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MASS ATTENUATION COEFFICIENT OF MARS SAMPLES OVER 1 KEV - 100 GEV ENERGY RANGE

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ABSTRACT

This work presents the calculation of the mass attenuation coefficient (μ) of Martian rocks and soils, in function of the energy, based on the knowledge of their chemical compositions. The samples were analyzed by *Viking 1*, *Viking 2* and *Mars Pathfinder* missions, all of them sent to different places at the planet Mars, in different times. The WinXCOM software was employed to determine the μ values for the samples in the range from 1 keV to 100 GeV. The obtained values were practically the same for energies larger than 100 keV, but marked differences among the samples were observed for energies below 25 keV, which is the energy range of interest for the XRF system used in space probes. These μ data calculated for several energies of Martian soils and rocks will also be useful in calculations or modeling related to new missions sent to Mars.

Keywords: Mars, rocks, soils, mass attenuation coefficient.

INTRODUCTION

More and more space missions are using equipments for *in situ* measurements of physical and chemical properties of rocks and soils of spatial objects surfaces, like natural satellites, asteroids and planets, for example. In 1967 and 1968, the first North American unmanned

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Abstract

This work presents the calculation of the mass attenuation coefficient (μ) of Martian rocks and soils, in function of the energy, based on the knowledge of their chemical compositions. The samples were analyzed by *Viking 1*, *Viking 2* and *Mars Pathfinder* missions, all of them sent to different places at the planet Mars, in different times. The WinXCOM software was employed to determine the μ values for the samples in the range from 1 keV to 100 GeV. The obtained values were practically the same for energies larger than 100 keV, but marked differences among the samples were observed for energies below 25 keV, which is the energy range of interest for the XRF system used in space probes. These μ data calculated for several energies of Martian soils and rocks will also be useful in calculations or modeling related to new missions sent to Mars.

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INTRODUCTION

More and more space missions are using equipments for *in situ* measurements of physical and chemical properties of rocks and soils of spatial objects surfaces, like natural satellites, asteroids and planets, for example. In 1967 and 1968, the first North American unmanned missions, forwarded to the Moon (Turkevich et al., 1969; Franzgrote et al., 1970) an equipment with alpha particles backscattering technique was employed to determine the chemical composition of samples of the lunar surface. The same kind of equipment was also used in the missions sent to Mars in 1976, called *Viking 1* and *Viking 2* missions, which analyzed surface samples in two different localities of the planet, *Chryse Planitia* (or *The Plains of Gold*) and *Utopia Planitia*, respectively (Massambani and Mantovani, 1997). Such technique had its efficiency proven in studies with terrestrial rocks of well-known chemical compositions (Economou et al., 1970).

Later, a new apparatus, the Alpha Proton X-ray Spectrometer (APXS), with a more sophisticated technique for the determination of chemical compositions, was created. The APXS can detect almost all the elements in the periodic table, with the exception of hydrogen and helium. It uses the X-ray fluorescence and the alpha and proton particles backscattering together. The equipment was sent to Mars in the year of 1997, in a mission called *Mars Pathfinder*, and obtained new data on the chemical composition of soils and rocks samples of the Martian surface in *Ares Vallis* (Economou, 2001).

Considering that the information of the mass attenuation coefficients (μ) of samples is important in a wide range of energy for the considered nuclear methodologies, this work aimed the calculation of this coefficient with the WinXCOM software, based on the knowledge of the chemical compositions of Martian soils and rocks, for energies in the range from 1 keV to 100 GeV. These μ data calculated for several energies of Martian soils and rocks will also be useful in calculations or modeling related to new missions sent to Mars. The evolution of the chemical composition determination techniques, alpha backscattering and APXS, is mentioned in this work too.

THEORY

The mass attenuation coefficient μ , whose unit is cm^2/g , is defined by the equation of the exponential absorption that characterizes the passage of a parallel beam of electromagnetic radiation through the matter, known as the Law of Lambert–Beer given by:

$$I = I_0 e^{-\mu x} \quad (1)$$

where x represents the material thickness used as sample, μ the of mass attenuation coefficient, ρ the physical density of the sample, I_0 the incident beam intensity in the sample and I the emergent beam intensity of the sample.

