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037356

FINAL REPORT

Assay of the Martian Regolith with Neutrons

Contract No: NASW-5030

Submitted to

NASA Center for Aerospace Information (CASI)
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Dated: 28 October 1998

Table of Contents

FINAL REPORT FOR NASA CONTRACT NASW-5030
"ASSAY OF THE MARTIAN REGOLITH WITH NEUTRONS"

I INTRODUCTION

The PIDDP proposal concerns the study of neutron counters as they might be used in the search for water on Mars. We proposed to use several detectors in a demonstration experiment that would show the relation of the shape of the neutron flux to water content and compare the results with Monte Carlo calculations. The first section of this report develops a simple analytic model that shows how the amplitude of the epithermal neutron flux changes as a function of water content of a Martian-like soil. We then give a short description of the three demonstration experiments used in this study. The results of the 3rd experiment and calculations are presented next and various detectors discussed. Finally we include some aspects of these experiments that were not mentioned in the proposal.

II CHRONOLOGY

When the proposal was written, it was planned that the experimental work would be done at the Ion Beam Facility of the Los Alamos National Laboratory (LANL). All the necessary equipment, neutron sources, electronics, and space, were available. During the review process this facility was closed and access denied due to tritium contamination. We contacted the nuclear engineering department at the University of New Mexico (UNM) in Albuquerque and were allowed to do the experiments during their vacation times. Two experiments were done there. The first was a trial run to check the technique and determine counting rates. The neutron source was a standard plutonium-beryllium mixture that makes neutrons through the reaction, $^9Be + alpha \Rightarrow {}^{12}C + n$. The spectrum shape was taken from Anderson (1).

Approximately 450 pounds of soil filled a rectangular container that was ten inches deep and 36 inches on a side. This container was suspended five feet from the floor by a forklift. Three pairs of ^{3}He neutron proportional counters were used for these tests. One of the two identical counters of each pair was covered with a 0.015-inch layer of cadmium. The three sets differed in size and pressure of the ^{3}H gas. The large pair, filled with ten atmospheres of ^{3}He, had diameters of two inches and was ten inches long. The second set filled with four atmospheres of ^{3}H had diameters of one inch and were eight inches long. The small pair, filled with ten atmospheres of ^{3}H, had diameters of 0.5 inches and was four inches long.

For the second UNM experiment we had three rectangular containers, each with about 150 pounds of soil, stacked in such a way that sheets of polyethylene could be inserted between them. A computer generated figure of the arrangement showing the model used in the Monte Carlo calculations is shown in Figure 1.This arrangement was supported five feet above the floor by poles at each corner. The floor was covered with blocks of borated polyethylene to minimize neutron return. In addition to simulating water by various arrangements of the polyethylene sheets (up to 1/2 inch thick) we added water to one of the three containers in amounts equivalent to 1.96, 3.86, 5.6, 7.4 and 16.7 weight percent. This tray could be positioned either as the top tray or the middle tray. A total of about 100 different measurements were made using different combinations of, plastic sheets, water concentrations and counters. Analyses of these data proved perplexing in that the computed counting rates were two to three times lower than the experimental ones.

In trying to resolve this discrepancy we again checked the elemental composition of the soil at LANL and for verification at commercial company, Huffman Laboratories, Inc, of Boulder Colorado. The results of the two analyses are shown in Table 1 and are in very good agreement (except possibly for water content as reflected in LOI). Because the neutron spectra are so sensitive to water content and the difference in LOI's was about 0.6%, we asked both laboratories how LOI was measured. It turns out to be the weight lost while the sample is heated to a specified temperature and as such represents a gross measurement of free water. LANL uses 1000 C while Huffman uses 750 C. The measure of LOI also depends upon the relative humidity. Reasonable changes in the soil composition had little effect on the factor 2-3 discrepancy between calculations and measurements. We then made extensive calculations to see if room return could account for the extra counting rate. Although the experimental hall was large, the floor, walls and ceiling were of concrete and the calculations showed that room return could be the cause the large counting rate. We therefor designed a third experiment.

The third experiment was carried out near the LAMPF experimental area at LANL. The neutron source in this case was ^{252}Cf. A comparison of the neutron spectra of these sources is shown in Figure 2 along with the spectrum used as the input for the Monte Carlo calculation. The shape of the ^{252}Cf source spectrum is clearly a better match to the model. The soil was replaced by 1984 pounds of solid glass blocks. This arrangement was not within a building but was located outside in open air with the blocks of glass centered about 45 inches above the ground. An area of ground (10 by 10 feet) was covered with two-inch thick borated polyethylene sheets. Layers of polyethylene inserted between layers of blocks again simulated water content. Elemental concentrations of the glass blocks are shown in Table 2. The macroscopic down scattering of neutrons for the blocks is almost the same as for the assumed Martian soil used in calculations for Martian neutron leakage. This arrangement eliminated any room return neutrons and the polyethylene inserts gave a good measure of hydrogen content independent of humidity or uncertainties concerning the amount of water in the soil used before.

III ANALYTIC ESTIMATE OF EPITHERMAL NEUTRON FLUX IN MARTIAN SOIL AS A FUNCTION OF WATER CONTENT

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The amplitude of the epithermal portion of a moderating neutron spectrum in a Martian-like soil depends upon the initial neutron production rate and how fast the neutrons lose energy. Neutrons are produced by cosmic-ray interactions with the Martian soil at the rate of about 15 neutrons per incident proton. At high energies (>1 MeV) most energy is lost by inelastic collisions in which the struck nucleus is left in an excited state. Below about 0.1 MeV energy is lost by elastic collisions. The rate of energy loss depends on the probability of a nuclear collision, $n_i*\sigma_i$, where n_i is the number of nuclei of element i σ_i is its elastic cross section, and a parameter, ξ, which is a measure of energy lost per collision. For hydrogen atoms, the value of this parameter is 1 for other nuclei it is approximated by 2/A. The expression for the epithermal amplitude of the neutron flux in an infinite medium is (2)

$$\varphi=Q/\Sigma\,(n_i*\sigma_i*\xi_i), \qquad \text{Eq. 1}$$

Where Q is the neutron source. In this section we derive an analytic expression that describes how the epithermal amplitude changes as a function of water content. Differentiation of Eq. 1 with respect to the hydrogen number density gives

$$d\varphi/\varphi = -(dn/n)*n*\sigma*\xi/\Sigma\,(n_i*\sigma_i*\xi_i) \qquad \text{Eq. 2}$$

where the unsubscripted variables refer to hydrogen. The minus sign means a loss in energy. Similar expressions apply to the other elements. Table 1 displays the elemental composition of the assumed Martian soil. Also shown are the elastic cross-sections for the epithermal region. Using Eq. 2, we have computed the fractional change in the epithermal neutron flux as a function of water concentration and compared to a second calculation in which we used the Monte Carlo code of LCS(3) to compute the epithermal flux for the same region of water concentrations.

Figure 3 shows the comparison of the amplitudes of the epithermal neutrons of the Monte Carlo calculation and those of Equation. 1. It is clear that, to a good approximation, the analytic expression and the Monte Carlo method give the same answers.

One can use Equation 1 for estimates of counters on penetrators, but not for surface counters. Neutron leakage from the surface tends to change the neutron spectrum shape during moderation.

For the most part hydrogen and oxygen are the two elements that determine the epithermal amplitude. Figure 4 is a plot of $n*\sigma*\xi/\Sigma\ (n_i*\sigma_i*\xi_i)$, which is essentially the moderating power of an element, for oxygen and hydrogen as a function of water content. About 85% of the moderation is done by oxygen for dry soil. When water content reaches 0.5% hydrogen and oxygen moderation are equal.

IV DEMONSTRATION EXPERIMENTS

A MEASUREMENT OF FAST NEUTRON WITH A 238 ION CHAMBER

We have investigated the feasibility of using a ^{238}U fission chamber to detect fast neutrons in a Martian like neutron environment. Such a counter has good characteristics for counting fast neutrons. It is insensitive to gamma rays and has a neutron induced fission threshold at about 1 MeV. These counters are frequently used as beam monitors at facilities that use fast neutrons in their experiments.

Other detectors that could be considered to be selective in measuring fast neutrons are primarily scintillation counters. Most of these are not insensitive to gamma rays and have the additional disadvantage that they require complex electronics.

The detector we used in this investigation contained 130 mg of ^{238}U deposited over a circular area of diameter 4 inches. The isotopic composition of natural uranium is 99.28% ^{238}U, 0.71% ^{235}U, and smaller amounts of ^{234}U and ^{233}U. Because ^{235}U has a very large thermal fission cross-section, the deposit must be highly depleted.

Before using the counter to detect fast neutrons from the californium source, we verified the mass of the deposit by counting the emitted alpha particles. Also, to check the rather old counter we took a fission spectrum with the source nearby. Figure 5 shows this spectrum. The counter was then placed on the moderating glass cube, which at that time had a one half-inch layer of polyethylene directly over the neutron source. Spectra were taken with and without the source in place. Figure 6 shows both spectra normalized to 1000 seconds. It is clear that the spectra are approximately the same. The primary decay mode of ^{238}U is by alpha particle emission but it has a small decay branch (4.5*10-7) via spontaneous fission. The fission rates reflected in Figure 6 are due almost entirely to spontaneous fission of the deposit.

If the fast neutron flux on the Martian surface is considerably larger than that of the moderated Californium source, a ^{238}U fission chamber may still be viable as a fast neutron monitor. We have computed the fast neutron flux on the Martian surface using the LCS codes. The parameters for this model calculation were galactic cosmic proton flux of 2/s-cm^ 2, spectrum shape of Castagnoli and Lal, (4), and 1% water concentration in the Martian soil. The computed fission rate due to fast neutrons on the Martian surface is about 0.05/g-s while the spontaneous rate is 0.08/g-s. In addition, the fission rate on the surface due to cosmic protons that remain after passing through 15 g of atmosphere is about 0.06/g-s. Thus the fission rate from the fast neutrons we wish to measure is only 1/3 of the total signal

It appears from the above considerations that a ^{238}U fission chamber would not be a reasonable choice as a fast neutron monitor in the Martian environment.

B EFFICIENCY Of A "STANDARD" ^{3}He COUNTER

One of the counters we used in the demonstration experiments was one of the most popular that Reuter Stokes (5) sells. We have calculated the counting rates as a function of energy for a counter emmersed in an isotropic neutron flux of neutron flux of 1/cm^2. The counter was eight inches long, one-inch diameter, and was filled with four atmospheres of ^{3}He. We took account of end effects and did the calculations for three different thicknesses of cadmium surrounding the counter. The results are shown in Figure 7. It is clear from this figure that 0.010 inches of cadmium is sufficient to absorb all thermal neutrons while 0.005 inches is marginal. The rise in the curve for 0.005-inch cadmium is due to a decrease in the cadmium cross section below the resonance. Figure 8 shows the effect of a 0.015 inch cadmium cover for a typical ^{3}He counter. Although these counters are sensitive to gamma rays, their pulse heights fall below those caused by neutrons. The effect of gamma rays is shown in Figure 9 where ^{3}He spectra are displayed with and without a gamma-ray source nearby.

C. ^{6}Li GLASS NEUTRON COUNTER.

Another counter that is used frequently to measure neutrons is a ^{6}Li glass scintillator. The detecting reaction is ^{6}Li + n= ^{4}He +^{3}H. This scintillator contains about 6% enriched ^{6}Li in a special glass. The one we used was two-mm thick, five-cm diameter. The neutron counting rate for the arrangement of 1/2-inch polyethylene sheet on top of the cube was 1.5 times that of the eight inch ^{3}He proportional counter and about 5 times that of the four-inch counter. Figure 10 shows pulse height spectra for this counter with and without a cadmium cover. The ratio of peak counts no cad over cad is 2.4 while the computed ratio using MCNP was 2.6. These results imply that a rather small ^{6}Li glass-PMT assembly would be equivalent to ^{3}He counters. They would have about the same electronic complication.

