LOW-ENERGY NEUTRONS AND REACTION PRODUCTS IN THE LUNAR SURFACE.* J. Masarik and R. C. Reedy, Astrophysics and Radiation Measurements Group, Mail Stop D436, Los Alamos National Laboratory, Los Alamos, NM 87545 USA.

Depth-dependent neutron production rates, the neutron induced fission rate of ^{235}U, and rates of ^{60}Co, ^{41}Ca, and ^{36}Cl produced by neutron-capture reactions were calculated using the LAHET Code System. Both the absolute magnitudes and the depth profiles for all investigated reactions are in good agreement with experimental data down to 400 g/cm^2. All calculated nuclide-production-rate-versus-depth profiles rise sharply from the surface to a broad maximum from 100–200 g/cm^2 and drop off at greater depths with an e-folding length of about 180 g/cm^2.

Nuclides produced by neutrons in the lunar surface are important as an indicator of exposure history and as a tracer of lunar surface mixing processes. Proper interpretation of the lunar sample data requires knowledge of neutron capture rates and their depth dependence in the lunar surface. Because of their low energies, most solar cosmic rays are stopped by ionization energy losses in the outermost few g/cm^2 without reacting, and therefore we ignored them in our simulations. The nuclear processes involved in the interaction of high-energy galactic cosmic rays (GCR), which penetrate deep inside the irradiated body and produce a large number of secondary particles, were simulated in detail by the LAHET Code System (LCS) [1], which is a system of 3D Monte Carlo particle production and transport codes. The transport of high-energy particles is done within LAHET, and neutrons with energies below a cutoff energy of 15 MeV are further transported to thermal energies (~0.02 eV) by the Monte Carlo Neutral Particle (MCNP) code [2]. LCS together with its adaptations to planetary applications are described in [3]. LCS has been used to calculate cosmogenic-nuclide production rates both in meteorites and lunar samples and gave results that are almost always in good agreement with experimental data [4,5].

The target body was simulated as a sphere with the radius of the Moon, 1738 km. Irradiation of the lunar surface was simulated with an isotropic and homogenous GCR omnidirectional particle flux of 4.56 nucleons/cm^2/s with an energy distribution corresponding to the GCR primary particle flux averaged over a solar cycle [5]. As the particle fluxes are strongly depth dependent, the outer part of the sphere was divided into concentric shells with thickness 6 g/cm^2. In each shell, proton and neutron fluxes were calculated. Statistical errors of the calculated fluxes, running 100,000 primary GCR particles, were less than 3 %. Having calculated the neutron fluxes, the rates of the investigated reactions were calculated by integrating over energy the product of these fluxes with corresponding cross sections. Cross sections were taken from the ENDF/B-VI library [6], which is coupled with MCNP.

We started our calculations with the study of depth and energy dependences of neutron yields. The total neutron yield calculated by LAHET is (29.3±0.15) neutrons per primary GCR-nucleon, and (15±0.1) of them are produced or slowed below the 15 MeV energy cutoff for neutron transport by LAHET. Similar neutron yields were reported by [7]. The depth distributions of neutrons produced with energies above and below 15 MeV and their sum are presented in Fig. 1. The depth distribution of source neutrons with energy below 15 MeV at depths less than ~40 g/cm^2 is fairly flat and decreases exponentially at greater depths with an e-folding length of 165 g/cm^2. This neutron source profile is similar to those used in earlier calculations [e.g., 8,9]. However, this source e-folding length is not that for the lunar thermal-neutron flux because source neutrons (~0.1–10 MeV) have undergone much scattering in the volatile-poor Moon before they are thermalized.

Running MCNP with the above source spatial and energy distribution, differential fluxes of thermal and epithermal neutrons were calculated. The profiles presented in Figs. 2–4 were calculated by using the calculated neutron fluxes with the corresponding cross sections from the ENDF/B-VI file. For the ^{235}U fission rate, the agreement between the Lunar Neutron Probe Experiment data [10] and calculations is fairly good. There are two sets of experimental capture profiles in lunar samples: $^{59}Co(n,\gamma)^{60}Co$ [11] and $^{40}Ca(n,\gamma)^{41}Ca$ [12]. The good agreements between the calculated depth profiles and the measured data are presented in Figs. 3 and 4. The capture rate for $^{35}Cl(n,\gamma)^{36}Cl$ was also calculated, and the ^{36}Cl depth profile is identical with that of $^{40}Ca(n,\gamma)^{41}Ca$ but is (per g-Cl) 88 times larger.

References: [1] Prael R.E. and Lichtenstein H. (1989) *Los Alamos Report LA-UR-89-3014*. [2] Briesmeister J.F. (1993) *Los Alamos Report LA-12625-M*. [3] Masarik J. and Reedy R.C. (1994) *GCA*, *58*, 5307. [4] Reedy R.C. *et al.* (1993) *LPS XXIV*, 1195. [5] Reedy R.C. and Masarik J. (1994) *LPS XXV*, 1119. [6] Garber D. (editor) (1975) *Brookhaven Report BNL-17541*. [7] Dagge G. *et al.* (1991) *PLPSC-21*, 425. [8] Lingenfelter R.E. *et al.* (1972) *EPSL*, *16*, 355. [9] Spergel M.S. *et al.* (1986) *PLPSC-16*, D483. [10] Woolum D.S. and Burnett D.S. (1974) *EPSL*, *21*, 153. [11] Wahlen M. *et al.* (1973) *EPSL*, *19*, 315. [12] Nishiizumi K. *et al.* (1990) *LPS XXI*, 893. * Work supported by NASA and done under the auspices of the US DOE.