The dependence of μ with the atomic properties of the samples is given by the following relationship:

$$\mu = \sigma_{tot} (Z N_A / A) \quad (2)$$

where Z is the atomic number, N_A the Avogadro's number, A the atomic mass of the sample and σ_{tot} the sum of the cross-sections' contributions of the radiation photon interactions with the matter.

The sum of the cross-sections of the principal processes is given by (Hubbell, 1982)

$$\sigma_{tot} = \sigma_P + \sigma_R + \sigma_C + \sigma_{P_p} \quad (3)$$

where the indexes P , R , C and P_p designate the photoelectric effect, Rayleigh and Compton scattering, pair production, respectively.

CALCULATION

Calculations of the mass attenuation coefficients of several samples were carried out by the WinXCOM program (Gerward et al., 2001). The software can generate cross-sections and attenuation coefficients for elements, compounds or mixtures in the energy range between 1 keV and 100 GeV, in the form of total cross-sections and attenuation coefficients as well as partial cross-sections of the following processes: incoherent scattering, coherent scattering, photoelectric absorption, and pair production in the field of the atomic nucleus and in the field of the atomic electrons. For compounds, the quantities tabulated are the partial and total mass interaction coefficients.

The program possesses a comprehensive database for all elements over a wide range of energies, constructed through the combination of incoherent and coherent scattering cross-sections from Hubbell et al. (1977) and Hubbell et al. (1980), photoelectric absorption from Scofield (1973), and pair production cross-sections from Hubbell et al. (1980). The same cross-sections were used as in other recent tabulations of Hubbell (1977), Hubbell et al. (1980), Hubbell (1982) and Hubbell and Seltzer (1995).

The mass attenuation coefficients of 16 Mars samples i.e., three samples analyzed by the *Viking 1* mission, one sample by the *Viking 2* mission (Massambani and Mantovani, 1997) and 12 samples by the *Mars Pathfinder* mission (Economou, 2001) were calculated by the Win XCOM code.

EXPERIMENTAL

Table 1 presents the chemical compositions of samples analyzed by the *Viking 1* and *Viking 2* missions.

Table 1. Chemical compositions of four samples analyzed by the *Viking 1* and *Viking 2* missions (Massambani and Mantovani, 1997).

Chem. Comp.	<i>Viking 1-A</i>	<i>Viking 1-B</i>	<i>Viking 1-C</i>	<i>Viking 2</i>
Mg	5.0	5.2		
Al	3.0		2.9	
Si	20.9	20.8	20.5	30.0
S	3.1	3.8	3.8	2.6
Cl	0.7	0.8	0.9	0.6
K	<0.25			
Ca	4.0	3.8		3.6
Ti	0.5			0.61
Fe	12.7	12.6	13.1	14.2
O	50	49.7		50.4

The alpha particle scattering technique used by the *Viking 1* and *Viking 2* missions, employed a ^{242}Cm source of 6.11 MeV, silicon detectors and appropriate electronics, as described in Paterson et al. (1965). APXS used in the *Mars Pathfinder* mission employed a ^{244}Cm source, which emits a monochromatic beam of 5.8 MeV alpha particles. The principles of the APXS technique can be found in full detail in Economou et al. (1970).

Table 2 presents the chemical compositions of samples analyzed by the *Mars Pathfinder* mission, respectively. The data are expressed in the form of oxides percentage.

Table 2. Chemical compositions (in oxides), of samples analyzed by the *Mars Pathfinder* mission (Economou, 2001).

