SHORT-LIVED COSMOGENIC RADIONUCLIDE PRODUCTION IN LUNAR ROCKS; IMPROVED ESTIMATES FOR THE SOLAR PROTON FLUX IN RECENT SOLAR CYCLES. J.M. Sisterson[1], R.J. Schneider IV[1], A. Beverding[2], C.S. Gans[2], K. Kim[2], P.A.J. Englert[2], C. Castaneda[3], J. Vincent[4], and R. C. Reedy[5], [1]Harvard Cyclotron Laboratory, Harvard University, Cambridge MA 02138, [2]Dept. of Chemistry, San Jose State University, San Jose, CA 92192, [3]Crocker Nuclear Laboratory, University of California, Davis, CA 95616, [4]TRIUMF, University of British Columbia, Vancouver, British Columbia V6T 2A3, Canada, [5]Los Alamos National Laboratory, Group NIS-2, MS D436, Los Alamos, NM 87545.

Radionuclides are produced in lunar rocks by cosmic rays bombarding the Moon. Solar cosmic rays (SCR) can only penetrate the top 1-2 cm of the Moon's surface, while galactic cosmic rays (GCR) can penetrate several meters. The cosmogenic radionuclide archive can be analyzed to give information about the solar proton fluxes incident on the Moon over the past 2-10 million years (1). It is important to understand any variation in the Sun's activity over an extended time period so that the radiation hazards that might be met in space missions can be correctly assessed. Reedy, in 1977, analyzed the lunar rocks returned by the Apollo missions for the short-lived radionuclide production and compared the results with contemporary measurements of the solar proton flux (2). Now that there are a) many more direct measurements of the solar proton flux available; b) additional depth profiles measured in lunar rocks; and c) considerable progress in measuring the reaction cross sections needed as input to the theoretical models, new estimates for solar proton fluxes over solar cycles 19 and 20 have been made.

Systematic direct measurements of solar proton fluxes were made by the Solar Proton Monitor Experiment (SPME), which flew on several satellites from 1967 -1973; this period covered most of solar cycle 20 (1965-1975) (3). For solar cycle 19 (1954-1964), mainly indirect measurements were available (2). It should be noted that the solar proton fluxes in solar cycle 19 were generally much higher than those of solar cycle 20 for the period before the Apollo 12 mission. Additional information about contemporary solar proton fluxes is now available from direct measurements of the solar proton flux over solar cycle 21 reported by e.g. Goswami (4), Feynmann (5) and others.

The radionuclides used by Reedy (2) included 77-day ^{56}Co, 312-day ^{54}Mn, 2.73-yr ^{55}Fe, and 2.602-yr ^{22}Na. ^{56}Co and ^{54}Mn, with their short half-lives, were made only by solar protons of solar cycle 20; ^{55}Fe and ^{22}Na by protons of both solar cycles 19 and 20. The theoretical model used to analyze the lunar rock data was that of Reedy and Arnold (6), which requires as input data, good knowledge of the thin target cross sections for the interactions of all cosmic ray particles with all elements found in the lunar rocks. In practice, because 98% of all SCR and 87% of all GCR particles are protons, proton production cross sections are of primary importance. Good cross section data are required for energies higher than those normally found in SCR to allow good corrections to be made for the GCR contribution. The calculations of 1977 used the best data available at the time which were the cross section compilations generated in 1972 (6).

There are now much better cross section data available (for example, 7,8). Figure 1 shows most of the cross section measurements known for Fe(p,x)^{56}Co and Fe(p,x)^{54}Mn; most values shown in this figure were measured after 1977. For ^{22}Na production from Al, Mg and Si, best fit curves have been made to all the available cross section data. Figure 2 shows all known cross section measurements for Si(p,x)^{22}Na and the best fits obtained from all the data known now and the sub-set available in 1972 are shown. Significant differences in these best fits are near threshold - a very important region for production by SCRs, and at proton energies >100 MeV which are needed to make good estimates of the production of ^{22}Na by GCRs.

Using these new cross section values for ^{22}Na production, the Reedy and Arnold theoretical model predicts higher production rates for this radionuclide in lunar rock 12002 as shown in Figure 3. These higher production rates for ^{22}Na imply lower solar proton fluxes over the relevant time period which is solar cycle 20 up to 11/69 and all of solar cycle 19. Calculations made, without refining the GCR correction, indicate that the solar proton fluxes over this time period calculated from ^{22}Na data might be 0.6 of those estimated in 1977 (2).

