DEPENDENCE OF ENERGY INTEGRATED CROSS SECTIONS OF NEUTRON-INDUCED REACTIONS ON THE NEUTRON ENERGY SPECTRUM. J. M. Sisterson[1], R. C. Reedy[2], K. Nishiizumi[3], [1]Francis H. Burr Proton Therapy Center, Massachusetts General Hospital, 30 Fruit Street, Boston, MA 02114, USA, jsisterson@partners.org, [2]Institute of Meteoritics, University of New Mexico, Albuquerque, NM 87131, USA, rreedy@unm.edu, [3]Space Sciences Laboratory, 7 Gauss Way, University of California, Berkeley, CA 94720, USA, kuni@ssl.berkeley.edu.

Introduction: Theoretical models used to calculate production rates in extraterrestrial samples and the earth's surface need good cross section measurements for reactions induced by all cosmic ray particles. For solar energetic particles and near the surface for galactic cosmic rays, cross sections for proton-induced reactions are the most important, while at depth in an object; neutron-induced reactions also produce significant quantities of cosmogenic nuclides [1]. In the terrestrial environment, the primary cosmic rays interact with the earth's atmosphere so that on the earth's surface, neutron-induced reactions are the primary source of cosmogenic nuclides [2]. Ideally, one needs cross section measurements at unique proton and neutron energies. At this time, most of the cross sections for proton-induced reactions are well measured but this is not the case for neutron-induced reactions, where there are very few cross section measurements for relevant reactions at energies >~30 MeV. Over the past 10 years, we have been measuring as many relevant cross sections as possible using both quasi-monoenergetic neutron beams and 'white' neutron beams using facilities at iThemba LABS, South Africa (iTL), and the Research Center for Nuclear Physics, Osaka University, Japan (RCNP) for energies from ~70 – 400 MeV and at the Los Alamos Neutron Science Center, Los Alamos (LANSCE) for 'white' neutron beams with energies ranging from 0.1 – 750 MeV [3, 4, 5, 6, 7].

Experimental Method: The details of the irradiations at LANSCE and iTL are given in refs [3, 4], while the irradiation at RCNP adapted the technique used at iTL [7] and was completed recently so that little relevant data is available. In all cases, the cross sections for reactions producing relatively short lived radionuclides in the targets and monitor foils are measured using non-destructive gamma-ray spectroscopy. In the near future, we expect to have cross section measurements for the production of long-lived radionuclides (e.g., ^{10}Be, ^{26}Al, and ^{36}Cl) using Accelerator Mass Spectrometry. Targets that have been irradiated include: C, N (as Si_3N_4), O (as SiO_2), Mg, Al, Si, K (as KNO_3), Ca (as $CaCO_3$), Ti, Fe, and Ni. Monitor foils of Al, Ni, Cu, and Au were included in all target stacks.

One interesting feature that we have been able to incorporate into some of our measurements using 'white' neutron beams at LANSCE was the measuring of the same energy integrated (average) cross sections using beams with different but well known energy spectra. These beams were produced by adding either 5 cm or 15 cm of polyethylene well upstream of the target stack in the same beam line 4FP15R. The different spectra are shown in Figure 1: a significant number of the low energy neutrons are removed from the beam when the additional polyethylene is in place (15 cm, second from the bottom curve in Fig. 1) with lesser numbers being removed at higher energies (5 cm, top curve in Fig 1).

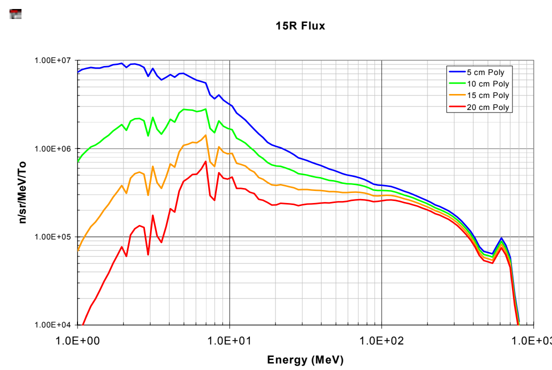

Figure 1: Different energy spectra used at LANSCE.

Results: Average cross sections for many reactions producing relatively short-lived radionuclides were measured using both the harder and softer energy spectra in both some targets and almost all monitor foils. It was estimated that for these two spectra, the average cross sections should differ by no more than a factor of 2 but the dependence on the exact composition of the spectra was unknown. Earlier work has shown that if cross sections measured at unique neutron energies are unmeasured that average cross sections are a good indicator of the values that a cross section might assume at high energies [8, 9] and that broad observation might still be true for different energy spectra.

To test these hypotheses, reactions for which there were at least 2 cross section measurements for a particular reaction, where the cross section was > 10 mb, and where the measurement errors were < 20% were selected. Thus a subset of all the measurements was selected and for the above criteria, these were selected reactions off Au, Ni and Cu. These measurements were made over a period of several years and the underlying assumption (more or less true) was that the beam conditions did not change significantly.

The results of these comparisons are given in Table 1, where the ratio of the cross sections measured with the harder spectrum to that measured with the softer spectrum are computed.

The cross sections in Table 1 cover a wide range of reaction parameters; span half-lives from 35.6 hour to 5.27 yr; have threshold energies (Th.) from 0 to 20 MeV; and have cross sections from ~11 to ~220 mb. The errors on the ratios were too high and sample sizes too low to be able to sensibly use any statistical techniques to see if the cross sections for these two energy spectra belonged to the same sample population, i.e., were indistinguishable. There does, however, seem to be a systematic trend where as the threshold increases, the ratio increases as well but never is greater than 2, thus confirming one of our original hypotheses.

Table 1: Average cross sections

	Half-life	Th.	Cross sections (mb)		
		MeV	5 cm	15 cm	Ratio
Au					
^{198}Au	2.70 d	0	15±2	11±1	0.8±0.2
^{196}Au	6.18 d	8	222±25	182±12	0.8±0.2
^{194}Au	1.58 d	23	113±13	126±9	1.1±0.3
Cu					
^{60}Co	5.27 yr	3.5	15±2	13±1	0.9±0.2
^{58}Co	70.9 d	15	28±3	35±1	1.3±0.3
^{57}Co	272 d	20	19±2	26±1	1.3±0.3
Ni					
^{58}Co	70.9 d	0	110±13	29±3	0.5±0.1
^{57}Co	272 d	10	130±15	124±3	1±0.2
^{57}Ni	35.6 hr	13	16±1	17±1	1±0.1
^{54}Mn	312 d	15	18±2	24±3	1.4±0.4
^{56}Co	77.3 d	15	29±3	32±2	1.1±0.3
^{51}Cr	27.7 d	20	25±3	33±1	1.3±0.3

Discussion: We have already shown [8, 9] that better estimates of production rates can be made if cross sections for neutron-induced reactions are included explicitly. We have also shown that for all the cross sections that we have measured for neutron-induced reactions that the average cross sections are consistent with those measured at unique energies and can constrain the range of values that cross sections at high energies might assume [4, 5]. Using these average cross sections might be the best method to use as a proxy at high neutron energies. There are other techniques commonly used as proxies, which include calculations of the cross sections from nuclear models [4]; extracting the cross section from irradiation of thick targets [10]; or using fits to measurements made in the forward direction of a neutron beam [11]. All of these techniques have strengths and weaknesses and have to be used with care; nothing is as good as cross sections measured at unique neutron energies, and the next best substitute, at least for high neutron energies, might be the measured average cross sections.

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