D. EFFECT OF NEARBY HYDROGEN MATERIALS ON A NEUTRON COUNTER IN SAPCE

One complicating factor that occurs for neutron counters in space is the scattering of neutrons by nearby materials that make up the spacecraft. The most important materials are those that contain hydrogen. Since the neutron spectrum of the third demonstration experiment resembles the leakage spectrum of Mars, we decided to measure this effect using a block of polyethylene placed at different distances from the counter. We put piece of polyethylene, weighing 61 grams, at two different distances from a ^{3}He counter and measured the counting rate increase compared the same arrangement without the polyethylene. The fractional increase should be proportional to the mass divided by the distance squared. For the two distances we measured, the proportional constants were 0.36 and 0.38 cm^2/g when the mass is in grams and the distance is in centimeters.

$$\text{(Fractional increase)}=0.37*\text{mass}/R\^{}2 \qquad \text{Eq. 4.}$$

A similar test with an aluminum block gives a proportional constant of 0.0024 cm^2/g. Using these parameters, designers should be able to estimate how the spacecraft will effect the neutron counting rate.

V RESULTS OF THE THIRD DEMONSTRATION EXPERIMENT USING ^{3}He COUNTERS

This experiment used a ^{252}Cf fission-neutron source placed near the center of a cube of glass. The cube was made of 128 solid blocks supported on a stand that was about 3 feet above the ground. A chemical analysis of the elemental composition of the glass was supplied, and the relevant macroscopic nuclear parameters were very close to those of the Martian type soil described earlier. Water was simulated by inserting layers of polyethylene horizontally between layers of blocks. The ground beneath this arrangement was covered by a layer of borated-polyethylene to eliminate neutrons that otherwise might have scattered back to the experiment. Several different geometric arrangements of polyethylene and glass were used. Computed neutron spectra of two of the arrangements are shown in Figure 11. One is without polyethylene and the other was computed for 5/8 inch polyethylene sheet located about 10 inches below the top of the block where the counters were placed. Also shown in this figure are three spectra computed for the surface neutron leakage flux on Mars. Neither the calculations for the glass cube nor those for the Martian fluxes are arbitrarily normalized. The Martian calculations were done using LCS codes beginning with a cosmic ray flux of 2 protons/cm^2. This figure shows that the demonstration experiment produces similar spectra and magnitudes as one might expect to encounter on Mars.

In this section we present comparisons between calculations and the demonstration experiment for 3 out of 7 experimental arrangements.

1) With no polyethylene, The setup with no polyethylene is shown in Figure 12. This figure was drawn by the MCNP program as an aid to trouble shooting the geometry description. The counter was placed sequentially in the center and then offset by 7.5 inches. Two counters were used, each with and without a cadmium

cover. MCNP was then used to compute counting rates for each counter at 4 distances. Results of this operation are shown in Figures 13 and 14.

2) The same arrangement as 1) with a sheet of polyethylene 3 layers below the top of the glass cube. Results are in Figures 14 and 15

3) The same arrangement as 1) with a sheet of polyethylene 2 layers below the top of the glass cube. Results are in Figures 16 and 17

The other configurations of glass and polyethylene gave similar results. In general the computed counting rates agreed with the measurements within about 20%. The demonstration experiments show that neutron experiments in space could be modeled with reasonable confidence.

VI ^{6}Li-SILICON SANDWICH DETECTOR

We submitted a proposal in response to NASA's NRA-97-16-OSS-048 describing a neutron detector based on the principle of placing a thin layer of ^{6}Li fluoride between two silicon detectors. The text of this proposal is included in this report immediately after the tables.

VII SUMMARY

We have investigated several neutron counters that possibly could be used in space missions. They included lithium-glass scintillator, ^{3}He proportional counters, a ^{238}U fission ion chamber, and a ^{6}Li-silicon sandwich detector. We used a cadmium absorber to separate the thermal and epithermal portions of the moderated neutron spectrum. We replaced the proposed "Martian" soil by a large glass cube made of 128 glass bricks. This eliminated any uncertainties in the amount of hydrogen and increased the mass of the sample by about a factor of 4. Many Monte Carlo calculations were made to model the experiments, and in the right environment reasonable agreement with experiment was obtained. We derived a simple analytical model that allows one to compute the amplitude of the epithermal flux, and checked it against the Monte Carlo calculations.

References.

1) Anderson, M. E., and R. A. Neff, Neutron energy spectra of different size^{239}Pu-Be (α-n) sources, Nucl. Instru. Meth. 99, (1972).

2) Fermi, E., Nuclear Physics, notes compiled by J. Orear, A. H. Rosenfeld, and R. A. Schluter. University of Chicago Press, Chicago, Ill., 1950.

3) Prael, R. E., and H. Lichtenstein, User guide to LCS, The LAHET Code System, Rep.LA-UR_89_3013, 1989.

4) Castagnoli, G. C., and D. Lal, Solar modulation effects in terrestrial production of carbon-14, Radiocarbon, 22,1980.

5) Reuter Stokes, Inc. Twinsburg, OH 44087.

FIGURES

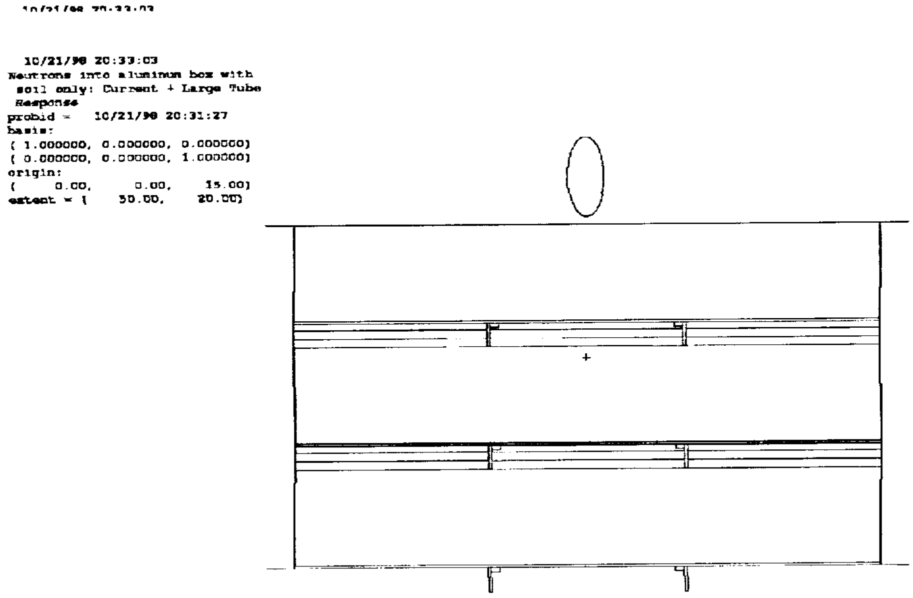


Figure 1. Computer drawing for the 2nd UNM experiment. Three trays are stacked vertically with space between them for polyethylene sheets. The scale is 5 to 2 horizontal to vertical. The width of the trays is about 36 inches. The ellipse on top represents the 3He counter

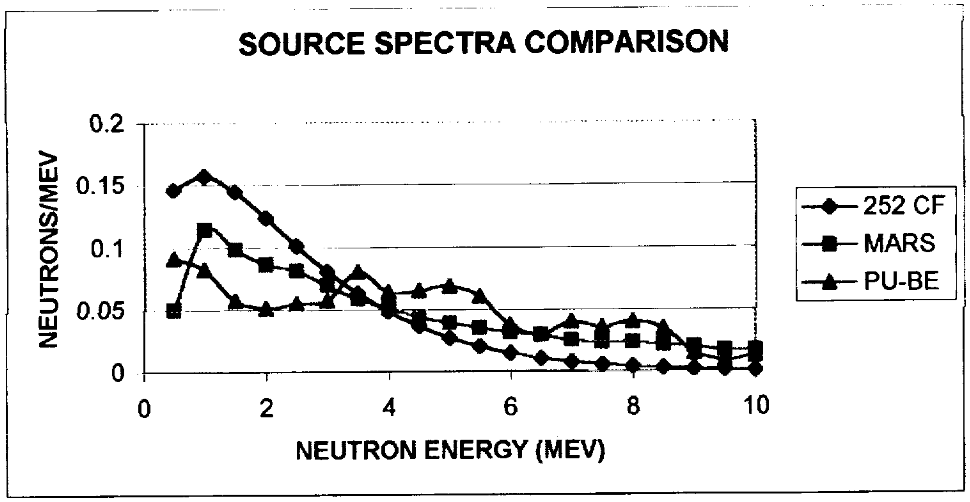


Figure 2. This figure shows the shape of the sources sources used in the demonstration along with the neutron spectrum produced by cosmic rays before being transported by the MCNP calculation.

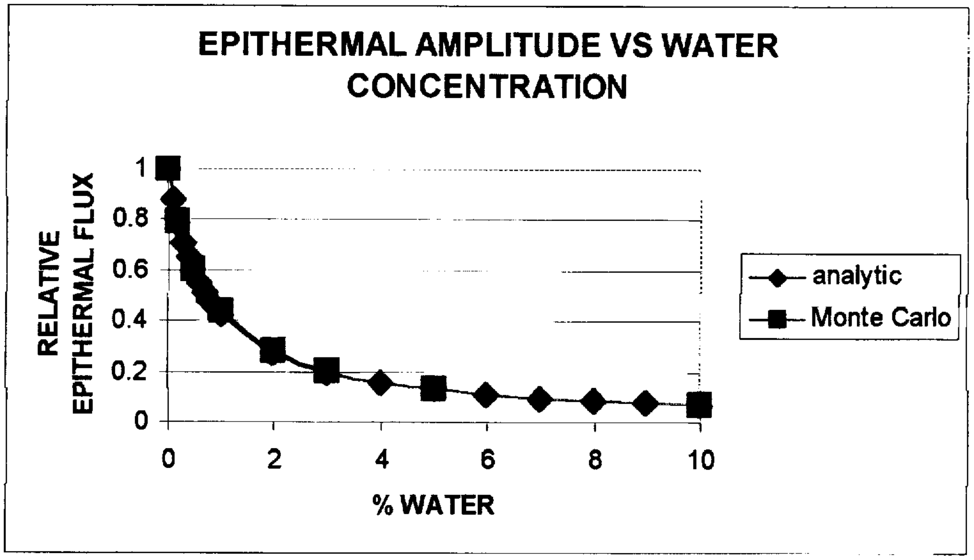


Figure 3. This figure shows the relative amplitude of the epithermal neutron flux for a Martian regolith with composition given in Table 1for water concentrations from 0 to 10%. The squares are from a Monte Carlo calculation while the diamonds are calculated from the analytic expression.

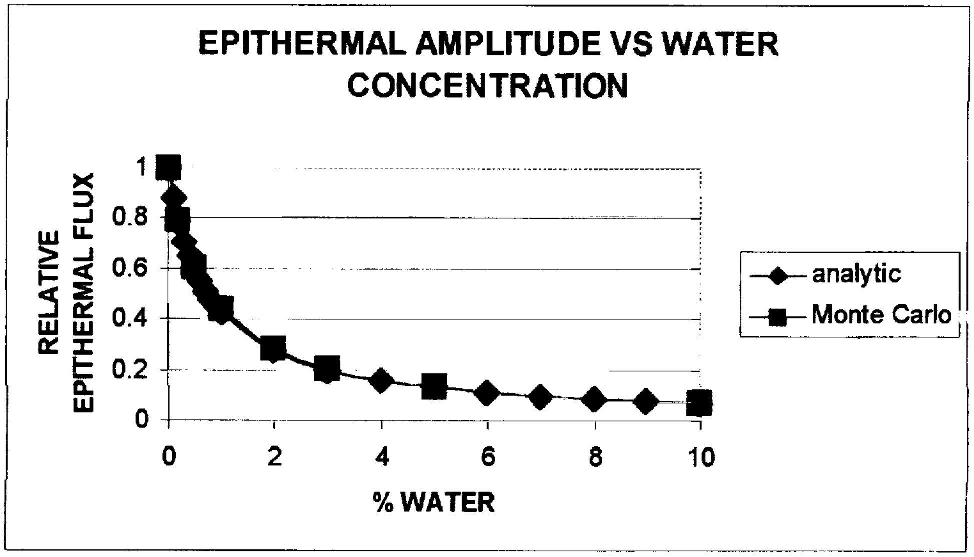


Figure 4. This figure shows the moderating strengths of oxygen and hydrogen as a function of water % for a Martian like soil. For dry soil oxygen is responsible for about 85% of the moderation. Hydrogen dominates after about 0.5%.

