Radiation Transport of Cosmic Ray Nuclei in Lunar Material and Radiation Doses

Jim Adams
University of Alabama in Huntsville

RADIATION TRANSPORT OF COSMIC RAY NUCLEI IN LUNAR MATERIAL AND RADIATION DOSES

R. Silberberg, C. H. Tsao, and J. H. Adams, Jr.

E. O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, D. C. 20375-5000

John R. Letaw

Severn Communications Corporation, Severna Park, MD 21146

The radiation environment on the lunar surface is inhospitable. The permanent settlers may work ten hours per 24-hour interval for the two-week-long lunar day on the lunar surface, or 20% of the total time. At moderate depths below the lunar surface (<200 g/cm^2) the flux of secondary neutrons exceeds considerably that in the upper atmosphere of the Earth, due to cosmic-ray interactions with lunar material. The annual dose equivalent due to neutrons is about 20 or 25 rem within the upper meter of the lunar surface. The dose equivalent due to gamma rays generated by nuclear interactions near the lunar surface is only on the order of 1% of that due to neutrons. However, gamma-ray line emission from excited nuclei and nuclear spallation products generated by cosmic rays near the lunar surface is of considerable interest: these lines permit the partial determination of lunar composition by gamma spectroscopy.

INTRODUCTION

The cosmic-ray environment on the lunar surface is inhospitable for permanent settlement. There is no radiation-absorbing atmosphere and no overall magnetic field that deflects charged particles. The annual dose equivalent due to cosmic rays at times of solar minimum is about 30 rem. Also, the lunar surface is not protected from solar flare particles; at energies above 30 MeV, the dose equivalent over the 11-year solar cycle is about 1000 rem. Most of those particles arrive in one or two gigantic flares, each lasting only about two days. These doses greatly exceed the permissible annual dose—0.5 rem for the general public and 5 rem for radiation workers. This difficulty can be overcome, however, by adequate shielding. For permanent lunar residents, it is necessary to construct shelters several meters below the lunar surface. In this paper we estimate the thickness of lunar regolith that must be used for shielding of habitats using the results of our radiation transport calculations.

The primary cosmic-ray nuclei (discussed by Adams and Shapiro, 1985) propagate in the lunar soil and undergo nuclear transformations. Our radiation transport calculations include nuclear interactions, ionization losses, and solar modulation for the stable as well as unstable cosmic-ray nuclides from H to Ni. Also, the production of neutrons and neutron-generated nuclear recoils are taken into account. For radiobiological analysis, the cosmic-ray energy spectra are converted into LET (Linear Energy Transfer or ionization energy deposition) spectra. These are then converted into absorbed doses and dose equivalents as a function of depth of lunar soil and compared with the permissible dose limit of 5 rem/year for radiation workers. The quality factors used are those of Silberberg *et al.* (1984), which are based on and are practically identical to those of the RBE committee to ICRP and ICRU of 1963. The quality factor for neutrons is that of Armstrong *et al.* (1969), *i.e.*, 10 for $0.2 \leq E\ (\mathrm{MeV}) \leq 3$, and somewhat smaller outside this energy interval.

THE PROPAGATION EQUATION

Cosmic-ray nuclei fragment in collision with the atomic nuclei in the lunar soil. The fundamental equation for cosmic-ray propagation that includes the effects of nuclear transformations and energy losses based in Ginzburg and Syrovatskii (1964), is

$$\frac{\partial J_i}{\partial x} = \frac{-J_i}{\lambda_i} + \sum_{j>i} \frac{J_i}{\lambda_{ij}} + \frac{\partial}{\partial E}\left[J_i\left(\frac{dE}{dx}\right)_i\right] \tag{1}$$

Here J_i is the differential flux of cosmic-ray particles of isotopes of type i; x is the path length in units of g/cm^2, dE/dx is the (positive) stopping power; λ_i is the fragmentation mean free path of a nucleus of isotope i; and λ_{ij} is the mean free path of a nucleus of type j yielding one of type i. The cross sections used are those of Silberberg and Tsao (1973), Letaw (1983), and Letaw *et al.* (1983). For a composite material, λ_i and λ_{ij} are weighted over the nuclei of a mixture, with N decomposed so as to represent the individual number of atoms/cm^3 of a given type in the lunar material. For our calculation we adopted the composition given by Reedy (1978), with the relative abundances of nuclei as shown in Table 1. The cosmic-ray fluxes and energy spectra used in our calculations are those of Adams and Shapiro (1985).