Chem. Comp.	Soil A-2	Soil A-4	Soil A-5	Soil A-8	Soil A-9	Soil A-10	Soil A-15
Na ₂ O	3.1	3.1	3.8	2.4	2.3	2.5	2.9
MgO	10.3	9.5	8.4	7.6	7.7	8.8	8.0
Al ₂ O ₃	10.0	10.2	10.0	10.2	9.9	9.4	9.6
SiO ₂	40.9	40.9	40.5	45.4	41.9	41.0	43.1
P ₂ O ₅	0.9	1.1	0.5	0.5	0.7	0.6	0.5
SO ₃	6.0	7.0	5.7	5.6	6.7	6.4	5.3
Cl	0.7	0.8	0.8	0.9	1.3	0.9	0.8
K ₂ O	0.5	0.5	0.5	0.9	0.7	0.4	0.7
CaO	6.1	5.6	6.1	7.1	6.5	6.0	5.6
TiO ₂	0.8	1.3	0.7	0.9	1.1	1.0	1.0
Cr ₂ O ₃	0.3	0.4	0.5	0.1	0.2	0.3	0.3
MnO	0.5	0.4	0.2	0.3	0.1	0.4	0.3
FeO	20.0	19.2	22.2	18.2	21.0	22.4	21.9
Chem. Comp.	Rock A-3	Rock A-7	Rock A-16	Rock A-17	Rock A-18		
Na ₂ O	3.4	3.6	4.3	2.5	4.3		
MgO	2.5	6.2	4.8	4.6	4.0		
Al ₂ O ₃	12.2	10.9	11.0	10.3	11.7		
SiO ₂	53.5	47.2	47.5	53.8	49.2		
P ₂ O ₅	0.7	0.5	0.5	0.4	0.5		
SO ₃	2.0	4.5	3.0	1.7	3.0		
Cl	0.5	0.9	0.7	0.5	0.7		
K ₂ O	1.2	0.8	0.8	0.9	1.0		
CaO	5.7	6.6	6.9	7.7	5.9		
TiO ₂	0.7	0.9	0.9	0.7	0.9		
Cr ₂ O ₃	0.1	0.1	0.0	0.1	0.1		
MnO	0.4	0.4	0.3	0.4	0.4		
FeO	17.3	17.8	19.3	16.5	18.5		

RESULTS

Figure 1 presents the behavior of the mass attenuation coefficient (cm^2/g) versus energy (keV) showing the partial contributions of the effects Compton, coherent, photoelectric and pair production for the soil sample A-5 of Mars. The Compton effect is dominant from E4120 keV to approximately 9 MeV, showing that, in this energy range the Compton scattering, which is directly proportional to Z , can be used for the direct measuring of the density of the material or of the average atomic number.

Table 3 gives the values of μ for the energies 1, 10, 100 keV, 1, 100MeV, 1 and 100GeV. Figure 2 presents the graph of μ (cm^2/g) versus energy (keV) for four samples of the *Viking 1* and *Viking 2* missions, in the energy interval between 10 and 50 keV.