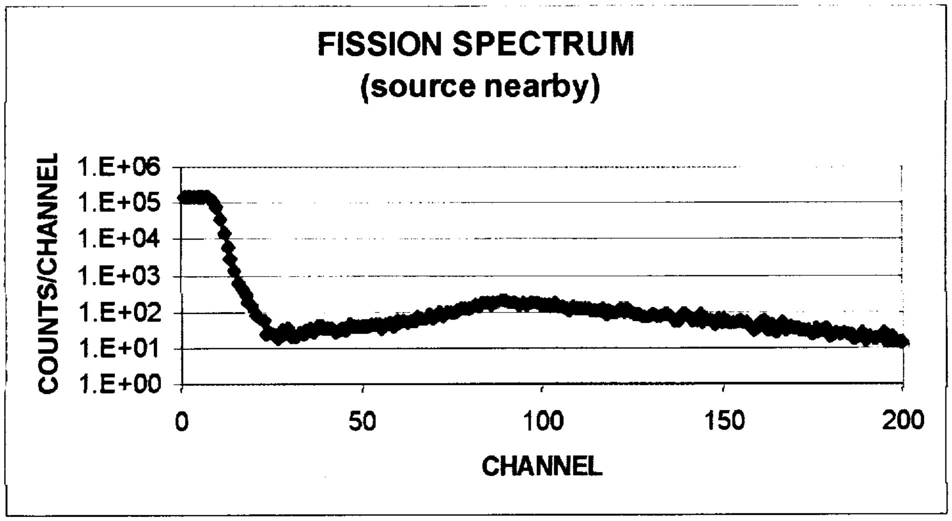


Figure 5. Fission spectrum for 238U ion chamber. The source was placed near the counter in order to check that the counter functioned correctly

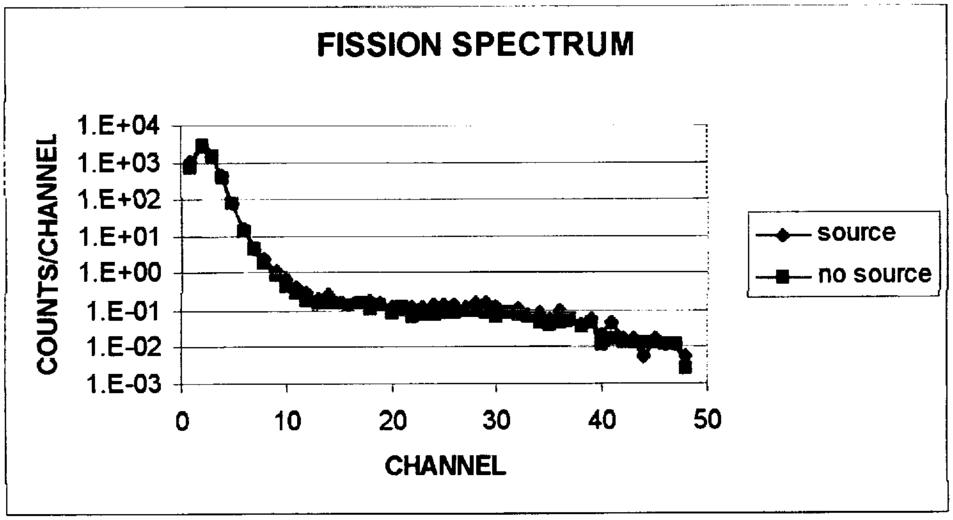


Figure 6. This shows two spectra of the 238U ion chamber, one taken with the source in the class cube, the second taken under the same conditions without a source.

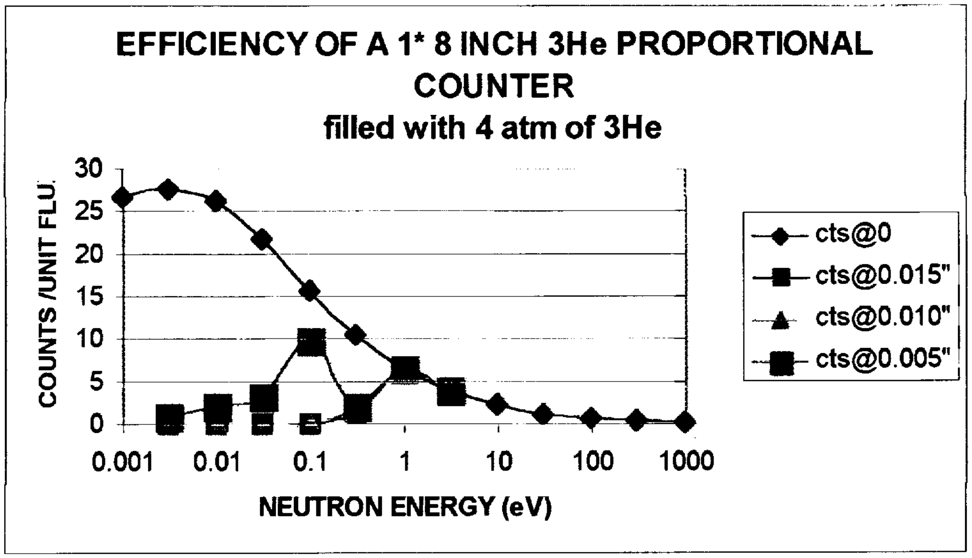


Figure 7. Counting rates for a 3He counter as a function of neutron energy. The flux was taken to be 1 neutron /s. Four atmospheres of 3He fill the counter whose case was 0.035-inch thick stainless steel. Calculations were also made with three thickness of cadmium surrounding the counter

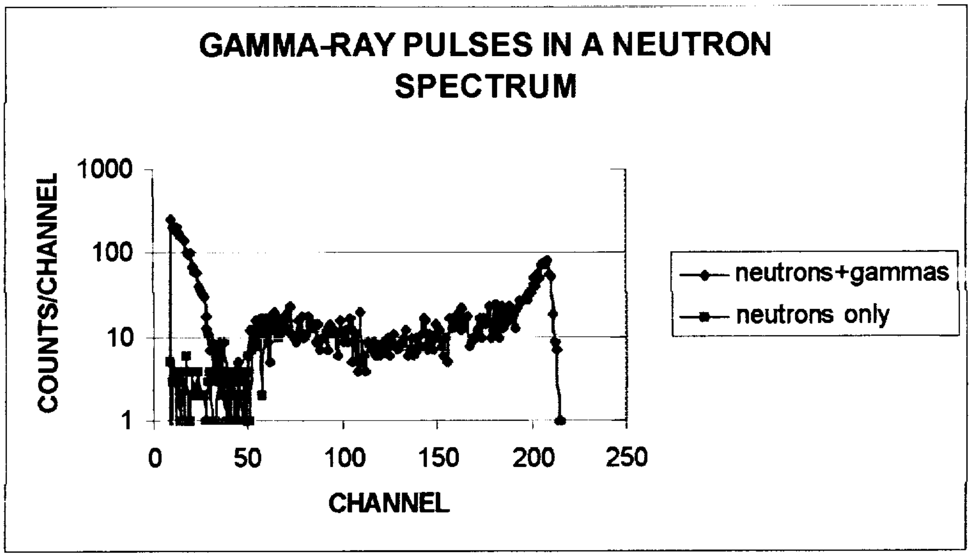


Figure 8. Two pulse height spectra are displayed. The diamonds are the spectrum of a 3He counter exposed to both neutrons and gamma rays. The squares represent a neutron spectrum without gamma rays. The full square spectrum is not shown since it is essentially identical. Gamma-ray pulses are clearly distinguished from those caused by neutrons.

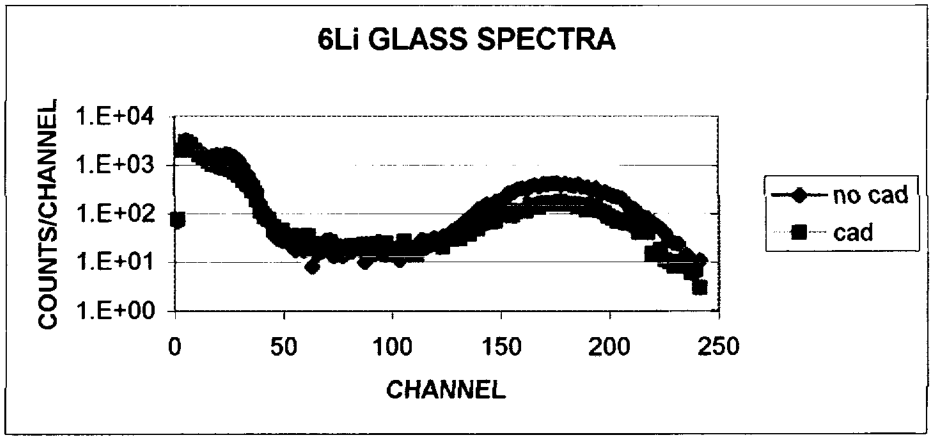


Figure 9. Pulse height spectra of 6Li glass scintillator with and without cadmium cover. The detector was on top of 1/2 inch polyethylene sheet, which was on top of the glass cube.

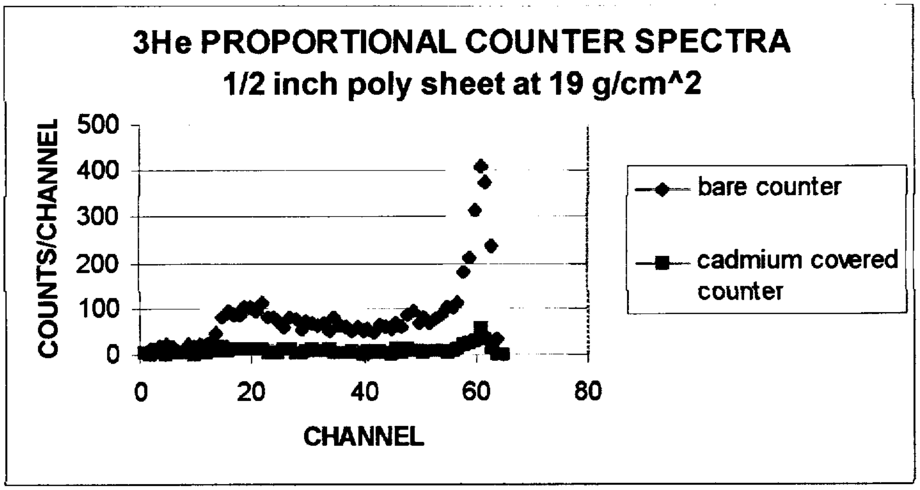


Figure 10. Typical spectra for a 3He counter with and without cadmium.