CALCULATION OF DOSE

The output of the propagation program yields the energy spectra $J_i(E)$ of all nuclear species at various depths of a given material. For the calculation of the dose, the energy spectra are converted into rate of ionization energy loss (or LET) spectra. Using the abbreviated notation $\frac{dJ_i(S)}{dS} = J_i'(S)$, where S is the stopping power or dE/dx, the integral LET spectrum $N_i(S_o)$ is given by

$$N_i(S_o) = \int_{S_o}^{\infty} J_i'(S)\, dS \tag{2}$$

The absorbed dose rate from nuclides of type i, with stopping power $S>S_o$ is given by

$$\dot{D}_i(S_o) = \int_{S_o}^{\infty} J_i'(S) S\, dS \tag{3}$$

Table 1. Relative abundances of the nuclei of the more common elements in lunar soil

Element	Abundance (%)
O	61
Mg	4
Al	9
Si	16
Ca	6
Fe	4

If x is in units of g/cm^2, J in units of particles/cm^2 s, and E is in units of 100 ergs, then $\dot{D}$ is given in units of rad/s. For the dose equivalent, the integral of (3) contains the quality factor Q(S), defined in terms of LET intervals and approximated as in Silberberg *et al.* (1984). The dose equivalent rate is given in units of rem/s. The doses have been calculated for energy deposition in water, *i.e.*, for biological tissue-like material.

DOSE DUE TO COSMIC RAYS

Figure 1 shows the LET spectra and the integral absorbed dose rates as a function of shielding in lunar material, from 1–200 g/cm^2. The total absorbed dose rate in units of rad/y can be read at the left hand side. (Example: If we want to determine the annual dose at values of LET exceeding 30 MeV/g/cm^2, at a depth of 50 g/cm^2 of shielding, we locate the point on the curve 50, vertically above a LET of 30 MeV/g/cm^2, and read the dose of 0.1 rad/y on the axis, horizontally from the above point.)

Figure 2 shows the corresponding LET spectra with the quality factor included in the integration of (3), *i.e.*, the integral dose equivalent rate, from 1–200 g/cm^2. The units

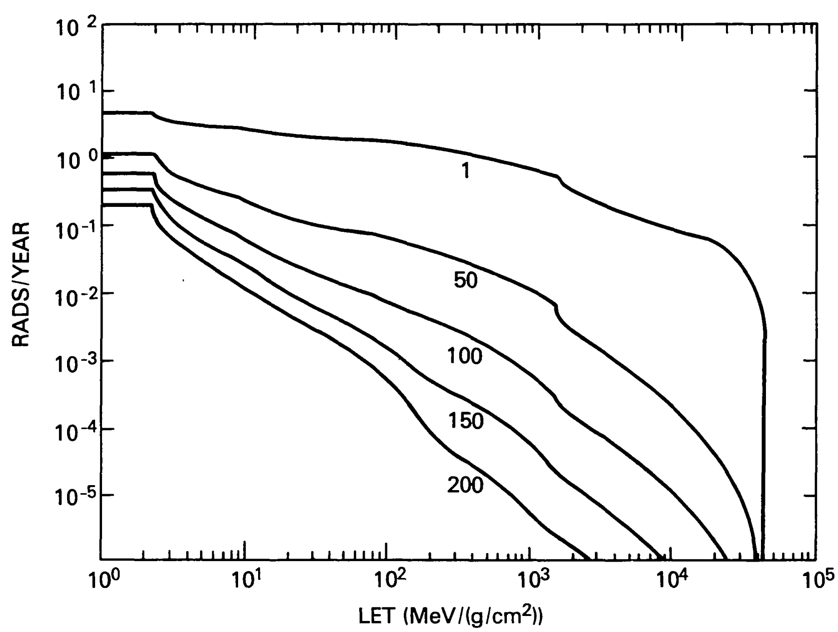

Figure 1. The integral absorbed rates in units of rads/y, as a function of the LET distribution, with shielding from 1 to 200 g/cm² as a variable parameter.