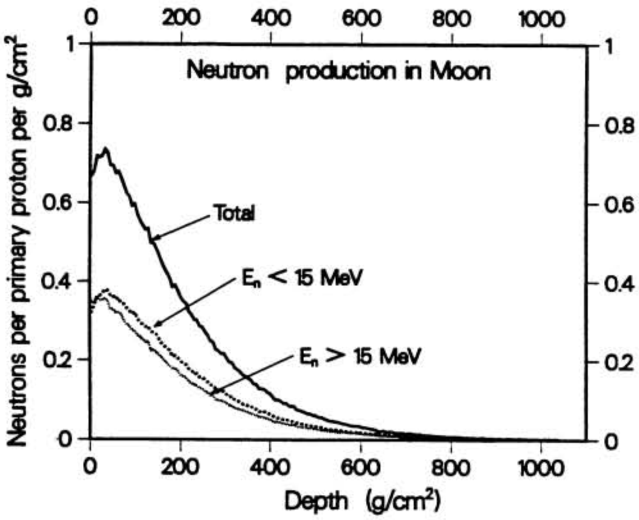


Fig. 1. Neutron production by GCR particles versus depth in the Moon.

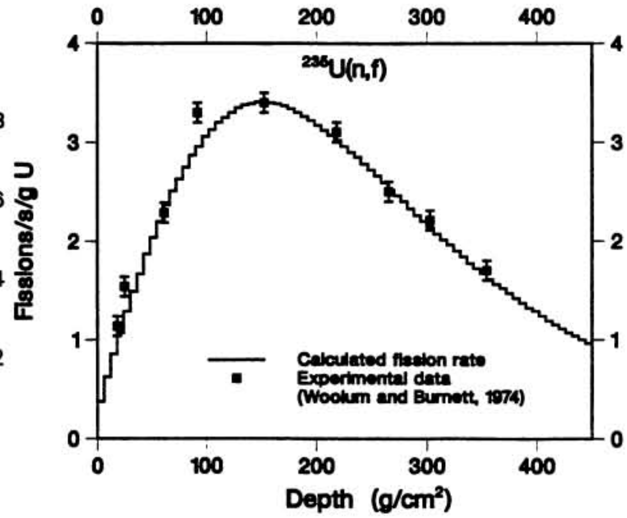
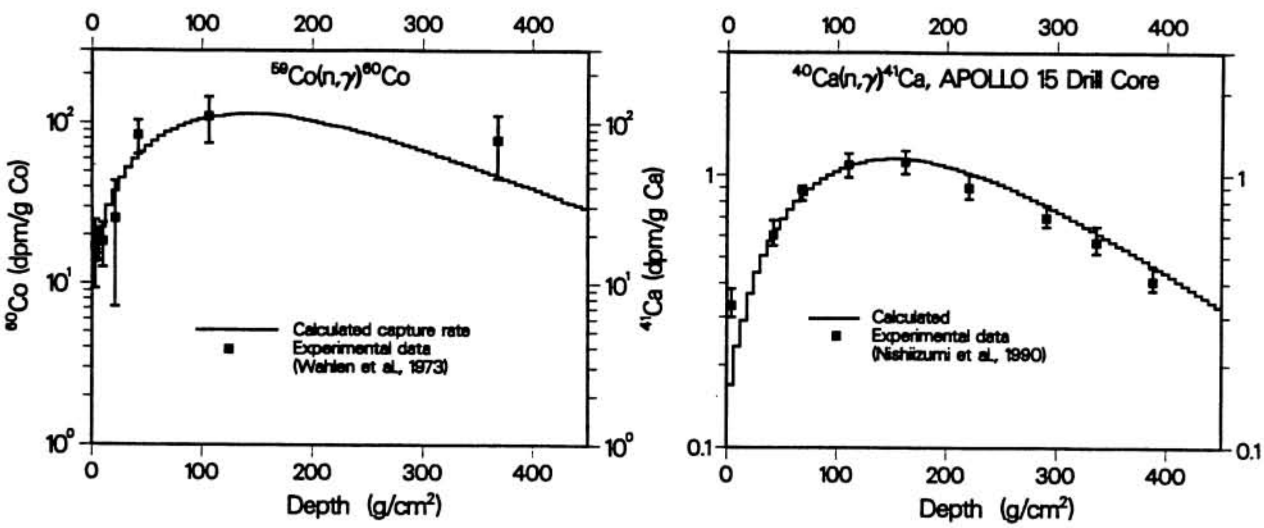


Fig. 2. Calculated (curve) and measured [10] ^{235}U fission rates in the Moon.



Figs. 3 and 4. Calculated activities versus depth (curve) are compared with measured activities of ^{60}Co [11] and ^{41}Ca [12].