

SENSITIVITY OF HELIUM-3 COUNTERS FOR DETERMINATION OF THE LUNAR HYDROGEN CONTENT;[†] William C. Feldman and Robert C. Reedy, Space Science and Technology Division, Mail Stop D438, Los Alamos National Laboratory, Los Alamos, NM 87545.

The portions of the Moon explored to date are extremely dry, having hydrogen contents $\lesssim 100$ ppm by weight. This result is expected because the Moon formed very depleted in volatiles and because lunar gravity is not sufficient to prevent escape over geological times. However, several researchers have suggested that this situation may not obtain over the entire lunar surface. In 1961, Watson *et al.* [1] pointed out that retention of water as ice may be possible at polar latitudes within isolated pockets that are permanently shadowed from the sun. Significant deposits could have been added by cometary impacts followed by mixing with surface material caused by the many small meteoritic impacts known to have occurred continuously throughout lunar history [2 – 5].

Hydrogen contents of up to ~ 100 ppm hydrogen by weight exist in mature lunar soils [6]. Indeed, the highest non-polar abundances would be a strong indicator of those surface sites that were exposed to the solar wind sufficiently long to have attained this equilibrium. Such mature soils could be a resource for H and other implanted volatiles.

Several techniques for the unambiguous detection of lunar hydrogen from orbit have been suggested over the years [7 – 11]. Most recently, Metzger and Drake [10] showed that a combined neutron and gamma-ray experiment, based on the gamma-ray-emitting neutron-absorber technique of Haines and Metzger [8], aboard a small lunar polar orbiter could provide a detection threshold of 0.01% water by weight in 10 hours observing time above a surface resolution element at a two-sigma significance limit.

Current plans by the Space Studies Institute of Princeton call for the launch in a few years of the Lunar Prospector spacecraft into a 100-km polar lunar orbit. It will carry two boom-mounted helium-3 (^3He) gas proportional counters. Both will have 20-cm active lengths, 5-cm active diameters, and will be filled to a pressure of 10 atmospheres. One will be wrapped with a 30-mil thick sheet of thermal-neutron-absorbing cadmium to provide a count rate proportional to the epithermal component of the lunar neutron leakage flux. The other will be bare, thereby providing a count-rate proportional to the sum of the thermal and epithermal neutron components. This neutron spectrometer is very similar to that suggested in 1961 by Lingenfelter *et al.* [7] and to the one flown aboard Phobos 1 [11]. A bismuth germanate (BGO) crystal, also planned for this mission, might be able to provide a measure of the fast neutron ($\sim 1\text{--}10$ MeV) flux through detection of (n,n') gamma rays made inside the BGO crystal.

It is of interest, therefore, to estimate the sensitivity of this design to lunar hydrogen and to compare the resultant sensitivity with that calculated for the passive absorber design by Metzger and Drake [10]. Calculations of the neutron leakage spectrum were done for six chemistries. Three chemistries, a ferroan anorthosite, norite, and KREEP basalt are the same as in Metzger and Drake [10]. The others include the KREEP with 1.5 times the concentrations of Gd and Sm in Apollo 14 soils, a mixture of the three Apollo 12 low-Ti chemistries in [10], and an average of anorthositic lunar meteorite compositions. The compositions have a range in effective $1/v$ cross sections for thermal neutrons (Σ_{eff}) covering the expected lunar range of $0.003\text{--}0.010$ cm^2/g . Hydrogen contents equivalent to water contents by weight of 0.01% and 3% were also used with each of these compositions.

The calculations were done using the ONEDANT code [9]. Infinite thicknesses were assumed throughout. Detector count rates were estimated by integrating the surface neutron flux spectrum (projected to 100 km using Liouville's theorem and lunar gravity [12]) weighted by an energy dependent sensor efficiency calculated at normal incidence. Absolute rates were fixed by normalizing to the rate measured using a bare, prototype ^3He counter placed in close proximity to a calibrated thermal neutron pile. Detector count rates ranged between 11/s and 86/s for all lunar chemistries.