Revised estimates for solar proton fluxes obtained from analyzes of the short-lived radionuclides in lunar rocks are lower than those calculated nearly 20 years ago, and the difference is due to the greatly improved cross section data that is now available to use as input to theoretical models. These revised estimates are consistent with the direct measurements of the solar proton flux that have been made over the past three solar cycles and also are in agreement with those interpreted from the long-lived radionuclide archive in lunar rocks. All these data indicate that the present solar proton flux is not that much different from the ancient solar flux so that using both modern and ancient fluxes to estimate the hazards that might be met in space by manned missions is entirely reasonable.

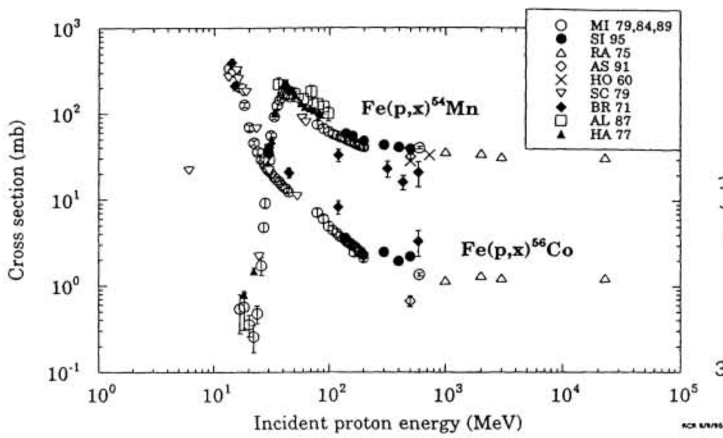

Fig.1. Cross sections Fe(p,x)^{56}Co & Fe(p,x)^{54}Mn.

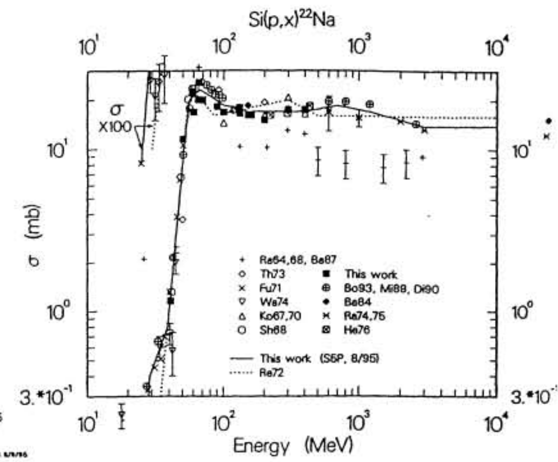

Fig.2. Si(p,x)^{22}Na cross section compilation.

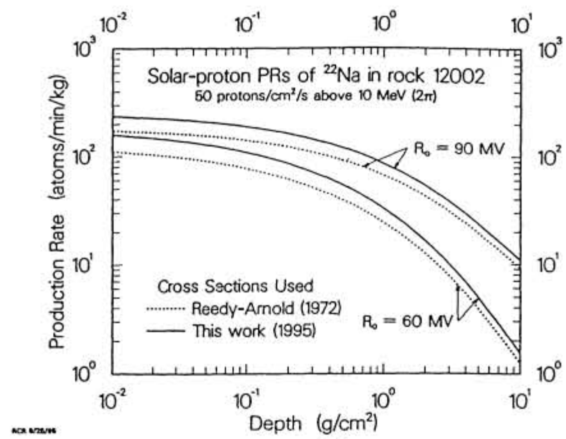

Figure 3. Production rate of ^{22}Na in lunar rock 12002.

REFERENCES. (1.) Reedy R.C. and Marti K., (1991), in *The Sun in Time*, (The University of Arizona Press), 260. (2.) Reedy R.C., (1977), *Proc. 8th Lunar Science Conference*, 825. (3.) Bostrom C.O. *et al.*, (1967-73), *Solar Geophysical Data*, Misc. Volumes. (4.) Goswami J.N. *et al.*, (1988), *J. Geophys. Res.* 93A,7195. (5.) Feynmann J. *et al.* (1990), *J. Spacecraft Rockets* 27, 403. (6.) Reedy R.C. and Arnold J.R. (1972), *J. Geophys. Res.* 77, 537. (7.) Bodemann R. *et al.*, (1993), *Nucl. Instr. Meth. in Phys. Res.* B82, 9. (8.) J. M. Sisterson *et al.*, (1995) *Meteoritics* 30, 579.