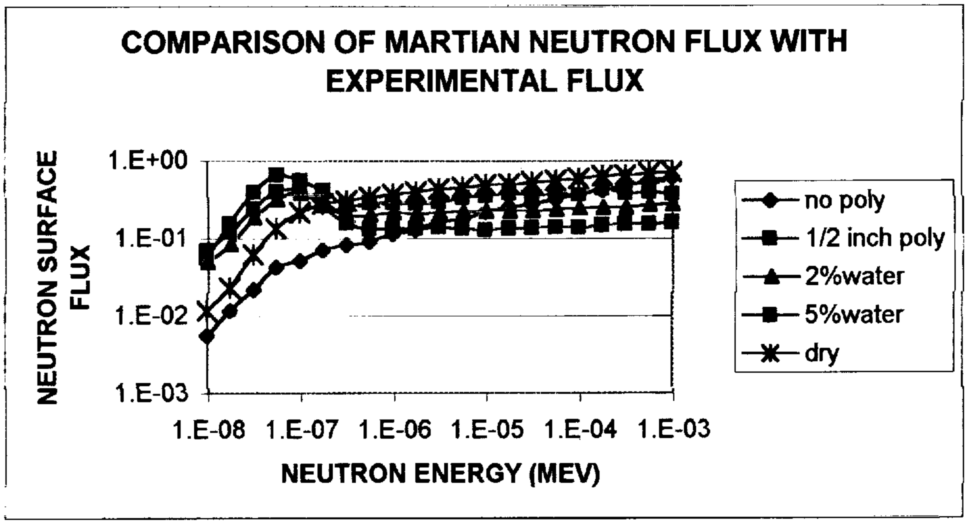
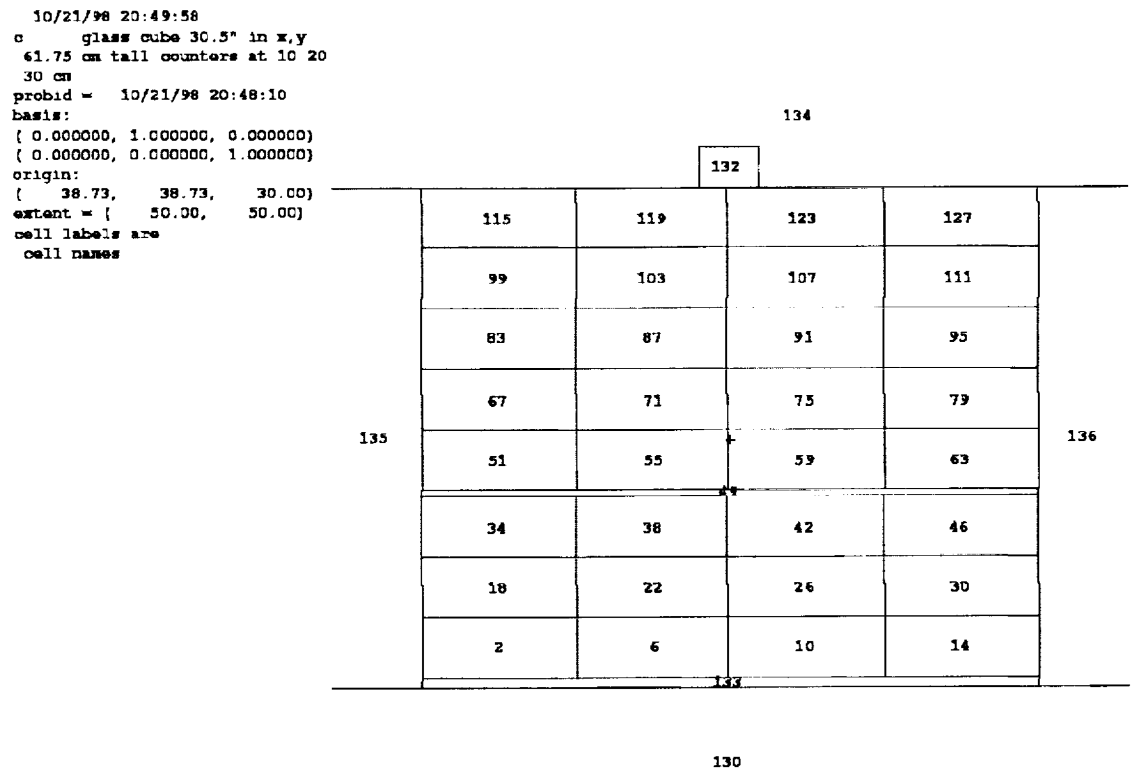


Figure 11. Computed neutron fluxes for the demonstration experiment and the Martian surface. The demonstration experiment used a calibrated Californium source with the neutron spectrum taken from the LCS Monte Carlo manual. The Martian flux was computed using LCS codes and a cosmic ray spectrum shape given by Castagnoli (2). Since the magnitude and shapes of the spectra are similar one should expect Martian counting rates to be similar to those in the demonstration experiment.



```
 10/21/98 20:49:58
c      glass cube 30.5" in x,y
 61.75 cm tall counters at 10 20
 30 cm
probid =  10/21/98 20:48:10
basis:
( 0.000000, 1.000000, 0.000000)
( 0.000000, 0.000000, 1.000000)
origin:
(   38.73,    38.73,     30.00)
extent = (    50.00,     50.00)
cell labels are
 cell names
```

Figure 12. Computer generated diagram of a cross section of the glass cube. The numbers represent cells defined in the program. Cells 133,134,135, and 136 are filled with air. Cell 132 is a 3He counter.

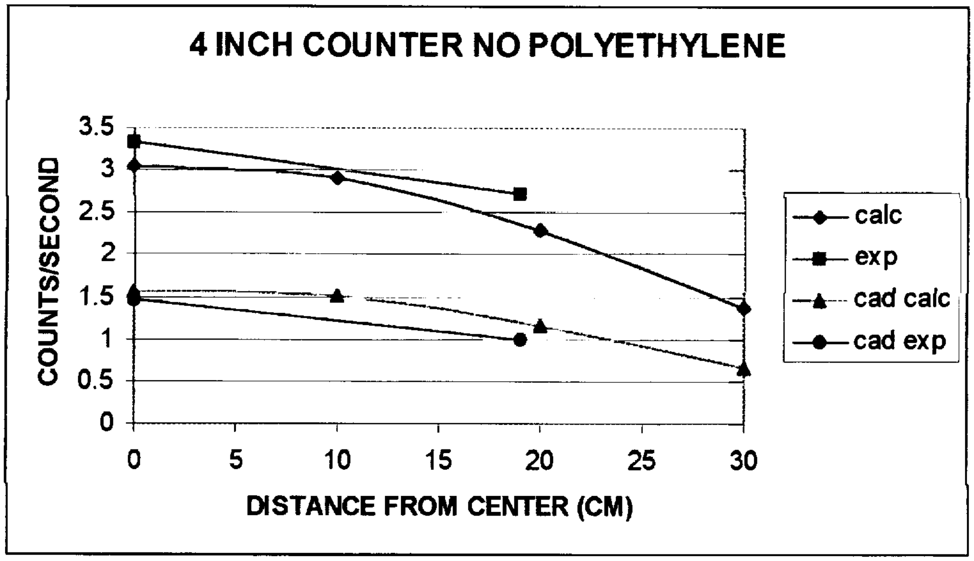


Figure 13. Experimental and calculational results for the glass cube. These results are for the 4-inch counter with and without cadmium.

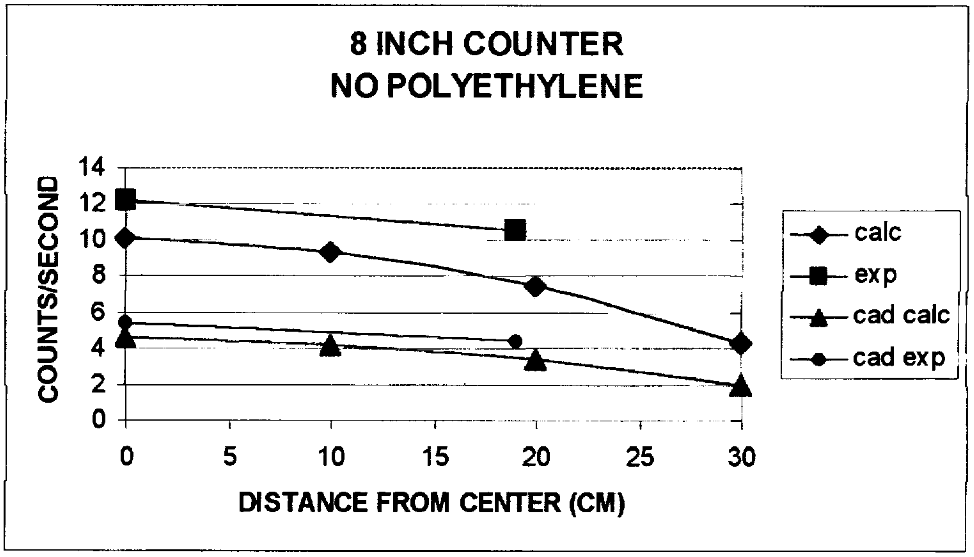


Figure 14. Experimental and calculational results for the glass cube. These results are for the 8-inch counter with and without cadmium.

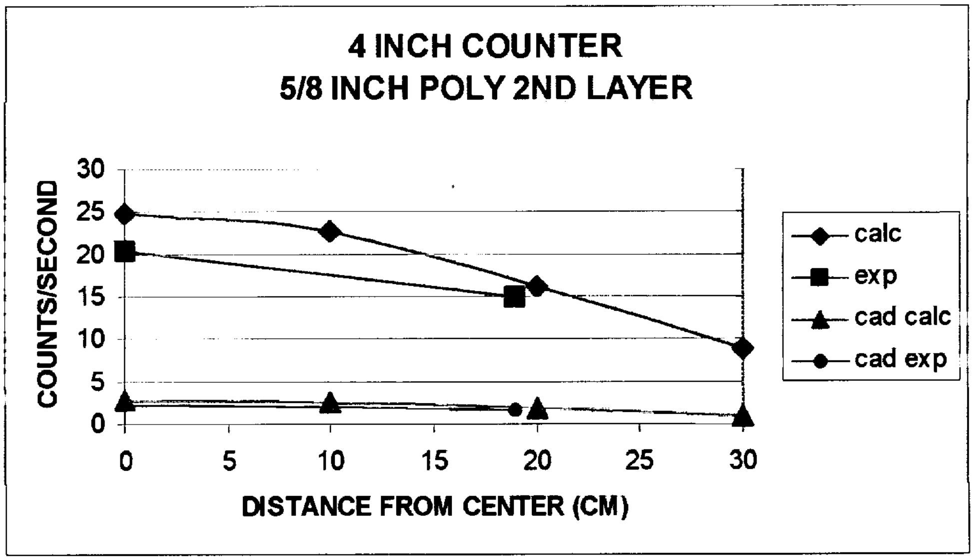


Figure 15. Experimental and calculational results for the glass cube with 5/8 inches of polyethylene inserted between the second and third layer of glass blocks. These results are for the 4-inch counter with and without cadmium.

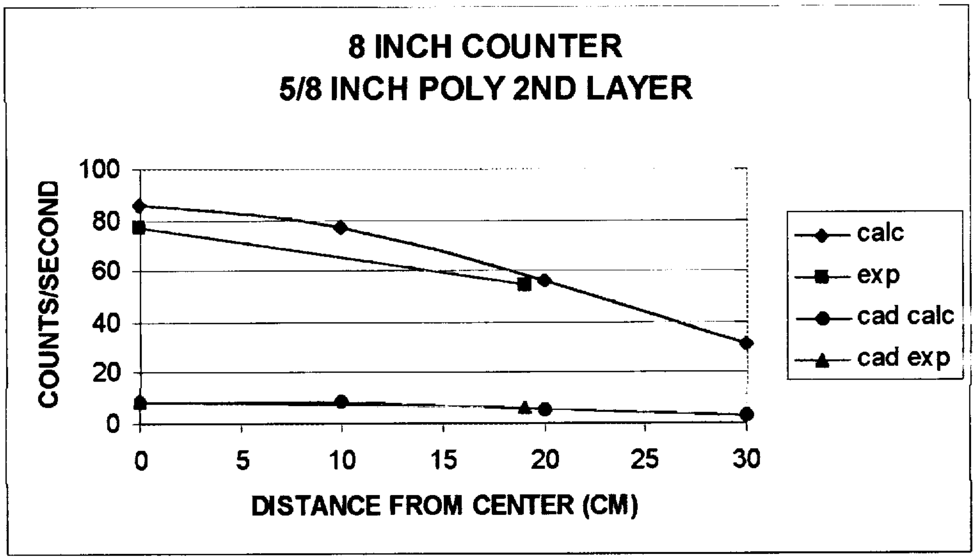


Figure 16. Experimental and calculational results for the glass cube with 5/8 inches of polyethylene inserted between the second and third layer of glass blocks. These results are for the 8-inch counter with and without cadmium.

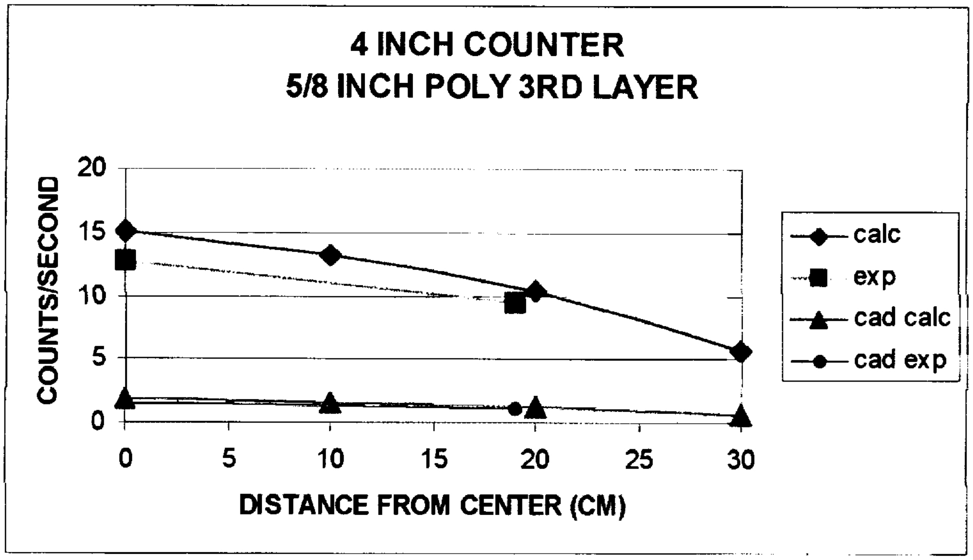


Figure 17. Experimental and calculational results for the glass cube with 5/8 inches of polyethylene inserted between the third and fourth layer of glass blocks. These results are for the 4-inch counter with and without cadmium.