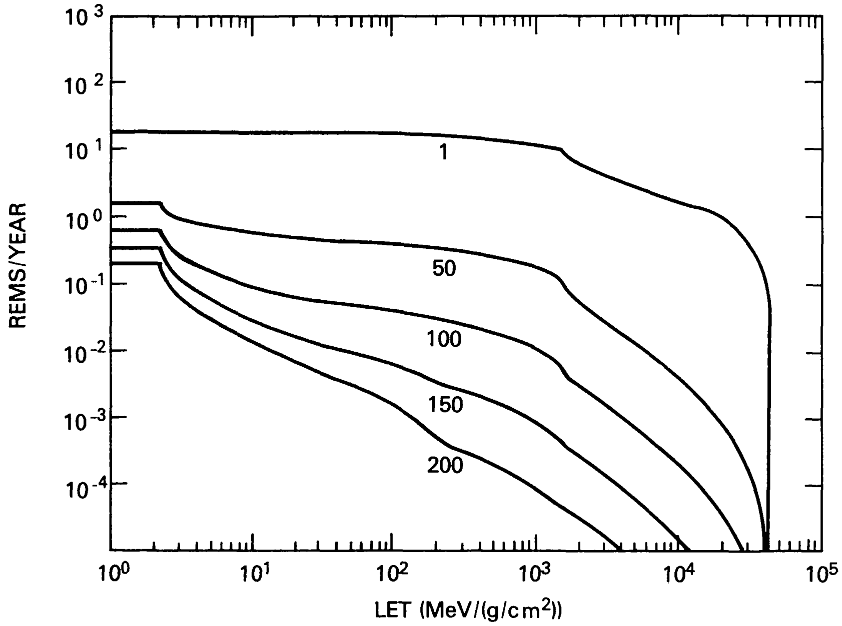

Figure 2. The integral dose equivalent rates in units of rems/y, as a function of the LET distribution, with shielding from 1 to 200 g/cm^2 as a variable parameter.

are rem/y. In both Fig. 1 and Fig. 2, the shoulder above approximately 1500 MeV/(g/cm^2) results from the contribution of the highly ionizing iron nuclei. The large reduction of the dose at high values of LET is due to the depletion of cosmic-ray iron with shielding, both because of its large spallation cross section and high rate of ionization loss, as a result of which slower iron nuclei stop in the shielding.

Figure 3 shows the attenuation of the annual integral absorbed dose and dose equivalent due to cosmic-ray nuclei. After about 100 g/cm^2, the dose equivalent due to nuclei is similar to that of the absorbed dose, because of the breakup of heavy nuclei. However, as we show later, when neutron generated nuclear recoils are considered, the difference between the absorbed dose and the dose equivalent persists.

