HISTORY OF THE LUNAR REGOLITH FROM NEUTRONS, E. L. Fireman, Center for Astrophysics, Harvard College Observatory and Smithsonian Astrophysical Observatory, Cambridge, Mass. 02138.

A statistical model for regolith development based on calculated neutron capture rates and Sm and Gd isotope measurements is used to: (1) obtain soil mixing and deposition rates from measurements of the Sm and Gd isotopes in the Apollo 16 and 15 drill stems, (2) relate parameters of meteor-impact calculations to those of neutron capture calculations, and (3) answer the question of whether the moon is gaining or losing mass by meteor impacts.

Neutron capture rates in Sm^{149} and Gd^{157} have been calculated by Kornblum et al.[1] and by Lingenfelter et al.[2] with procedures used in the theory of nuclear reactors. The capture rates calculated by Kornblum et al.[1] are applied in our analysis; however, the rates calculated by Lingenfelter et al.[2] could be used instead. There are differences between these calculations that change capture rates by approximately 50% and change the ratio of capture rates by much smaller but more physically significant amounts. The Sm and Gd data were taken from the measurements of Russ et al.[3,4]

It is conceivable that the lunar regolith cannot be treated statistically for any period of time; then the Sm and Gd measurements are essentially useless. All data could be fit by the deposition of properly preirradiated lunar material without any restriction on the deposition times. On the other hand, if it is possible to define a time of statistical applicability, then the data can be made very meaningful. This time can be set by two quantities: (1) the ratio of the capture rate in Sm^{149} to that in Gd^{157} and (2) the Gd^{158} enrichment at one depth. If the ratio of the calculated capture rates, $\langle Sm^{149}/Gd^{157}\rangle$, is the same as the ratio of captures that have occurred, then the calculated capture rates can be used back to when the initial Sm and Gd isotopic abundances were primordial. If, however, the ratio of capture rates differs from the ratio of captures that have occurred, then the calculated capture rates apply only for a shorter time. According to the calculations of Kornblum et al.,[1] the ratio of capture rates, $\langle Sm^{149}/Gd^{157}\rangle$, is 0.59 ± 0.01 for Apollo 16 soil, which is essentially the same as the measurement of the ratio of captures that have occurred, 0.60 to 0.64. For Apollo 15 soil, however, the capture rate ratio is 0.62 ± 0.01 and the ratio of captures that have occurred has values clustering around 0.77. The Apollo 16 Gd data can therefore be analyzed with an initial (Gd^{158}/Gd^{157}) ratio of 1.5866, but the Apollo 15 data cannot.

The number of neutron captures, $C(x_0)$, occurring in an isotope currently at depth, x_0, is related to the capture rate, R, by the equation

$$C(x_0) = \int_0^D R(x)\, t(x, x_0)\, dx \quad , \tag{1}$$

where $t(x, x_0)\,dx$ is the time that the material currently at x_0 spends between x and x + dx, and D is the soil thickness. The irradiation time, T, is related to $t(x, x_0)$ by

$$T = \int_0^D t(x, x_0)\, dx \quad . \tag{2}$$

If no soil deposition occurs, then T is independent of x_0, otherwise, generally not. The present (Gd^{158}/Gd^{157}) ratio is related to the initial ratio, $(Gd^{158}/Gd^{157})_i$, by

$$(Gd^{158}/Gd^{157}) = \frac{(Gd^{158}/Gd^{157})_i + \int_0^D R(x)\, t(x, x_0)\, dx}{1 - \int_0^D R(x)\, t(x, x_0)\, dx} \quad . \tag{3}$$

Values for R can be taken from the calculated curves given in Fig. 1. The expression for $t(x, x_0)$ and the boundary conditions necessary to determine (Gd^{158}/Gd^{157}) as a function of depth in (3) can be supplied by a model of soil development. Fig. 2 shows the model we have used. Conversely, some of the parameters in this model can be determined by use of (Gd^{158}/Gd^{157}) measurements in equation (3).

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The deepest samples recovered in the Apollo 15 and 16 drill stems were at 230-cm depth. We therefore chose the bottom boundary in our model of soil motion to be slightly larger, i.e., 250 cm. In our model, soil currently at x_0 spends approximately equal times at depths between $250 - Y(x_0)$ and 250 cm. The time distribution, $t(x, x_0)$, is a square wave; essentially identical results are obtained when $t(x, x_0)$ is a gaussian with width, $Y(x_0)$. With the square waveform for $t(x, x_0)$,

$$T(x_0) = \frac{\left[(Gd^{158}/Gd^{157})_{Meas} - (Gd^{158}/Gd^{157})_i\right] Y(x_0)}{\left[1 + (Gd^{158}/Gd^{157})_{Meas}\right] \int_{250-Y(x_0)}^{250} R\,dx} \quad . \tag{4}$$

The irradiation time, T(230), is assumed to be the minimum time for the occurrence of the deposition of a thick soil blanket (>250 cm). This minimum time occurs when Y(230) = 150 cm. Table 1 gives the irradiation times, the turnover depths, h, and the lunar mass escape rate obtained from the Sm and Gd data, with the condition that the soil thicknesses at Apollo 16 and 15 sites are constant. Since h is defined to be the median depth that has turned over once, $h = x_0/2$ when $Y(x_0) = 250$ cm. The irradiation times at shallow depths are affected by the net balance of irradiated and unirradiated material that leaves and enters the surface. By use of mass balance requirements, the mixing, deposition, and escape rates are determined. The escape rate given in Table 1 is the average for the entire lunar surface. The average escape rate of 80 g/cm^2 aeon can replace the condition of constant soil thickness at the sites to obtain the second approximation to the average mass escape rate from the moon in an iterative approach. If estimates of meteor mass influx rates based on soil composition are used, then the moon is losing rather than gaining mass.