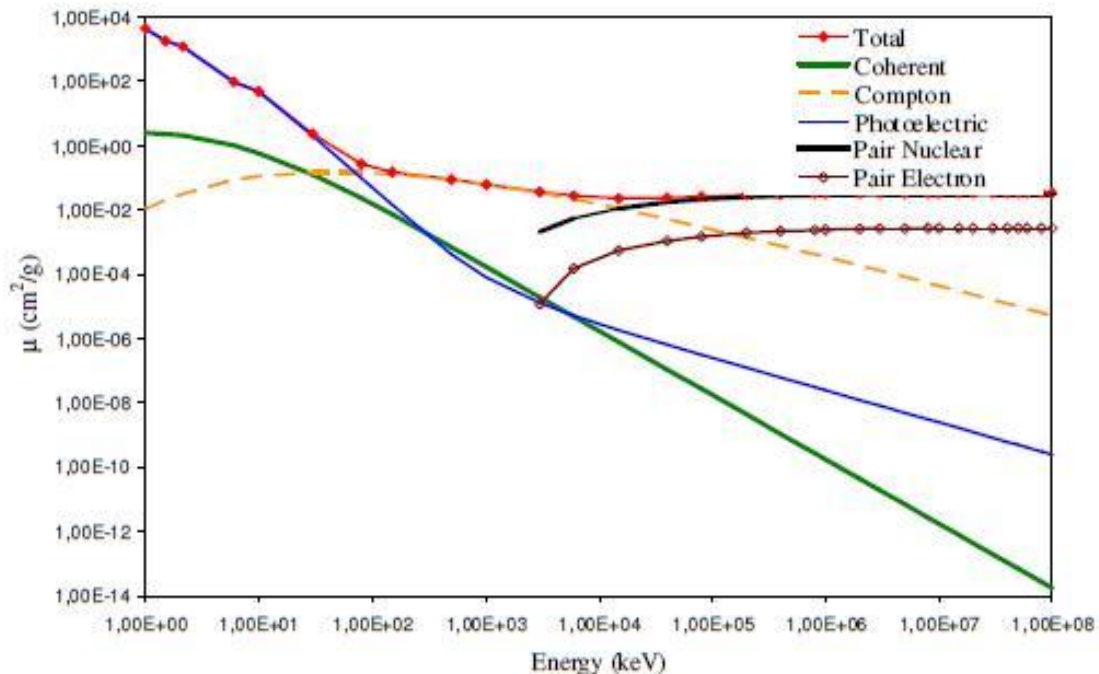


Figure 1. Total mass attenuation coefficient total and the individual contributions of the processes of radiation interaction with the matter versus energy, for Mars Pat. A-5 sample.

Figure 3 shows the mass attenuation coefficients of four samples analyzed by the *Pathfinder* mission in the energy interval between 10 and 50 keV, in a graph of μ (cm^2/g) versus energy (keV). In this graphic, only curves for the larger and smaller μ samples and two intermediaries are presented to facilitate visualization.

Finally, Figure 4 shows data for the mass attenuation coefficients of samples versus energy for 6 samples analyzed by *Viking 1* and *Viking 2* and *Mars Pathfinder* missions (and two techniques, alpha particles backscattering and APXS), in the range from 10 to 65 keV. In Figure 5 the same graph can be visualized, in the range from 10 to 25 keV, where it is possible to have a better differentiation between the samples.

Calculations were accomplished taking into account the experimental deviations in the chemical compositions presented by the studies of the literature (Turkevich et al., 1969; Franzgrote et al., 1970; Paterson et al., 1969). However, these deviations did not influence significantly the values of μ , once the spread of μ deviations were typically in the interval between 0.2% and 0.9%.

The mass attenuation coefficients calculated were highly similar to each other comparing the *Vikings* mission results. However, Table 3 shows that this similarity does not prevail when data of μ for the *Viking 1* and *Viking 2* missions are compared with the data for the *Mars Pathfinder* mission. The differences found can be explained by the improvement in the technique for the determination of the chemical composition of samples

used by the *Mars Pathfinder* mission (APXS), in relation to the alpha particles scattering technique used by the *Viking 1* and *Viking 2* missions, or, yet, by real differences in the chemical compositions of the soils analyzed by the three missions.

Table 3. Values of μ for the energies of 10 keV, 100 keV, 1 MeV, 100 MeV, 1 GeV and 100 GeV.

Samples	μ (cm ² /g)						
	1 keV	10 keV	100 keV	1 MeV	100 MeV	1 GeV	100 GeV
<i>Viking 1-A</i>	4181.495	39.95645	0.19632	0.06307	0.02510	0.03030	0.03185
<i>Viking 1-B</i>	4240.175	39.83447	0.19646	0.06315	0.02504	0.03021	0.03177
<i>Viking 1-C</i>	4039.236	78.84999	0.24463	0.06225	0.03281	0.04000	0.04203
<i>Viking 2</i>	4279.447	42.23796	0.19943	0.06312	0.02552	0.03083	0.03241
<i>Mars Pat.A-2</i>	4173.813	46.10381	0.20389	0.06281	0.02617	0.03163	0.03325
<i>Mars Pat A-4</i>	4148.842	45.30595	0.20276	0.06281	0.02605	0.03149	0.03311
<i>Mars Pat A-5</i>	4277.645	48.54769	0.20717	0.06274	0.02649	0.03205	0.03368
<i>Mars Pat A-8</i>	4120.306	44.60879	0.20176	0.06289	0.02603	0.03146	0.03307
<i>Mars Pat A-9</i>	4252.377	47.62878	0.20583	0.06280	0.02642	0.03196	0.03359
<i>Mars Pat A-10</i>	4313.219	48.96156	0.20775	0.06276	0.02656	0.03213	0.03377
<i>Mars Pat A-15</i>	4275.854	48.17412	0.20669	0.06277	0.02645	0.03199	0.03362
<i>Mars Pat A-3</i>	4055.612	42.78205	0.19938	0.06289	0.02574	0.03109	0.03269
<i>Mars Pat A-7</i>	4077.499	43.79681	0.20067	0.06287	0.02589	0.03129	0.03290
<i>Mars Pat A-16</i>	4144.801	45.45740	0.20292	0.06283	0.02611	0.03156	0.03318
<i>Mars Pat A-17</i>	4048.341	42.72681	0.19928	0.06295	0.02578	0.03115	0.03275
<i>Mars Pat A-18</i>	4100.688	44.28025	0.20135	0.06283	0.02593	0.03134	0.03295