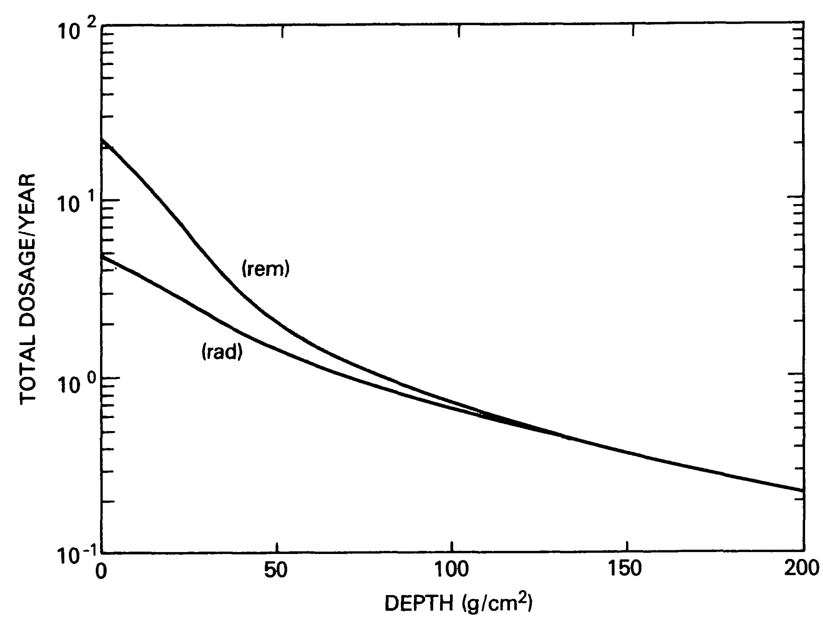

Figure 3. The attenuation of the annual dose due to cosmic-ray nuclei with shielding. The upper and lower curves show the dose equivalent and absorbed dose rates, respectively.

Table 2. The annual dose equivalent due to cosmic-ray generated neutrons

Depth (g/cm^2)	Annual Dose (rem/y)
0	1.5
10	3
20	5
100	13
200	12
300	8
400	5
500	2

DOSE DUE TO NEUTRONS

The dose rate due to neutrons is calculated using, first, the neutron depth profile in lunar material measured by Woolum and Burnett (1974) and the calculations of Lingenfelter *et al.* (1972); second, the energy spectrum of neutrons in lunar soil, calculated by Reedy and Arnold (1972); and third, the relationship between the neutron flux and the absorbed dose and dose equivalent, as a function of energy, given by Armstrong *et al.* (1969). The quality factor for neutrons thus is that of Armstrong *et al.* (1969). Table 2 gives the annual dose equivalent of the neutron dose in lunar material, as a function of depth.

PERMISSIBLE DOSE AND SHIELDING REQUIREMENTS

We note from Table 2 that only for >400 g/cm^2 does the annual dose equivalent become smaller than 5 rem, the permissible annual dose for radiation workers. At the time of a giant flare, like that of February, 1956, the dose over the two-day duration of the flare exceeds the annual dose of Table 2 by an order of magnitude. At the time of such a flare, a shield of 700 g/cm^2 is required to reduce the dose to the level permissible for radiation workers.

For a few astronaut-volunteers over 30 years of age, the Radiobiological Advisory Panel (Langham, 1970) has permitted higher dosages: an annual dose of 38 rem and a lifetime limit of 200 rem. The latter limit is reached in about ten years on the lunar surface even in the absence of solar flares.

Figure 4 shows a comparison of the annual dose equivalent due to cosmic-ray nuclei and neutrons, as a function of depth in lunar material, down to 500 g/cm^2. It can be seen that for a shielding >400 g/cm^2, the annual dose is brought down to the level permissible for radiation workers. Even with such shielding, one receives a dose of 200 rem in 40 years, the permissible lifetime dose for a few astronaut-volunteers. On rare occasions, a few days per 11-year solar cycle, additional shielding is needed at the time of giant solar flares.