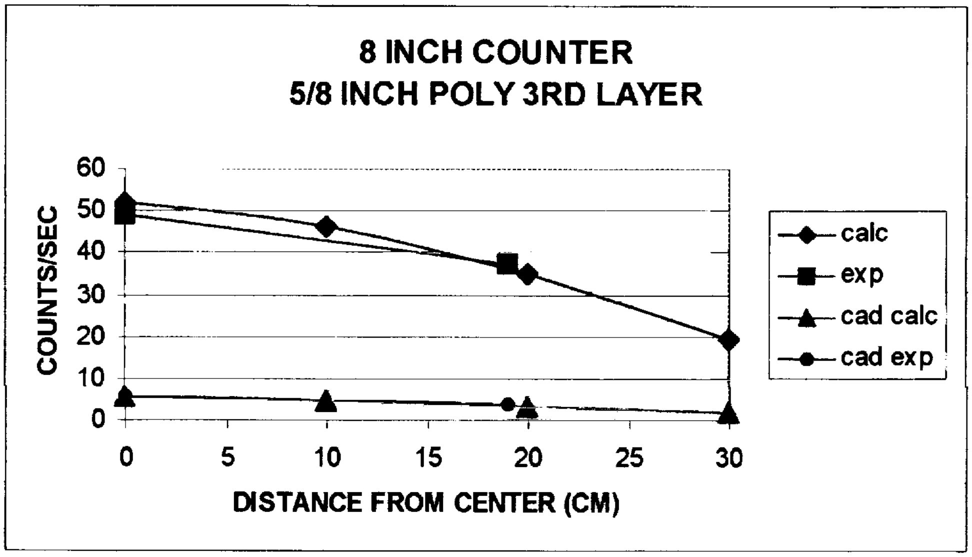


Figure 18. Experimental and calculational results for the glass cube with 5/8 inches of polyethylene inserted between the third and fourth layer of glass blocks. These results are for the 8-inch counter with and without cadmium.

TABLES

Com-pound	SiO2	Al2O3	CaO	MgO	Na2o3	K2o	Fe2O3	Tio2	LOI
Wt %	73.5	11.37	1.21	0.41	3.57	3.47	2.80	0.25	1.5
Wt %	75.11	12.02	1.1	0.40	3.44	3.65	2.42	0.264	2.1

Table 1. This table lists the results of the soil composition for two separate analyses of the soil used in the second demonstration experiment. The results are nearly identical. The second row is from LANL, the third is from Huffman Laboratories.

	SiO2	Al2O3	CaO	MgO	Na2O3	K2O	SO3	FeO2	Sb2O3	ZrO2	TiO2
Wt%	72.67	2.40	5.73	4.04	15.71	0.01	0.28	0.027	0.127	0.011	-.003

Table 2. This table list the compounds that compose the solid glass blocks used in the third demonstration experiment.

ELEMENT	WEIGHT %	CROSS SECTION	$n_i*\sigma_i*\xi_i$	$n*\sigma*\xi//\Sigma\ (n_i*\sigma_i*\xi_i)$
HYDROGEN	0.111	19	0.0127	0.561
OXYGEN	45.96	3.7	0.00798	0.353
MAGNESUIM	5.35	3.9	0.000435	0.0193
ALUMINUM	3.24	2.1	0.000112	0.00497
SILICON	22.42	2.1	0.000721	0.0319
SULFUR	3.31	0.96	0.0000372	0.00165
CHLORINE	0.75	8.0	0.000059	0.0026
POTASSIUM	0.27	1.5	0.000003	0.00014
CALCIUM	4.3	2.6	0.000008	0.0037
TITANIUM	0.58	8.2	0.000025	0.0011
IRON	13.69	9.0	0.00047	0.02082

Table 3. This table shows the elemental concentration of the soil containing 1% water used for the Martian regolith and the parameters used to compute the amplitude of the epithermal flux. Note that the last column, when multiplied by the fractional change in an element, gives the fractional change in the epithermal amplitude.

Solid State Water Prospector-Prospectores de Agua

ABSTRACT

Neutron spectrometry has been widely recognized as a leading candidate experiment for future planetary exploration. A system employing this technique has never been quantified or optimized for operation on a planetary surface. Applications include rovers, soft-landers and hard probes (penetrators or hard-landers). For almost three years, under a PIDDP award, Amparo Corporation scientists have been investigating the responses and optimization of neutron spectrometric systems for this application. We have evaluated several approaches, including those employing ^{3}He counters (as flown on Lunar Prospector) and solid-state detectors. For a highly miniaturized system, we have found the latter is preferable and have devised methods of stacking detectors and tailored converter foils to achieve a promising new technique for small, simple, and highly affordable neutron spectrometric systems for use on rovers. The resulting instrument can be used by several future missions to planets, comets, and asteroids, with special value to a lunar polar scouting mission and to Mars rover missions to detect concentrations of water (and/or organics) in the regolith. This not only provides important information on heterogeneity of the deposits, but also serves as a rover screening tool for resource-limited evolved gas analyzers. The Water Prospector instrument can be converted to flight-qualified status with a low-cost program which capitalizes on sensor improvements and nuclear electronics developed for numerous space programs, including the recent Pathfinder mission to Mars.

INTRODUCTION

The study of the presence and distribution of the light elements on planetary bodies, such as Mars, the moon, and asteroids is widely recognized by the scientific community as one of the most important endeavors of planetary science. The instrumentation proposed for final development under this proposal is aimed primarily toward the detection of these elements in the near-surface regolith by the technique of neutron spectroscopy. Neutron spectrometry is so much more difficult than other types of energetic particle spectrometry that the more sophisticated laboratory solutions to this problem are totally unsuited for space flight. We have developed high fidelity models of the planetary surface and the instrumentation we propose in order to understand both the capabilities and limitations of the technique. Because of this depth of understanding and insight into the precise nature of the problem it is possible to approach this set of measurements with confidence in being able to correctly interpret the data from the measurements.

For Mars, thermal modeling and water vapor transport calculations predict that permafrost ice deposits could exist as stable shallow deposits in the regolith at higher latitudes, down to 30 degrees from either pole. More equatorward, ice may be deeper or nonexistent. The geographic distribution of certain morphological features tends to corroborate this predicted trend. Anti-solar slopes and other special local conditions could provide exceptions to this generality. The existence of water-rich "oases" cannot be ruled out; liquid deposits may be strong salt brines. The detector and experiments we propose are also clearly appropriate to a polar setting, where the observed layering indicates, even at orbital-measurement scale, the heterogeneity of ice and soil deposits.

RESEARCH OBJECTIVES and SCIENCE JUSTIFICATION

From many lines of evidence, water has played a major role in shaping the surface of Mars. It remains controversial as to the total amount of water which is/was available to surface processes, with estimates ranging all the way from low values of a few meters equivalent depth (planet-wide surface average) to more than 100 times these amounts. Outflow channels, valley systems, rampart crater lobate debris flows, softened physical features, chaotic terrain, and other geomorphological evidence indicate abundant liquid water and ice activity in the past. Water in the soil may consist of any of a large number of physical and chemical forms, including free ice, adsorbed thin water films, water of crystallization, mineral hydroxides, etc. Water vapor in the atmosphere and H_2O released by heating the martian soil (Viking Lander GC/MS experiment) are consistent with the presence of subsurface water, but are not strictly diagnostic and are certainly not predictive of the amounts of H_2O- and OH-containing minerals. Measurements of soil samples by thermal evolved gas analysis (TEGA) should be capable of identifying some of the types of water present, but only for a limited number of small samples mostly or totally from the topmost surface. This is planned for the Mars-98 Lander, but no neutron instrumentation is included to provide a reference measurement of total bulk hydrogen content of the general vicinity of the lander. Only tiny, milliliter-class samples will be analyzed.

On mars, a variety of forms of water—adsorbed, frozen permafrost ice, hydrated minerals, intercalated molecules in layer-lattice silicates (clays), water of hydration in soils, etc. —are both possible and likely.

Viking GC/MS found up to 1.9% bound water in "dry soil", and other potential water containing surface components are listed in the following table:

Hydrated minerals	
Clays	3%
Fe-oxyhydroxides	1%
Salts ($MgSO_4$, NaCl, etc.)	2%
Pore, Inclusion	1%
Adsorbed Water	up to 15%
Frost, Permafrost	up to 100%
Hydrate Clathrate	71%

Water was once relatively ubiquitous on Mars, and obviously now mostly sequestered in the regolith. Under our proposed approach, neutron spectroscopy will be used to quantitatively assay a large volume of the regolith in the vicinity of a mini-lander or rover for hydrogen concentration content without sampling and within hours. No sample acquisition is required. Thus, the measurements will be quite separate from, and complementary to, TEGA or other sample-specific analyses. In addition, our experiment can be transported by a rover or manipulated by an articulated arm, such as the sample acquisition device, to investigate small scale variability to better understand the nature of the martian surface and to enable the opportunity for specifically sampling water-rich material for TEGA, spectroscopic, and other analyses. The system is not only more compact than the analogous ^{3}He proportional counter approach, but totally eliminates the requirement for high voltage power supplies (HVPS) that counters entail. These HVPS impose volume, mass and risk penalties, especially on Mars where the thin atmosphere presents special design challenges for high voltage operation. In addition our proposed counter is insensitive to elastic scattering of fast neutrons, which in ^{3}He counters produce pulses in the same range as the captured neutrons. This proposal addresses the final optimization and development of flight-worthy neutron-based instrumentation that can be used in a search for these volatiles deployed on either Mars or lunar landers or rovers, and Mars balloons. Techniques proposed here have a history of successful application in industry and research (Caldwell et al, 1966; Schrader et al, 1962, Schrader and Stinner 1961; Monaghan et al, 1963). Optimization and compatibility with the realistic engineering constraints of planetary missions has not been realized to date. This is the primary focus of the proposed development. Our combination of neutron physics experience, space instrumentation expertise, available computing facilities and unique transport codes, and martian scientific expertise represented by the investigators submitting this proposal provides the basis for development of ultra-lightweight instrumentation.

PIDDP ACHIEVEMENTS TO DATE

For the past three years we have been conducting a program entitled "Assay of the Martian Regolith with Neutrons" in which we have used a variety of neutron counters and sources in conjunction with a large amount of material that resembles regolith in composition to study the moderation of neutrons. Two experiments have been made, one using several hundred pounds of soil and the other about one ton of glass. The down scattering cross section of the glass matched the assumed composition of martian soil within a percent or so. Moderation due to hydrogen was measured by inserting layers of polyethylene between layers of the soil or glass and adding known amounts of water to various layers of the soil. For neutron counters we have used a ^{6}Li-silicon detector similar to the one proposed here, a variety of ^{3}He proportional counters, a Li-glass scintillator, and a ^{235}U fission chamber. We have modeled these experiments using the MCNP code developed by LANL. Among other things we have managed to predict the change in leakage flux from the bulk materials as a function of location and amount of hydrogen. We have computed the thickness of the cadmium layer necessary to absorb the thermal neutrons. We have determined and quantified the effect that hydrogen and aluminum components of the rover or lander would have on the neutron counting rate by placing pieces of polyethylene and aluminum at various distances from the counters.