References

[1]J. J. Kornblum, E. L. Fireman, M. Levine, and A. Aronson (1974) Neutrons and the moon. To be submitted to EPSL.

[2]R. E. Lingenfelter, E. H. Canfield, and V. E. Hampel (1972) The lunar flux revisited. EPSL, 15, 325.

[3]G. P. Russ III, D. S. Burnett, and G. J. Wasserburg (1972) Lunar neutron stratigraphy. EPSL, 15, 172.

[4]G. P. Russ III, D. S. Burnett, and G. J. Wasserburg (1973) Regolith stratigraphy and neutron capture. In "Lunar Science IV," p. 642.

Table 1. Quantities obtained for the lunar regolith from Sm and Gd data with the model (Fig. 2).

	Apollo 16	Apollo 15
$(Gd^{158}/Gd^{157})_i$	1.5866	>1.591 <1.592
Irradiation time*	0.90 aeon	<0.35 aeon >0.15 aeon
Turnover	75 cm < h < 115 cm	10 cm < h < 40 cm
Escape rate (first approximation)	~80 g/cm^2 aeon	~80 g/cm^2 aeon

*Equals deposition time of blanket (≥250 cm thick).

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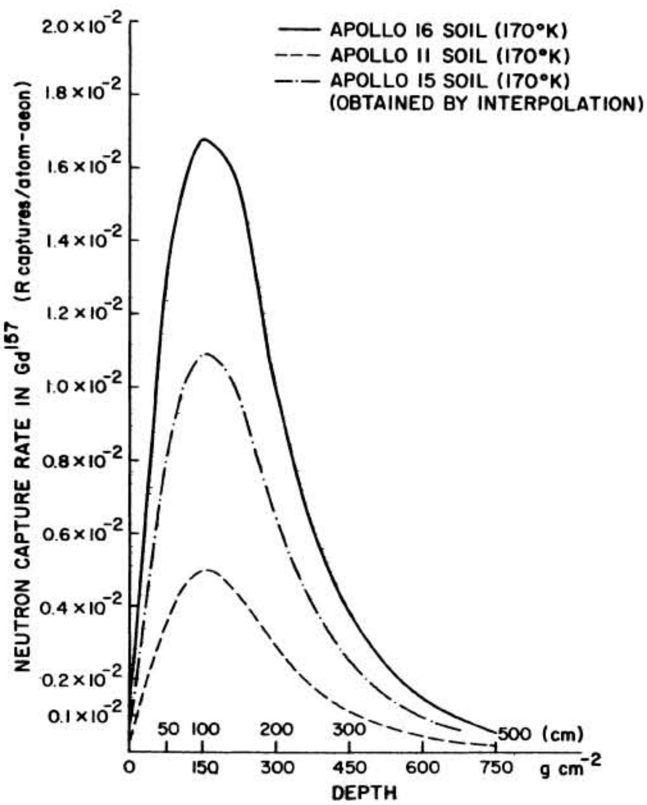

Fig. 1. Calculated neutron capture rates in Gd^{157} vs. depth.

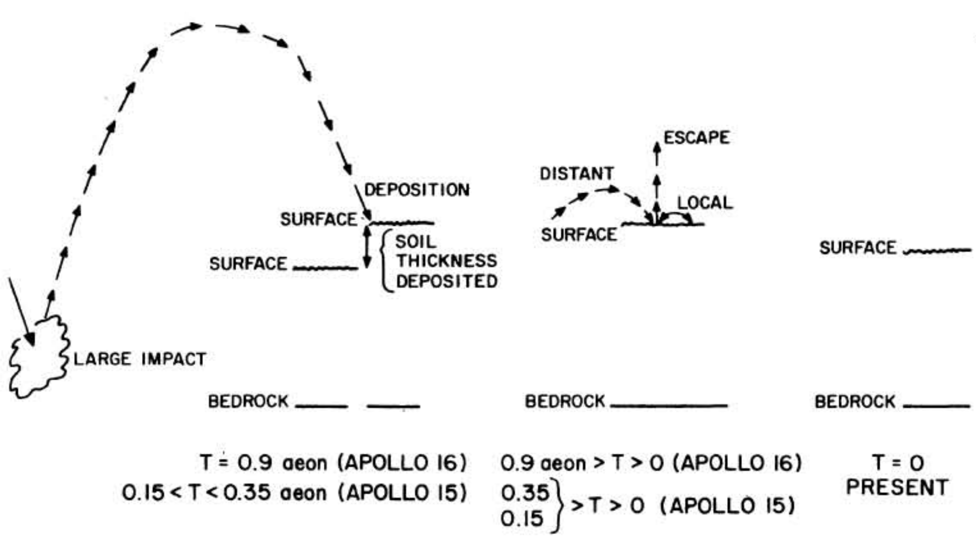

Fig. 2. Model for the development of the lunar regolith.

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