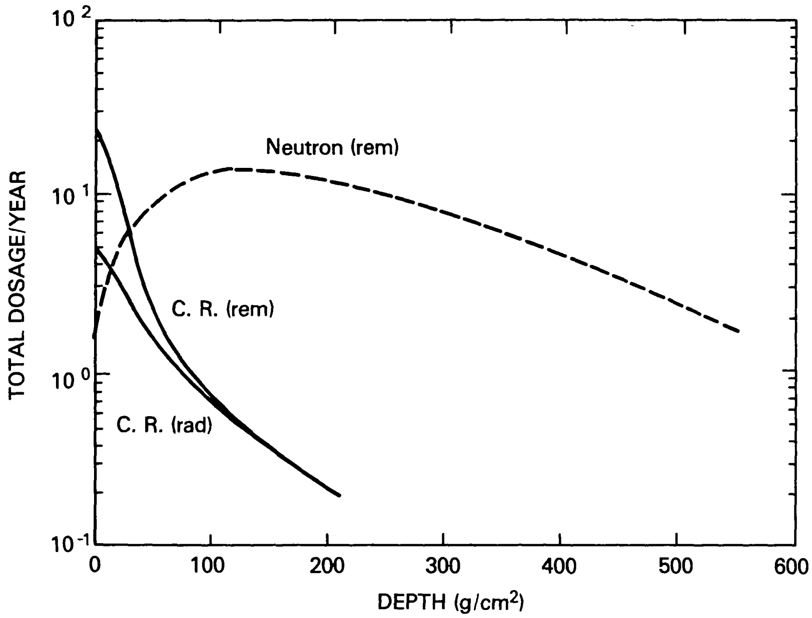

Figure 4. A comparison of the annual dose equivalent due to secondary neutrons and cosmic-ray nuclei, as a function of shielding. Also, the absorbed dose rate due to cosmic-ray nuclei is shown.

The introduction of materials that have large neutron cross sections (Li, Gd) would help to some extent; however, the cross section is large below 0.3 MeV, while a large fraction of neutrons have higher energies and thus are not absorbed; the neutron energy spectrum is given by Reedy and Arnold (1972).

GAMMA-RAY LINES

The biological effects of gamma rays induced by cosmic ray and solar flare particle interactions in the lunar soil are relatively minor. On the other hand, the gamma-ray lines are likely to be useful for mineral prospecting on the Moon. Concentrations of elements like U, Th, Ti, and K can be located as well as the more common elements shown in Table 1. The emission rates of gamma-ray lines on the lunar surface have been explored by Reedy (1978).

CONCLUSIONS

Permanent residents on the Moon can spend about 20% of the time (or 40% of the two-week daylight time) without significant shielding. Most of the time should be spent in shelters of >400 g/cm^2 or about two meters of densely packed lunar soil, either below the surface or at the surface beneath a shielding mound. At the time of rare gigantic flares, shelters >700 g/cm^2 are needed; such a protection is particularly important for radiation-sensitive fetuses.

REFERENCES

Adams J. H., Jr. and Shapiro M. M. (1985) Irradiation of the Moon by galactic cosmic rays and other energetic particles. This volume.

Armstrong T. W., Alsmiller R. G., Jr., and Barish J. (1969) Calculation of the radiation hazard at supersonic aircraft altitudes produced by an energetic solar flare. *Nucl. Sci. Eng., 37*, 337–342.

Ginzburg V. L. and Syrovatskii S. I. (1964) *The Origin of Cosmic Rays.* Pergamon, New York. 426 pp.

Langham W. H. (editor) (1970) *Radiation Protection Guides for Space-Mission and Vehicle-Design Studies Involving Nuclear Systems.* Radiobiological Advisory Panel, Committee on Space Medicine, Space Science Board, NAS/NRC, Washington, D.C.

Letaw J. R. (1983) Proton production cross sections in proton-nucleus collisions. *Phys. Rev. C, 28*, 2178–2179.

Letaw J. R., Silberberg R., and Tsao C. H. (1983) Proton-nucleus total inelastic cross sections: An empirical formula for E > 10 MeV. *Ap. J. Supp., 51*, 271–274.

Lingenfelter R. E., Canfield E. H., and Hampel V. E. (1972) The lunar neutron flux revisited. *Earth Planet. Sci. Lett., 16*, 355–369.

Reedy R. C. (1978) Planetary gamma ray spectroscopy. In *Gamma Ray Spectroscopy in Astrophysics* (T. L. Cline and R. Ramaty, eds.), pp. 98–148. NASA TM-79619, NASA, Washington, D.C.

Reedy R. C. and Arnold J. R. (1972) Interaction of solar and galactic cosmic ray particles with the Moon. *J. Geophys. Res., 77*, 537–555.

Silberberg R. and Tsao C. H. (1973) Partial cross sections in high-energy nuclear reactions, and astrophysical applications. *Ap. J. Suppl., 25*, 315–333.

Silberberg R., Tsao C. H., Adams J. H., Jr., and Letaw J. R. (1984) Radiation doses and LET distributions of cosmic rays. *Rad. Res., 98*, 209–226.

Woolum D. S. and Burnett D. S. (1974) In-situ measurement of the rate of 235-U fission induced by lunar neutrons. *Earth Planet. Sci. Lett., 21*, 153–163.