The results are summarized in Figure 1. Two count-rate curves are presented. Each data point in the top curve gives an average over all chemistries of the differences in count rates between bare and cadmium-covered detectors ratioed to the count rate of the cadmium-covered detector at a given water fraction (or $[bare/Cd] - 1$), normalized to the same ratio calculated for dry conditions. The error bars give the standard deviation about the mean. The bottom curve gives the normalized mean and standard deviation for the ratio of the current of 1–10 MeV neutrons to the count rate of the cadmium-covered detector. The top and bottom horizontal lines that intercept the top and bottom curves, respectively, give the fractional deviation from the average ratios calculated for each of the dry chemistries. They therefore provide the ultimate detection threshold for determination of water fraction from neutron data without any knowledge of the surface chemistry.

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Inspection of Figure 1 shows that both normalized count-rate ratios increase with increasing water fraction according to a power-law relationship at low water fraction levels. Furthermore, they both display considerable leverage; the fractional change in count-rate ratio is of order 50 times larger than the fractional change in water content. That means that considerably lower precision in determining the count-rate ratio is required to determine any given fractional water content. For example, measurement of a 1×10^{-4} fractional weight of water requires 1% and 0.5% statistics for the top and bottom curves in Figure 1, respectively. This translates to about 0.5 hours of observing time over a given spatial resolution element for the top curve at the 2-sigma level of significance. The required time for that level of precision using the bottom count-rate ratio will be somewhat longer but depends on the size of the BGO crystal used for the gamma-ray detector and its ability to resolve the internally-produced BGO (n, n') signal from ~ 1 –10-MeV lunar leakage neutrons. However, this time limit only pertains if the chemistry can be determined accurately from the gamma-ray data. If the chemistry is not known *a priori*, then the lowest detection threshold is set by the two horizontal lines in Figure 1, about 3.5×10^{-3} and 6.5×10^{-4} for the top and bottom curves, respectively. The time required to achieve this accuracy will then be less than 30 minutes, considerably less than that required by the passive detection technique of Haines and Metzger [8]. However, we emphasize that the ultimate threshold will depend on our ability to determine the chemistry precisely through gamma-ray spectroscopy, as pointed out by Metzger and Drake [10]. The variation for each of the data points in Fig. 1 is a systematic function of Σ_{eff} , the variations of which are mainly determined by the concentrations of Fe, Ti, Gd, and Sm. The first two elements were determined from the Apollo NaI(Tl) spectra and should be easily determined by a BGO detector, while Gd and Sm, if not directly determined, could be estimated from easily detected Th.

References: [1] Watson K. *et al.* (1961) *J. Geophys. Res.* **66**, 1961. [2] Arnold J. R. (1979) *J. Geophys. Res.* **84**, 5659. [3] Arnold J. R. (1987) *Lunar Planet. Sci. XVIII*, 29. [4] Hodges R. R., Jr. (1980) *Proc. Lunar Planet. Sci. Conf. 11th*, 2463. [5] Lanzerotti L. A. *et al.* (1981) *J. Geophys. Res.* **86**, 3949. [6] Bustin R. *et al.* (1984) *Lunar Planet. Sci. XV*, 112. [7] Lingenfelter R. E. *et al.* (1961) *J. Geophys. Res.* **66**, 2665. [8] Haines E. L. and Metzger A. E. (1984) *Nucl. Instrum. & Methods* **226**, 517. [9] Drake D. M. *et al.* (1988) *J. Geophys. Res.* **93**, 6353. [10] Metzger A. E. and Drake D. M. (1990) *J. Geophys. Res.* **95**, 449. [11] Surkov Yu. *et al.*, in *Remote Geochemical Analysis*, in press. [12] Feldman W. C. *et al.* (1989) *J. Geophys. Res.* **94**, 513. † Work was supported by NASA and done under the auspices of the US DOE.

Fig. 1. The calculated ratios of count-rates in the bare or cadmium-wrapped ^3He detectors and of the 1–10 MeV neutron currents as a function of water fraction by weight normalized to that for no water. The horizontal lines are the fractional deviation from the average calculated for the six dry chemistries for each type of ratio.