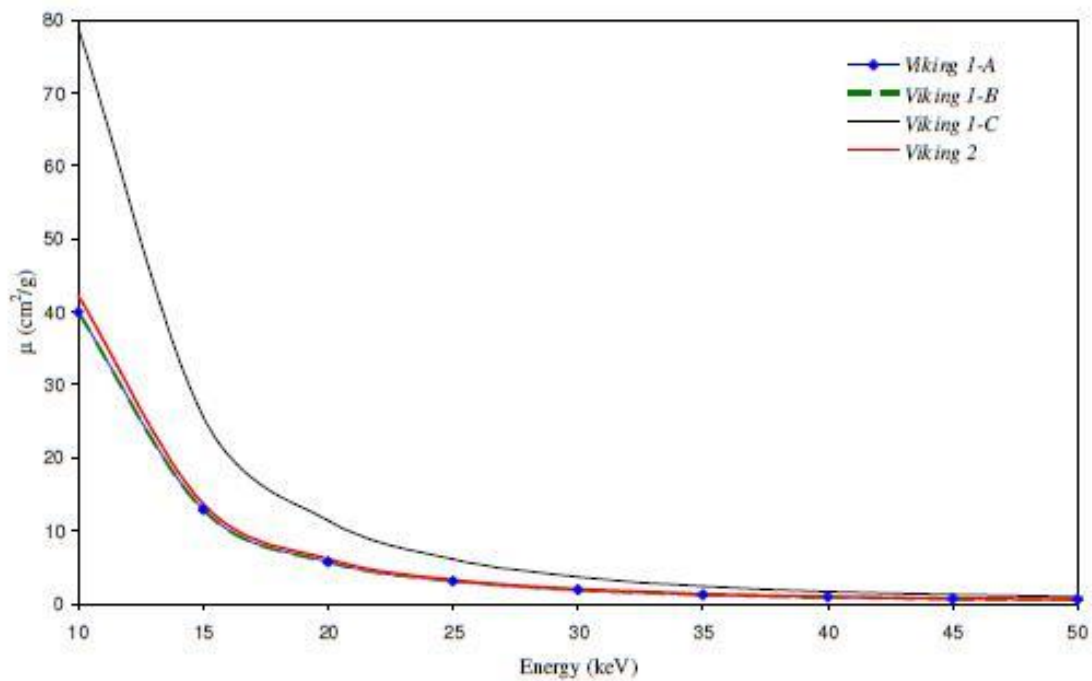


Figure 2. Mass attenuation coefficient versus energy for four samples analyzed by the *Viking* 1 and 2 missions, at 10 to 50 keV energy range.