NEUTRON CALCULATIONS NEUTRON SOURCES AND EXPERIMENTAL TECHNIQUES

We propose to use neutrons as a probe to detect volatiles in the upper meter or so of the martian surface. The basic unit of the detectors considered here combine thin layers of ^{6}LiF with totally depleted silicon diodes. This unit will be well characterized in terms of its response to various neutron fluxes. The neutrons in this technique for measuring water are made by the interaction of high-energy galactic cosmic-ray particles with nuclei in the martian surface. The proposers are well aware that a gamma ray spectrometer can also determine elemental abundances of the regolith by detecting characteristic gamma rays emitted from either neutron capture or inelastic nuclear collisions, and for missions that have sufficient resources, suggest characterization simultaneously. However, future martian surface missions are projected to have modest payload delivery capabilities. The weight penalties associated with gamma ray spectroscopy are larger by a factor of more than 10 compared to a neutron experiment of the type we propose. The elemental analysis techniques of alpha backscater, proton emission, and x-ray fluorescence have been combined into one instrument (APX) to cover as many elements as possible. The one element that cannot be identified by any of these techniques is hydrogen, the element that our technique does best. As discussed above, hydrogen is of critical importance for understanding geochemical composition of the regolith (as well as for comets and several types of asteroids). It also should be clearly recognized that the APX approach is extremely surficial in nature, penetrating only microns into the surface of rocks or soil grains, whereas the neutron spectrometry technique is sensitive to much larger and more representative regolith volumes, up to roughly one meter in depth. We first present analyses that demonstrate the utility of neutron detection techniques for probing near surface chemistries. We next describe a variety of neutron sources that could be used as an active probe and the end this section by describing the detectors we propose to evaluate and optimize.

Calculations

The calculations begin by using the cosmic-ray proton spectrum shown in the Handbook of Geophysics and Space Environment as input for LAHET(Prael and Lichtenstein,1989), a high-energy production and transport code. The input file is arranged so that the protons impinge isotropically on the martian surface. All particles produced by this code are followed until some low energy cutoff is reached. The resulting neutron spatial and energy distributions are then used in a Monte Carlo code MCNP, which computes the equilibrium spectrum of leakage neutrons. The model of Mars is essentially the same as that of Masarik and Reedy (1996) with 15 g/cm^2 atmosphere.

A variety of leakage spectra shaped by moderation within the upper few meters are shown in Fig. 1 and are similar to earlier calculations (Drake et al, 1988) which used a different neutron transport code (note that the flux in Fig. 1 is not plotted as "per MeV" because details are lost on a 6 decade plot). The main feature of these curves shows that the dominant effect of adding water to the regolith is to depress the epithermal and increase the thermal amplitudes. The fast component (> 10MeV) is relatively unaffected by small amounts of water and its amplitude remains rather constant. Similar calculations in which carbonates are added to the soil show that the thermal component increases relative to the fast component.

Although both of these effects are weakened by more realistic regolith stratigraphies (Drake et al, 1988; Feldman and Jakosky, 1990), they remain detectable at low mixing concentrations using on-site neutron detectors. For example, water mixed in regolith is detectable at very low levels (Feldman and Drake, 1986; Drake et al, 1988). Fig. 2, shows how the computed thermal and epithermal counting rates vary as a function of water content in typical martian regolith. To first order this figure shows that a two-detector sensor, capable of measuring the thermal and epithermal portions of the neutron spectrum separately, can determine accurately the amount of water mixed in the regolith. For example, in the 0 to 8% region, the ratio of thermal to epithermal counting rates changes by about 9. We propose to define detection sensitivity for thick magnesium carbonate and calcium carbonate deposits more precisely by laboratory experiments.

Using MCNP we will evaluate the response of our neutron experiment for both lander and rover implementations. This will include the important effects of interference from hydrogenous and other low-Z materials on the carrier. Because mass is an important constraint on these missions, materials such as graphite epoxy may be used for certain structures. Using the expertise of our aerospace industry consultant, we will evaluate various candidate rover and lander design implementations. The resultant effects of potential interference will also help define any desired deployment conditions for the neutron experiment. In addition, we will evaluate the response for the balloon mission concept, which could provide an outstanding prospector mode for surveying widespread regions on Mars for volatiles. In this approach, we propose that the neutron experiment be suspended on a short tether beneath the balloon (perhaps as part of the dangling antenna for a microwave sounder). Floating a few kilometers above the terrain, traverse maps of thermal/epithermal ratios could be obtained in bands around the planet dependent only upon the number and lifetime of the balloons employed. This could provide ground track maps of up to two orders of magnitude better resolution than is possible with an orbitallly-hosted neutron monitor. Detailed calculations are needed to evaluate this option and we will perform these under this Mars Instrument Development Program.

Neutron Sources

Galactic cosmic ray generated secondaries provide a ubiquitous and free source of neutrons that is sufficiently intense to allow a survey of Mars for volatiles. However, several mini-lander and rover concepts may allow the use of other neutron sources such as alpha-beryllium, ^{252}Cf or a deuterium-tritium accelerator. Earlier concepts for Mars Rover and mini-landers incorporated a Radioisotope Thermoelectric Generator (RTG) for electric power. Because of the costs and approval processes attendant on the high radioisotope inventory of RTG's, their use is not likely on future Mars missions. However, small Radioisotope Heater Units (RHU) may be employed to provide thermal energy during local Mars nighttime. Both RTGs and RHUs emit neutrons. Although the use of RHUs would raise the background level in the counters, it also would increase the signal due to additional neutrons interacting with the regolith.

A Monte Carlo calculation can indicate whether an RHU would be useful in certain geometries and give an estimate of associated background. Possible interferences from hydrogenous materials on the lander or rover can also be evaluated with these calculations. Another possible application involves penetrators that operate at depths where the natural occurring neutron flux may not be sufficient to make a meaningful measurement or rovers where a detailed study of an isolated rock formation is desired. Here a radioisotopic neutron source or RHUs may be used to obtain higher signal. Radioisotopic sources that are available to be used in our proposed study include alpha-Be sources such as ^{241}Am-Be and ^{238}Pu-Be, and spontaneous fission sources such as ^{252}Cf. Both sources produce continuous neutron spectra from about 100 keV to 10 MeV. They can be made with high emission intensities (10^6 n/s) and are easily encapsulated and ruggedized. Because neutrons interact only sparingly with most materials, these sources do not pose a threat to the spacecraft electronics.

Neutron Detector

The fundamental technique for measuring thermal and epithermal components of moderated neutron spectra employs two identical neutron detectors with one of the pair surrounded by a thin foil of cadmium as originally suggested by Lingenfelter et al, (1961). Because cadmium has an extremely large cross-section for neutron capture below about 0.4 eV, the counter surrounded by cadmium counts only epithermal (> 0.4 eV) neutrons while its twin counts both thermal and epithermal neutrons

The basic unit of our proposed detector consists of a thin layer of ^{6}Li F deposited between two silicon detectors. Detection of a neutron is accomplished when a neutron is captured by one of the lithium atoms, which immediately splits into ^{3}H (triton) and a ^{4}He (alpha particle). The Q value of this reaction is about 4.8 MeV and the energies of the alpha particle and triton are 2 and 2.8 MeV respectively for low energy neutron capture. The alpha particle and triton are emitted back-to back so that, if a triton or alpha particle is detected by one of the silicon counters, the counter on the opposite side will detect its counterpart. As the neutron energy increases, the reaction products share its kinetic energy and the sum of the pulses of the two counters gives a measure of the neutron's kinetic energy. Because the pulses produced in the diodes are coincident in time, it is possible to eliminate pulses caused by any other radiation.

The proposed instrument, shown in two configurations in Fig. 3, will consist of two stacks of silicon detectors, each stack consisting of four diodes and three ^{6}Li layers. Being totally depleted, the diodes respond to particles entering either from the front or back. The two additional diodes in each stack triples the counting rate of a single pair.

The upper part of this instrument will be covered with a layer of boron-10 to absorb neutrons that come from the atmosphere. The mean free path of neutrons in the martian atmosphere is several kilometers and these neutrons may not be representative of the local regolith. Fig. 4 shows the relative up-down surface flux. The bottom side of one of the stacks will be covered with a cadmium foil, which can be as thin as 0.013 cm. The electronic compartment will be on top of the stacks. The silicon detectors will be 150-micron thick, 2000 mm^2 in area and can be totally depleted by 24 V.

A simplified electronic diagram is shown in Fig. 3 also. Recording of the spectra can be done in a variety of ways. The diagram shows a pulse height analyzer but it could as well be a series of discriminator-scalars. A sixteen-channel analyzer would be sufficient for each stack. The final stage of this package would depend upon resources supplied by the central electronics package. For the designs shown in the figure we estimate the instrument's weight to be 250 g, power consumption about 200 mW and volume of 270 cm^3. Fig. 5 shows two spectra that can be recorded by this neutron spectrometer. The top curve is the pulse height spectrum of a single silicon counter, The bottom curve shows the pulse-height spectrum with the coincidence required and the pulses summed.

Cosmic rays and their high energy secondaries can pass through the silicon counters, but as minimum ionizing particles deposit about 0.1 MeV of energy. This is far below the energy deposited by the alpha particle or triton and will not appear in the significant portion of the spectrum.

Demonstration Experiments

Some simple exploratory experiments that are scalable and can be easily modeled by calculation were done recently under the PIDDP award to explore the feasibility of the techniques just described and to illustrate the type of data one could expect. Even though this technique is thought to be rather insensitive to carbonate deposits (Feldman and Jakosky, 1990), we can also test this hypothesis.

Summary

Use of neutrons to probe the upper meter or so of the martian or lunar regolith is a powerful method to determine concentrations of water in all its mineralogical forms. Characterization of the lower end of the leakage neutron spectrum is a very sensitive indication of water concentration in the regolith. We propose a neutron detector system that essentially measures only neutrons eliminating by coincidence other pulses that may be caused by elastic scattering or other reactions.

Statement Of Work

The goal of our proposed research is to finalize the design and build a working prototype of a neutron experiment for a mission to Mars or the moon. This Instrument design could also be used on mini-landers on either body or in the balloon payloads for Mars. The proposed work will be split among the co-investigators in accordance with past experience and the availability of institutional facilities: Darrell Drake will provide leadership for the entire project. Ken Spencer, an engineer with years of experience designing LANL space instruments will be the lead for non-procured circuitry, especially the digital threshold levels and coincidence/anti-coincidence logic. He will work with a commercial fabricator, Circuits Plus, to produce the final electronic package. Robert Reedy and Michael Fikani will assist in numerical simulations and verification methodologies for the various missions. Ben Clark and James Walker will assist in developing specific experiment implementation concepts, provide instrument and experiment environment specifications, and guidelines for flight hardware as appropriate.

The specific tasks to be accomplished in this program are:

- develop the conceptual design of the neutron spectrometer;
- model the performance of the chosen design using the various codes available to us (MCNP, LAHET);

- specify the particulars of the system so as to achieve a flight worthy design;
- fabricate a prototype model of the chosen design;
- conduct a test program using the prototype that simulates as well as possible actual conditions, for this we will need to avail ourselves of JPL's Arizona facilities;
- modify as required the prototype system so as to incorporate any changes prompted by the testing effort;
- prepare a detailed document detailing the design of the prototype, its tested performance results and describing just how the system can be deployed for its potential role in a planetary exploration scenario;
- on the basis of the above a second system will be fabricated which will be optimized for an explorer role. This system will incorporate flight qualifiable components but will not have been put through all the tests necessary for it to be designated as flight qualified.

Expected Results

Use of neutrons to probe the upper meter or so of the martian or lunar regolith is a powerful method to determine concentrations of water in all its mineralogical forms. Concentrated deposits of organic materials might also be detected in this way.

With our Water Prospector instrument, neutron spectroscopy will be used to quantitatively assay a large volume of regolith in the vicinity of a mini-lander or rover for hydrogen content without sampling and within several rens of minutes. No sample acquisition is required. Thus, the measurements will be quite separate from and complementary to, TEGA or other sample-specific analyses. In addition, our experiment can be transported by a rover or manipulated by an articulated arm, such as the sample acquisition device, to investigate small scale variability to better understand the nature of the martian surface and to enable the opportunity for specifically sampling water-rich material for TEGA, spectroscopic, and other analyses. This system is not only more compact than analogous ^{3}He proportional counter approach, but totally eliminates the requirement for high voltage power supplies (HVPS) that these counters entail. These HVPS impose volume, mass, and risk penalties, especially on Mars where the thin atmosphere presents special design challenges for high voltage operation.

