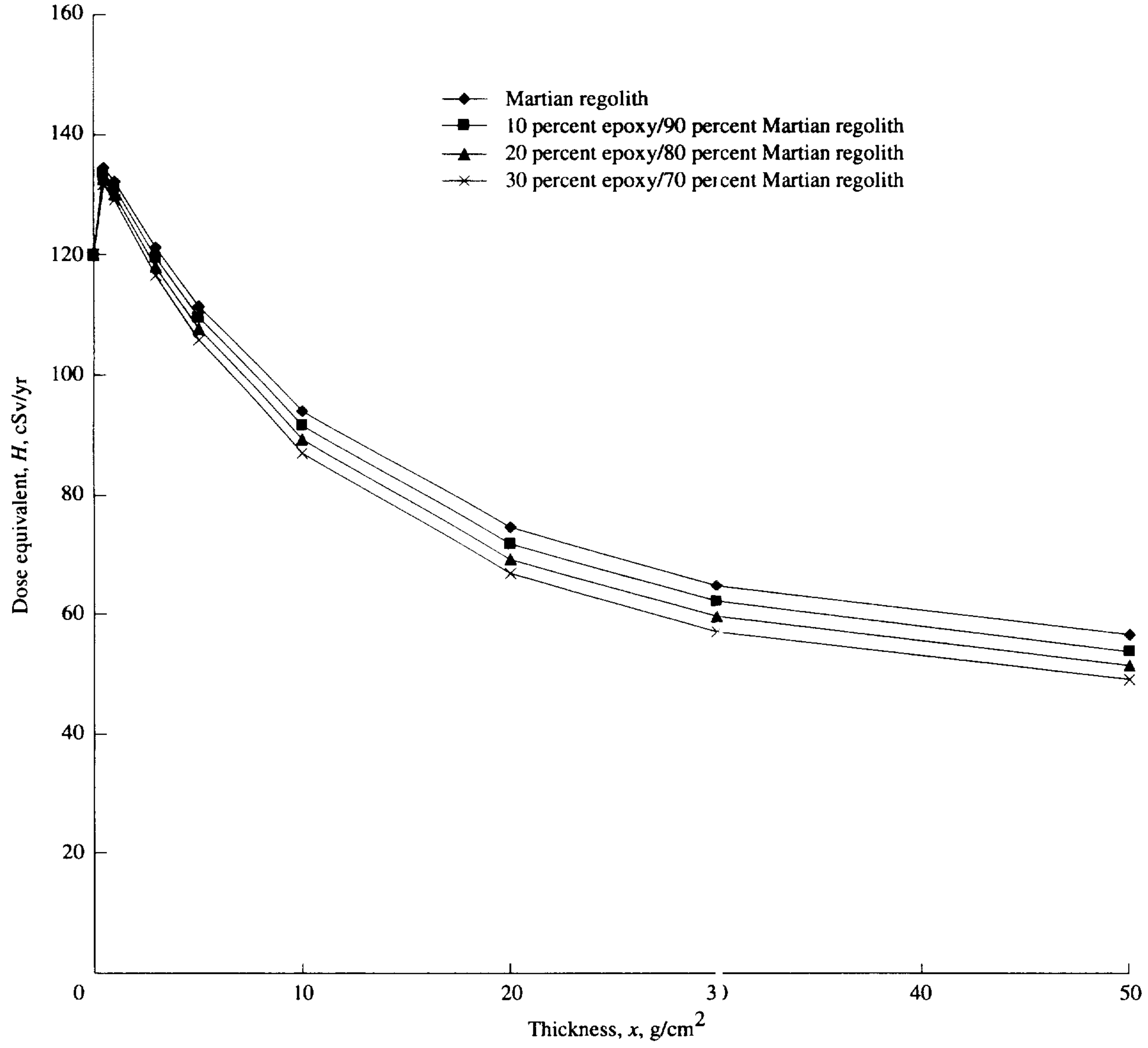

Figure 5. Annual dose equivalent behind Martian regolith and composites of Martian regolith by varying weight fractions of epoxy for thicknesses up to 50 g/cm^2.