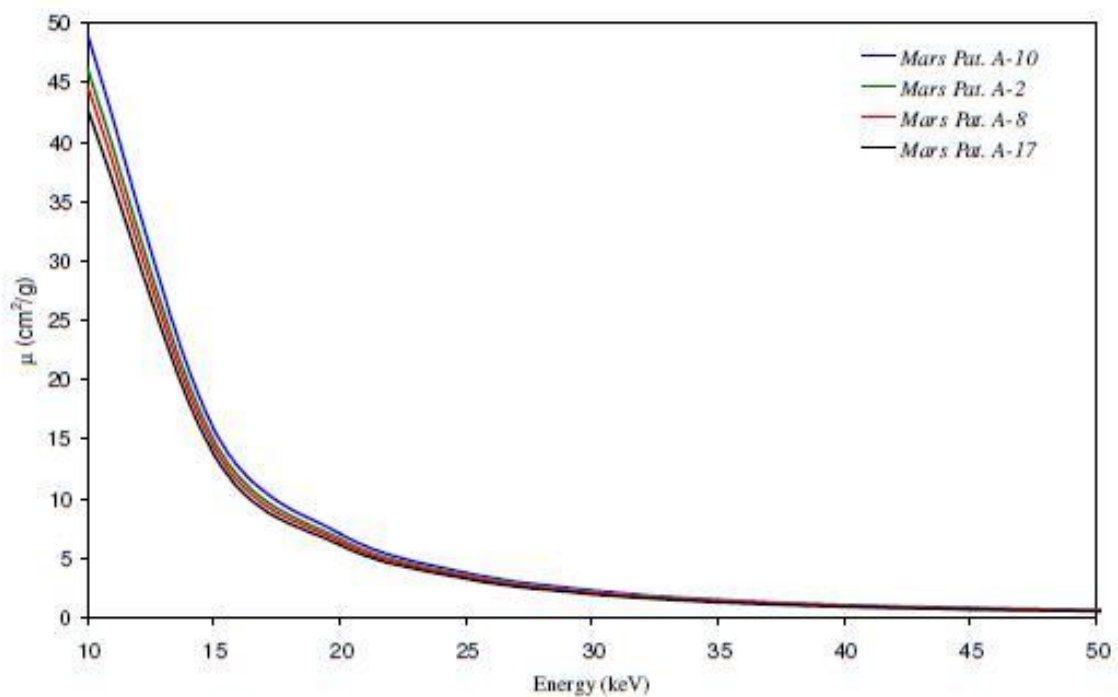


Figure 3. Mass attenuation coefficient versus energy for four samples analyzed by the *Mars Pathfinder* mission, at 10 to 50 keV energy range.

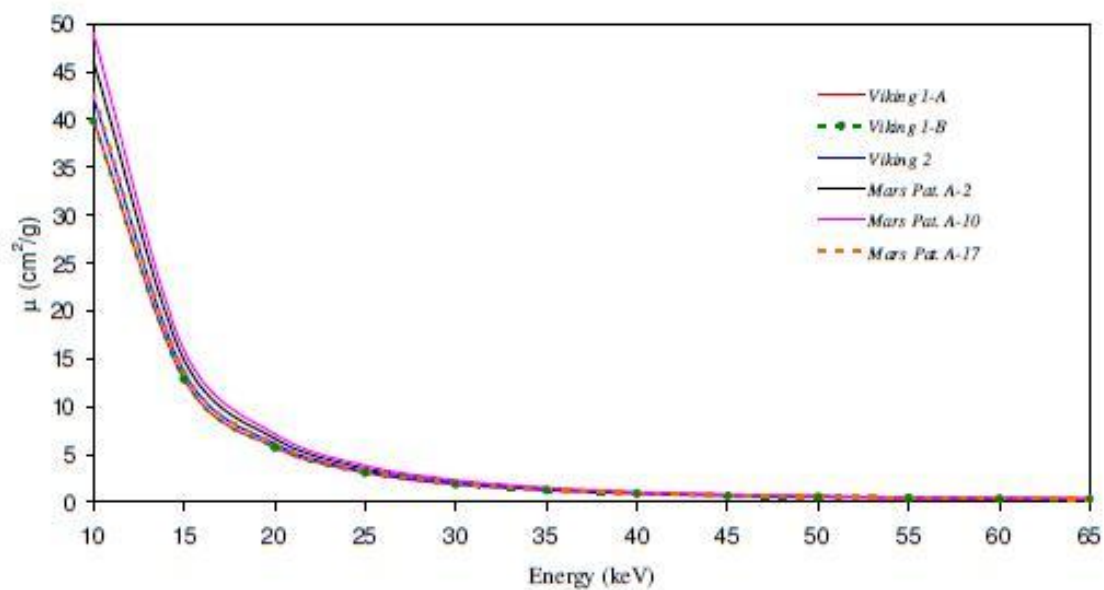


Figure 4. Mass attenuation coefficient versus energy for the Mars surfaces, at 10 to 65 keV energy range, analyzed by the three missions.