The scientific objective of such an experiment is to assay the uppermost several meters of martian regolith for light elements, with special emphasis on locating significant deposits of hydrogen containing compounds such as H_2O and organic matter. This measurement technique poses unique problems that need to be addressed. Foremost is the need to determine both experimentally and by numerical simulation the sensitivity of neutron methods in determining the abundances of low-mass elements from measurements made near the surface of Mars. Uniqueness in interpretation of measured signatures of specific elements needs to be quantified. Another factor here is to explore the relative merits of active interrogation using radioisotopic and/or active neutron sources versus passive detection of naturally occurring galactic cosmic ray generated neutrons.

Although specific measurement objectives will no doubt evolve as the project progresses, a logical beginning would be an extension of the current PIDDP with laboratory verification of numerical simulations. New configurations would address carbonate influence on neutron fluxes produced by experimental simulation of cosmic ray interaction with the martian surface A second set of experiments will simulate the active neutron interrogation of martian surface materials using radioisotopic neutron sources such as ^{252}Cf. Several experiments will be configured to mimic measurement scenarios allowed by proposed mini-landers or rover mission concepts. To perform this research, we have assembled a team of very qualified individuals who are highly interested in the scientific implications of water, carbonates, and other light element compounds in the "martian" regolith. This team not only is strongly motivated but also includes the technical competence needed to develop flight-worthy, practical measurement systems, which can be used for probing the "martian" surface for these elements.

Facilities And Experience

Los Alamos National Laboratory has been a premier laboratory in neutron physics since 1943. Current experimental programs and facilities show that neutron physics continues to be a major part of the LANL effort.

These facilities are each equipped with a comprehensive inventory of standard nuclear physics electronic hardware (NIM, CAMAC, high-purity germanium and other detectors). The hardware development, evaluation and calibration tests proposed here can therefore be carried out at no extra cost for capital equipment to NASA.

During the early stages of the PIDDP research, the University of New Mexico helped with neutron sources, and data acquisition. Their facilities are available at moderate cost .

Amparo Corporation now has the neutron production and transport codes, LAHET and MCNP, and computers that can be dedicated to this project. The LANL group that developed these codes is available to consult on code related problems.

We have contacted Amptek Corporation and they are willing to work with Spencer in designing the electronic package.

References

Beimer, K., G. Nyman, and 0. Tengblad, Response Function for ^{3}He Neutron Spectrometers, Nucl. Instru. and Meth. A245 402--414 (1986).

Caldwell, R. L., W. R. Mills, L. S. Allen, P. R. Bell, and R. L. Heath, Combination Neutron Experiment for Remote Analysis. Science 152, 457--467 (1966).

Cuttler, J. M., S. Shuler, and Y. Dagan, A High-Resolution Fast Neutron Spectrometer. Trans. Am. Nucl. Soc. 12,63 (1961).

Drake, D. M., W. C. Feldman, and B. M. Jakosky, Martian Neutron Leakage Spectra. J. Geophys. Res. 93, 6353--6368 (1988).

Drake, D. M., S. Wender, R. Nelson, E. R. Shunk, W. Amian, P. Englert, J. Brueckner, and M. Drosg, Experimental Simulation of Martian Neutron Leakage Spectrum. Lunar and Planetary Science XXI, p. 300 (1990).

Englert, P. A. J., D. M. Drake, E. R. Shunk, M. Drosg, R. C. Reedy, and J. Brueckner, Simulation of Cosmic-Ray Interactions with "Martian-Soil;" Implications for Cosmogenic Nuclide Studies and Planetary Gamma-Ray Spectroscopy. Lunar and Planetary Science XXI, pp. 325--326 (1990).

Evans, A. E., H. O. Menlove, R. B. Walton, and D. B. Smith, Radiation Damage to ^{3}He Proportional Counter Tubes. Nucl. Instru. and Meth., 133, 577--578 (1976).

Feldman, W. C. and D. M. Drake, A Doppler Filter Technique to Measure the Hydrogen Content of Planetary Surfaces. Nucl. Instr.and Meth., A245, 182--190 (1986).

Feldman, W. C. and B. M. Jakosky, Thermal Neutron Leakage from Martian Carbonates. Lunar and Planetary Science XXI, pp. 361--362 (1990).

Feldman, W. C., W. V. Boynton, and D. M. Drake, in Remote Geochemical Analysis Elemental and Mineralogical Composition, Pieters, C. M. and Englert, P. A. J., eds., LPI, Houston (1991).

Lingenfelter, R. E., E. H. Canfield, and W. N. Hess, The Lunar Neutron Flux. J. Geophys. Res. 66, 2665--2671 (1961).

Monaghan, R., A. H. Youmans, R. A. Bergan, and E. C. Hopkinson, Instrumentation for Nuclear Analysis of the Lunar Surface. IEEE Trans. Nucl. Sci., 10, 183--189 (1963).

Masarik,J., and R. Reedy, Gamma Ray Production and Transport in Mars, J. Geophys. Res. 101, 18, 891-912, (1996).

Prael,R. E., and H. Lichtenstein, User Guide to LCS. LA-UR-3014, Los Alamos National Lab., Los Alamos,N.M., 1989.

Schrader, C. D., J. A. Waggoner, J. H. Zinger, R.J. Stinner, and E. F. Martina, Neutron-Gamma Ray Instrumentation for Lunar Surface Composition Analysis. A.R.S. Journal, 32, 631--634 (1962).

Schrader, C. D. and R. J. Stinner, Remote Analysis of Surfaces by Neutron-Gamma-Ray Inelastic Scattering Technique, J. Geophys. Res. 66,1951--1956 (1961).

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EDUCATION:
BS, Engineering Physics, University of Oklahoma, 1954
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Darrell Drake has 26 years experience in nuclear physics and six years experience working in the Space Plasma Physics group at LANL. The subject of his thesis at the University of Washington was experimental measurement of neutron evaporation from excited nuclei. At the University of Illinois he did experiments scattering mono-energetic gamma rays. At Los Alamos he has participated in a wide variety of nuclear physics experiments from neutron-induced gamma ray production to heavy ion reactions. He discovered the giant isovector quadrupole resonance via fast neutron capture. He has participated in several pion experiments at LAMPF. During a sabbatical year at Centre d'Etudes de Bruyeres la Chatel he developed a program to measure fast neutron capture. In a second sabbatical at CERN he worked with a group from Saclay measuring antiproton scattering reactions and developed an optical model for antiproton-nucleus interactions. He was principle investigator for the BDD instrument on the GPS satellite system. He was the US co-investigator for the PGS instruments for the USSR Mars '94 Mission. In 1987 and again in 1993 he was given the LANL Distinguished Performance Award. In addition to working on PIDDP NSAW-5030,"Assay of the Martian Regolith with Neutrons" he is a consultant and visiting scientist at LANL for an experimental facility consisting of an array of 30 High purity germanium counters. This facility measures gamma ray producing reactions for neutrons from 0.5 to 200 MeV.

For several months in 1993-94 he worked with a group at the Max Planck Institute in Mainz on radiation damage experiments to determine germanium characteristics in high-energy proton environments. With this Mainz Group he worked on "thick target" experiments to measure gamma rays that leak from proton bombardment of thick targets that resembled martian regolith. In 1994-95 he worked with a group from Centre d' Etudes Etudes de Bruyeres la Chatel and Saclay measuring high-energy (p,n) reactions for transmutation of nuclear waste studies.

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EDUCATION:
BS, Physics, University of Oklahoma, 1959
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Ph.D., Biophysics, Columbia University, 1968 EXPERIENCE: Ben Clark has 29 years experience in space sciences, analysis of future planetary missions, and development of advanced instrumentation for specialized applications. His early work involved design of radiation-measurement instrumentation for several scientific satellites, including two Gemini missions and the active dosimeter for Skylab experiment D-008. Dr. Clark was responsible for conceiving and developing the x-ray fluorescence spectrometers for geochemical analyses of Martian soil samples onboard the Viking landers. Development of this experiment included experiments on characterization of detector response to RTG radiation fields, working with RTGs at Mound Laboratory, at Teledyne, and at KSC. He is Co-Investigator and also was Project Manager for development of the lightflash detector and sunshade for the Particle Impact Analyzer (PIA) experiment flown successfully on the ESA Giotto mission to Comet Halley.

In analyzing PIA data, he discovered organic particulates (CHON particles) among the more preponderant cosmic-composition grains and has resolved these particles into distinct sub-populations. He also is Co-Investigator on the Surface Science Package (SSP) for the Huygens probe on the Cassini mission. In addition to his Viking, Giotto, and CRAF/Cassini activities, Dr. Clark has led a laboratory program for innovating new experiments and techniques for planetary exploration, including an x-ray diffractometer for Mars and lunar missions, a rockcrusher/grinder, a Mars sample return canister, Mars drill, advanced x-ray fluorescence spectrometer, and a rover hazard detection system. He has served on NASA's Comet Science Working Groups, the AIAA Space Sciences/ Astronomy and Life Sciences Committees, the Planetary Geosciences advisory committee for Space Station, and the Exobiology Working Group for advanced flight instruments for Mars missions.

In 1979 he participated in the National Science Foundation's "21 North" expedition to the East Pacific Rise and performed field geochemical analyses of copper-rich sulfides recovered from active hydrothermal vents on the ocean floor by the deep submersible, Alvin. Dr. Clark has over 45 publications and 80 reports, abstracts, and presentations in instrumentation, radiation, space science, planetary geochemistry, exobiology and other fields.

Prior to joining Martin Marietta, he was employed by Avco Corporation, Columbia University, Air Force Phillips Laboratory, IBM, and the Los Alamos National Laboratory.

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Dr. Robert C. Reedy has been doing research involving nuclear interactions in extraterrestrial matter and planetary remote sensing since 1969. He received his B.A. in chemistry from Colgate University in 1964 and his Ph.D. in chemical physics from Columbia University in 1969. His doctoral thesis project on mechanisms of nuclear reactions was partially supported by a NASA Predoctoral Traineeship. Dr. Reedy worked as a Postgraduate Research Chemist from 1969 to 1972 with Professor James Arnold of the University of California at San Diego studying cosmic-ray-produced radionuclides in lunar samples and gamma rays emitted from the Moon.
In 1972 he became a Staff Member in the Nuclear Chemistry group of the LosAlamos National Laboratory. In 1986, he switched to the Space Plasma Physics group at Los Alamos. Dr. Reedy has been supported as a NASA PI for lunar and planetary research since 1974. In 1975, he was a Visiting Scientist for two months at the Lunar Science Institute in Houston. For one year in 1982--1983, he was a Guest Scientist at the Max-Planck-Institute for Chemistry in Mainz, Federal Republic of Germany, where, with partial financial support by the Fulbright Commission and the Max-Planck Society, he studied planetary gamma-ray spectroscopy and nuclear interactions in meteorites and planetary surfaces.
He was a Lunar Sample Co-I from 1969 to 1976, a Co-I on the Apollo Gamma-Ray Spectrometer experiment from 1971 to 1973, a PI under the Lunar Data Analysis and Synthesis program for 1974--1978, a member of the Lunar Science Review Panel in 1974--1976, and a member of the comet Rendezvous Asteroid Flyby mission proposal review panel in 1986. Since 1978, he has been a PI in the Planetary Materials and Geochemistry program with his proposals awarded multi-year status. He was appointed to the X- and Gamma-Ray Instrument Development Science Team in 1984 and was selected for the Mars Observer Gamma-Ray Spectrometer Flight Investigation Team in 1986.

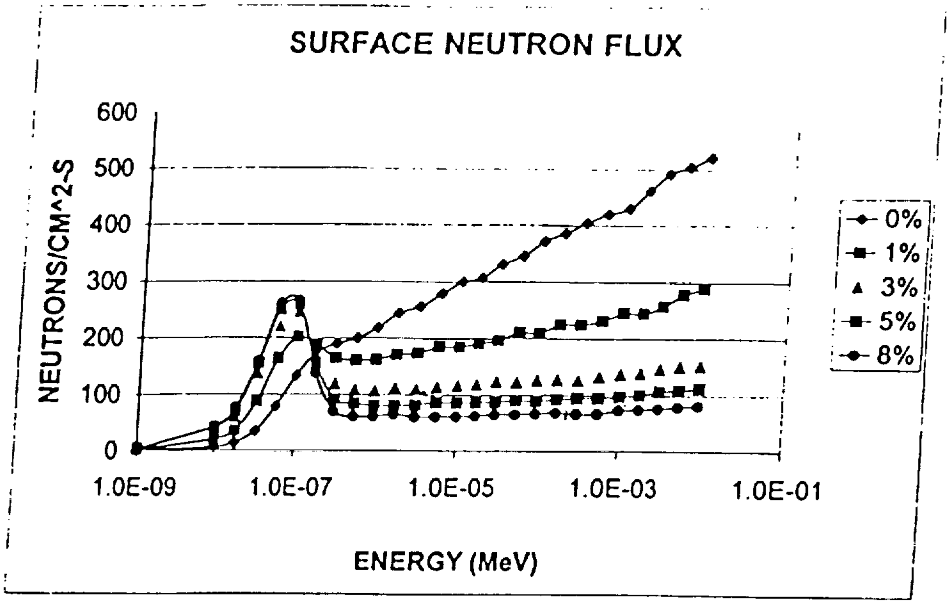

Fig. 1 Martian neutron surface flux from 0.001 to0.01 MeV for different water concentrations. The ordinate scale is arbitrary and is not "per MeV".

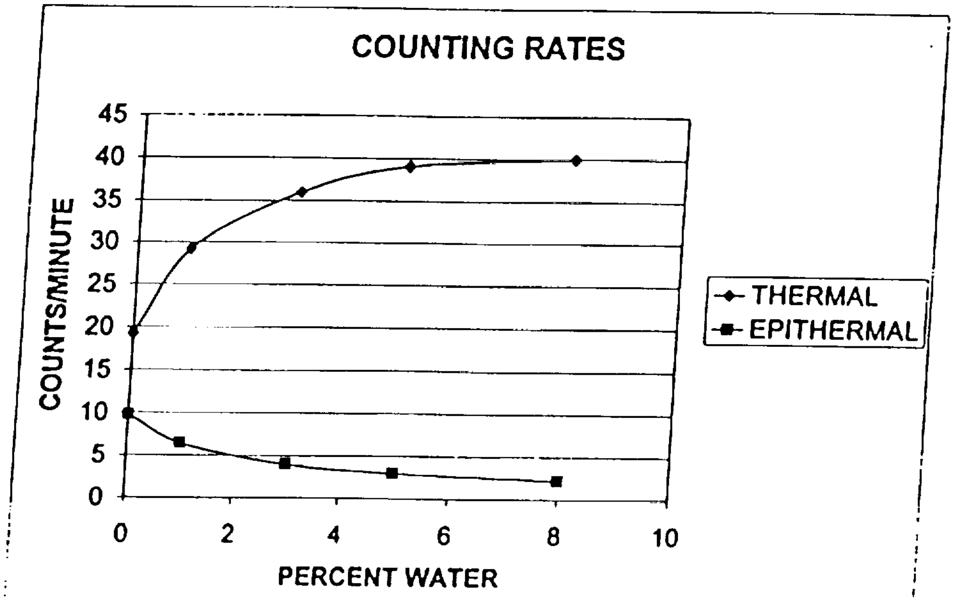

Fig. 2 Counting rates for thermal and epithermal neutrons as a function of water concentration.

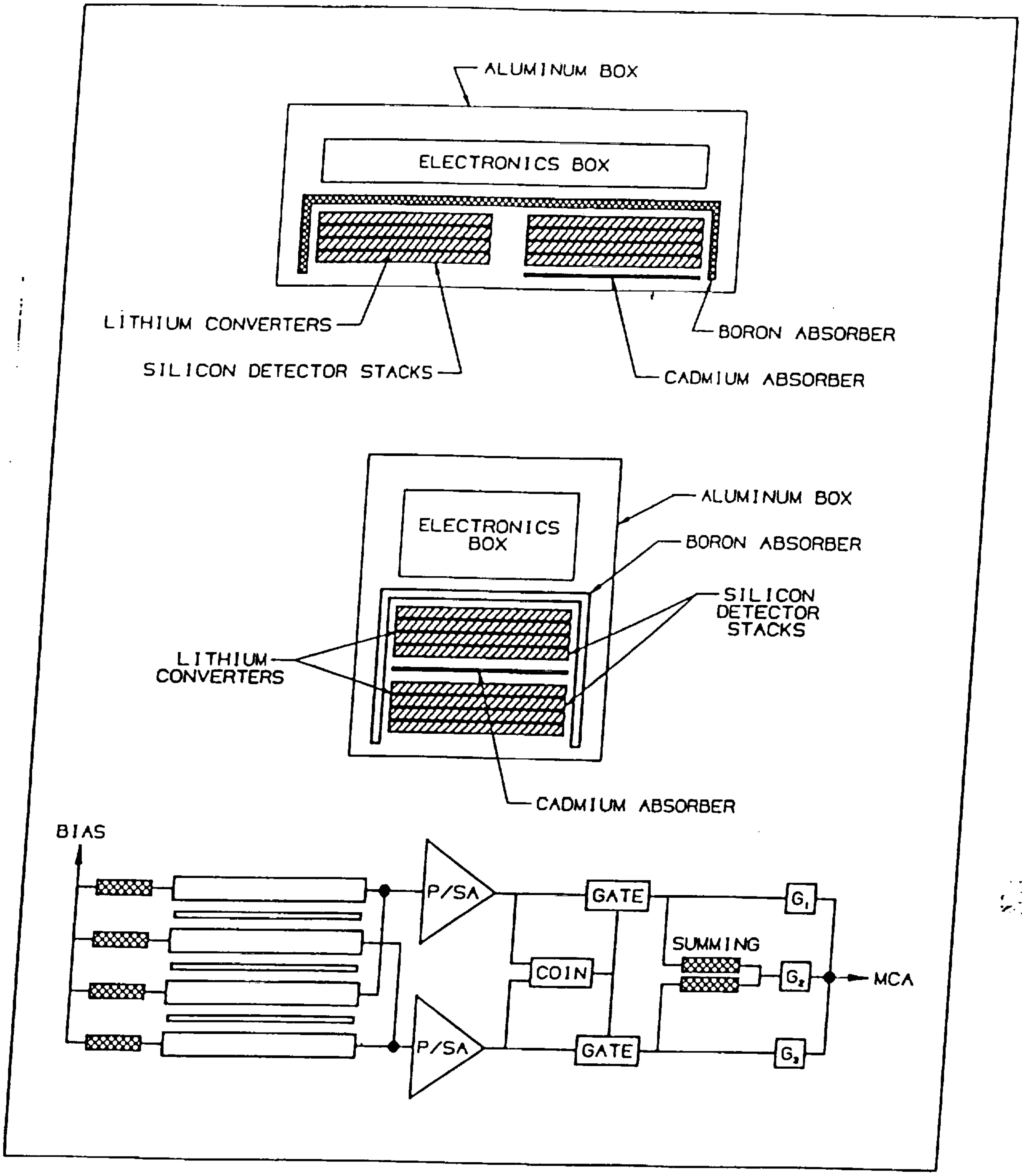

Fig.3 This figure shows two concepts of the detector packaging. Also shown is a simplified electronic block diagram. The silicon detectors are about 5 cm in diameter.

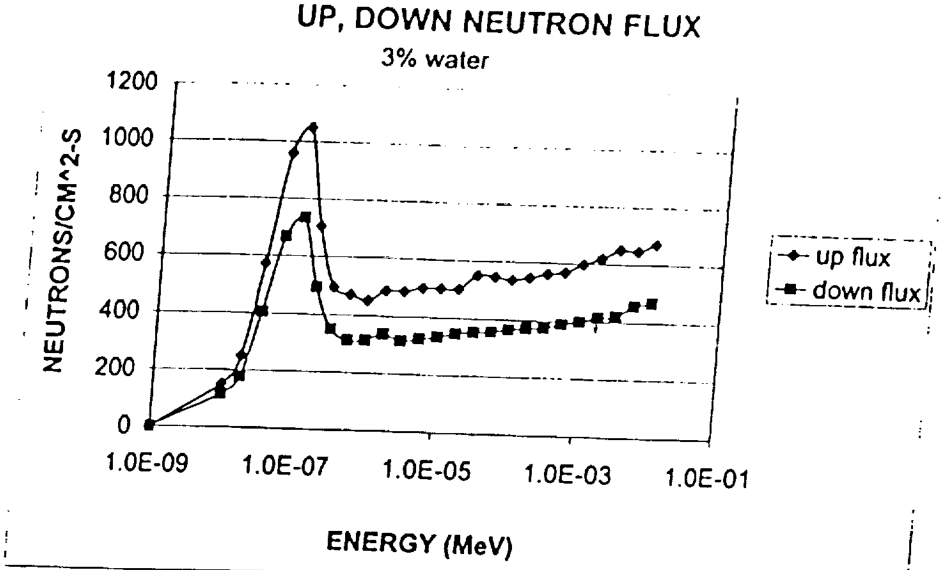

Fig. 4 Neutron flux at martian surface showing the division between up and down flux.

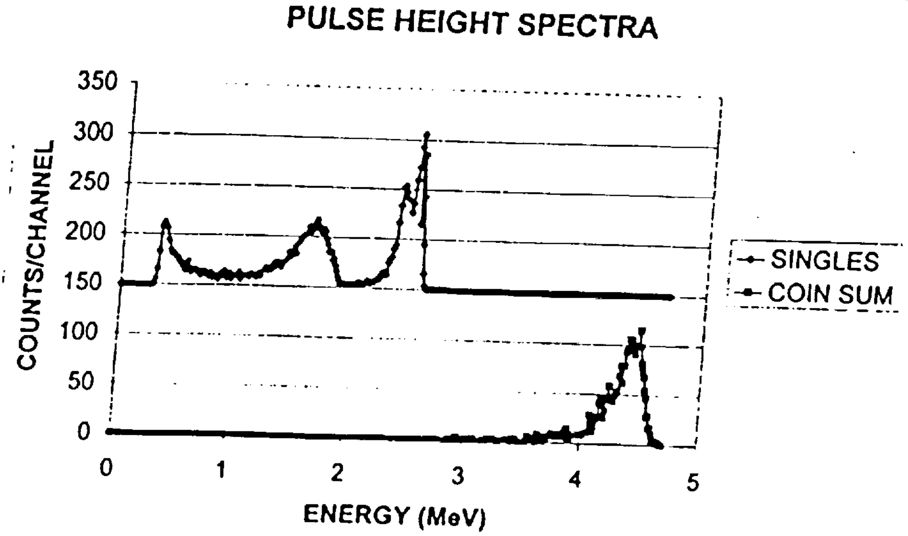

Fig. 5 Pulse height spectra from a silicon+ lithium sandwich detector. the upper, singles curve is displaced by 150 counts. The bottom curve is the coincidence-summed pulse height.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
10/28/98

3. REPORT TYPE AND DATES COVERED
FINAL 9/10/97 to 10/31/98

4. TITLE AND SUBTITLE
Assay of the Martian Regolith with Neutrons

5. FUNDING NUMBERS
C NASW-5030

6. AUTHORS
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Amparo Corporation
P. O. Box 2687
Santa Fe, NM 87504-2687

8. PERFORMING ORGANIZATION REPORT NUMBER
Final 95-78

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
NASA Headquarters
Washington, D.C. 20546

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Different aspects of assaying Martian regolith using neutrons have been investigated. The epithermal portion of moderated neutron spectra is dramatically effected by the presence of hydrogen (usually in the form of water). A simple analytic formula has been derived to describe the amplitude of this portion of the neutron spectrum as a function of water concentration. Several demonstration experiments have been performed and modeled with a Monte Carlo code. Results of these experiments generally agreed with the calculations to within 20%. In addition to ^{3}He detectors, lithium-glass scintillators and ^{238}U fission ion chambers were investigated to determine their applicability to space experiments.

14. SUBJECT TERMS
Neutron counters, epithermal neutrons

15. NUMBER OF PAGES
34

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
UNCLASSIFIED

18. SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

19. SECURITY CLASSIFICATION OF ABSTRACT
UNCLASSIFIED

20. LIMITATION OF ABSTRACT

NSN 7540-01-280-5500

Computer Generated

STANDARD FORM 298 (Rev 2-89)
Prescribed by ANSI Std 239-18
298-102