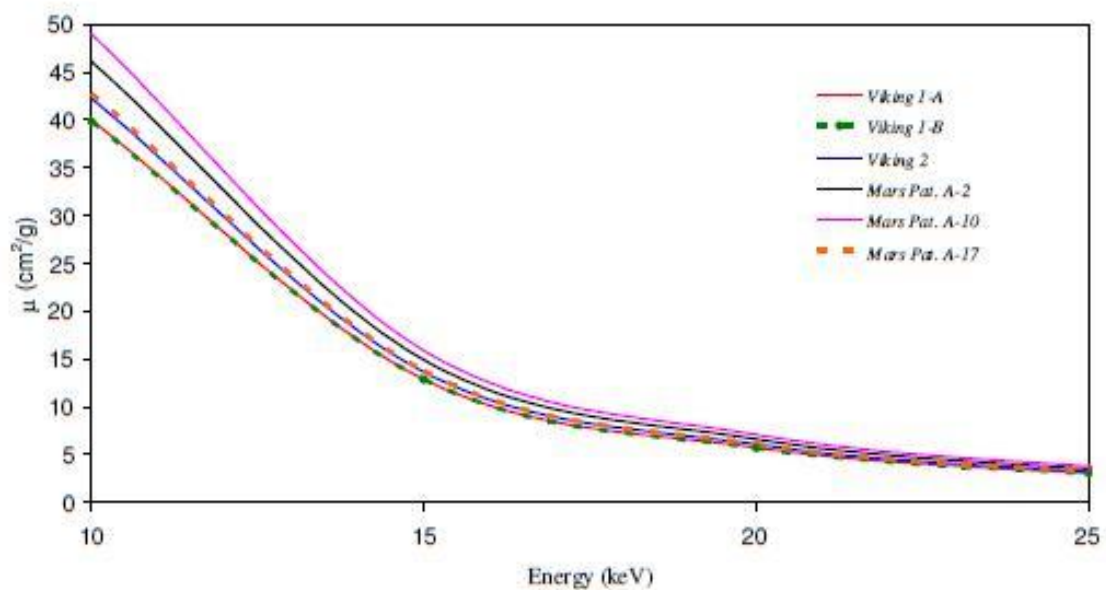


Figure 5. Mass attenuation coefficient versus energy for the Mars surfaces, at 10 to 25 keV energy range.

The graph in Figure 2 shows the difference between the results of μ for the *Viking 1-C* sample in relation to the other samples. The lack of some chemical elements data for the sample, as shown in Table 1, could have caused such difference. When the data for

chemical composition are inserted in the WinXCOM program, the sum of the element percentages should be equal to 1, however, it did not happen for sample 1-C, as can be seen at Table 1. In this case, the program normalizes the distribution of the percentages of the elements automatically. Due to this normalization, the program generates, for some elements, a larger concentration, resulting in different values of m . For example, in the case of the *Viking 1-C* sample, Al concentration instead of 2.9%, turned to be 7%, and Si concentration instead of 20.5%, turned to be 49.7%.

On the Table 1, some values of *Viking 1-B*, *Viking 1-C* and *Viking 2* samples chemical composition don't appear. These data were not determined by the system, probably due to operational conditions on martian surface.

Figure 5 and Table 3 show that the values of μ calculated for the samples were also similar for energies greater than 25 keV (excepting *Viking 1-C* sample). Although the differences among the values of μ at low energies are not large, they clearly reflect the differences in their chemical compositions.

More calculations and analysis made on a group of Earth and Moon surface samples, using the techniques cited above, can be find in Moreira & Appoloni (2006).

CONCLUSION

The mass attenuation coefficients calculated for the Mars samples using the *Mars Pathfinder* mission data were highly similar to each other, as well as the coefficients calculated for the *Viking 1* and *2* missions, with exception for the *Viking 1-C* sample. But differences between the μ results were found when the APXS technique data was compared with the alpha particles scattering technique data.

The values of μ for energies larger than 50 keV, are practically the same, but present significant differences for energies smaller than 25 keV, which is exactly the energy range of operation of the X-ray fluorescence systems used in space probes for the study of chemical compositions of materials. This information must be taken into account in the measurements performed by this methodology, especially for the samples auto attenuation corrections.

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