Accelerator-based Sources to Simulate Albedo Neutrons

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What is meant by albedo neutrons?

Albedo, by definition, refers to radiation reflected back by the surface or atmosphere of a planet or moon. When referring to the neutron component of the radiation field, however, the definition is slightly altered to include neutrons that are created by interactions of the primary radiation field in the surface or atmosphere and backscatter in directions opposite to the direction of the incoming, primary radiation. For example, in low-Earth orbit, primary GCR, SPE, and belt radiation can interact as they enter the atmosphere and create secondary neutrons. Those secondary neutrons are emitted in all directions from the point of interaction. The secondary neutrons that are directed back towards space, away from the atmosphere, are referred to as albedo neutrons. In this case, the neutron albedo will add to the dose received by humans in low-Earth orbit.

A looser definition of albedo neutrons includes all secondary neutrons produced by interactions, not just the ones backscattered towards the point of interest. Although technically this is not a correct definition, it is used to simplify the discussion of neutron dose for operations in low-Earth orbit or on the surface of a moon or planet. As such, many times when you see "albedo neutrons" being discussed, they are referring to all neutrons present on the surface or just above the atmosphere of a planet, with no regard for their direction.

How are albedo neutrons created?

Free neutrons, because of their short lifetimes, are not present in the primary radiation field in space. Neutrons are created as secondary products of interactions between the primary radiation field (GCR, SPE, trapped belt) and any matter it encounters in its path, such as the atmosphere or surface of a planet. When the primary radiation undergoes an interaction, it can break up into smaller fragments, with most of the fragments moving forward along the original direction of the primary. Those fragments, such as neutrons, can then undergo further scattering with other target nuclei and eventually scatter back towards the direction of the incoming primary ion. This can be considered part of the "reflected" part of the albedo. Generally, any fragment that has scattered enough to be directed back towards space has lost most of its original momentum, and as a result can have relatively low kinetic energies. In addition to the break up of the primary ion, the stationary, target atom struck by the primary ion can also break up. That breakup is referred to as "target fragmentation" and results primarily in low energy nucleons (neutrons, protons, deuterons, alphas) produced isotropically. Because target fragmentation neutrons are produced isotropically, a fraction of those secondary neutrons are directed back towards space and can arrive there with no further scattering. These neutrons also have low kinetic energies, at least when compared to the kinetic energy of the original primary ion.

What does a spectrum of albedo neutrons look like?

Many measurements of the neutron energy spectrum have been done here on the surface of Earth. Figure 1 shows a typical spectrum of the number of neutrons (energy times the differential flux, or $E \cdot d\Phi/dE$) versus neutron energy at various locations in the United States. Note that in this case, "albedo" refers to the looser definition mentioned in the introduction, where the neutrons being measured come from all directions – from the surface, and from the atmosphere above.

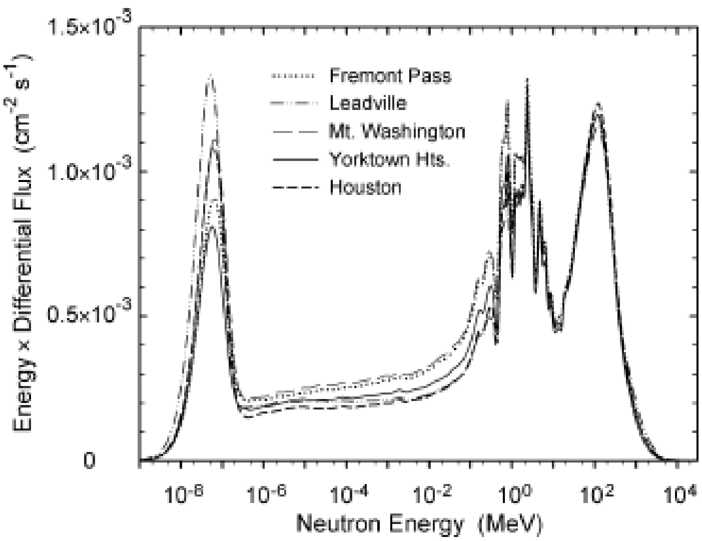

Figure 1. Neutron spectrum as a function of neutron energy at various locations in the United States. Reprinted from "Measurement of the flux and energy spectrum of cosmic-ray induced neutrons on the ground", M. S. Gordon, P. Goldhagen, K. P. Rodbell, T. H. Zabel, H. H. K. Tang, J. M. Clem, and P. Bailey, IEEE Trans. Nucl. Sci 51 (2004).

Technically, the spectrum on the surface of any planet or moon with an atmosphere will have both albedo neutrons with low energies (below 20 MeV) and high energy neutrons that are created by interactions high above in the atmosphere and then continue down towards the surface. The broad peak of neutrons peaked around 100 MeV in Fig. 1 come from high-energy neutrons created by interactions in the upper atmosphere. The series of peaks between 0.5 MeV and 20 MeV come primarily from multiple scattering of high-energy neutrons in the atmosphere and in the ground, and from target fragmentation induced by neutron interactions. There is a large peak of neutrons between 10^{-8} and 10^{-7} MeV that are from thermalized neutrons (neutrons that undergo so many scatterings that they slow down to velocities that are in thermal equilibrium with the surrounding material). The albedo neutrons in this case can be considered to be all of the neutrons except for the high-energy (greater than 20 MeV) neutrons. From the standpoint of radiation protection, however, it doesn't matter what labels are affixed the neutrons. The most important issue is to accurately describe the neutron energy spectrum, no matter what mechanism created them.

In the case of the Earth, with its thick atmosphere and magnetic field, nearly all of the primary GCR and SPE that are not deflected will stop before striking the surface. As such, the dominant mechanism of producing albedo neutrons on the surface will be from backscattering of the high-energy neutrons that strike the surface. Note that in the case of Mars (thin atmosphere) or the Earth's moon (no atmosphere), primary GCR and SPE make it to the surface and can then create low-energy albedo neutrons that scatter back up through the surface.

For surfaces of planets or moons with no atmosphere, the surface spectrum of neutrons will look like Fig. 1 except for the absence of the high energy peak around 100 MeV. Figure 2 shows the results from a calculation done by John Wilson of NASA Langley Research Center, showing the spectrum of neutrons on the surface of Mars that were created by the September 1956 solar particle event. The lines show the neutron spectrum for (1) the total neutron fluence (light-blue line), (2) the forward-propagated neutrons (brown line), and (3) the backscattered albedo neutrons (orange line). Note that the low-energy portion of the spectrum is dominated by albedo neutrons. At about 10 MeV the forward-propagated neutrons start to become dominant, with little albedo contribution above 20 MeV.

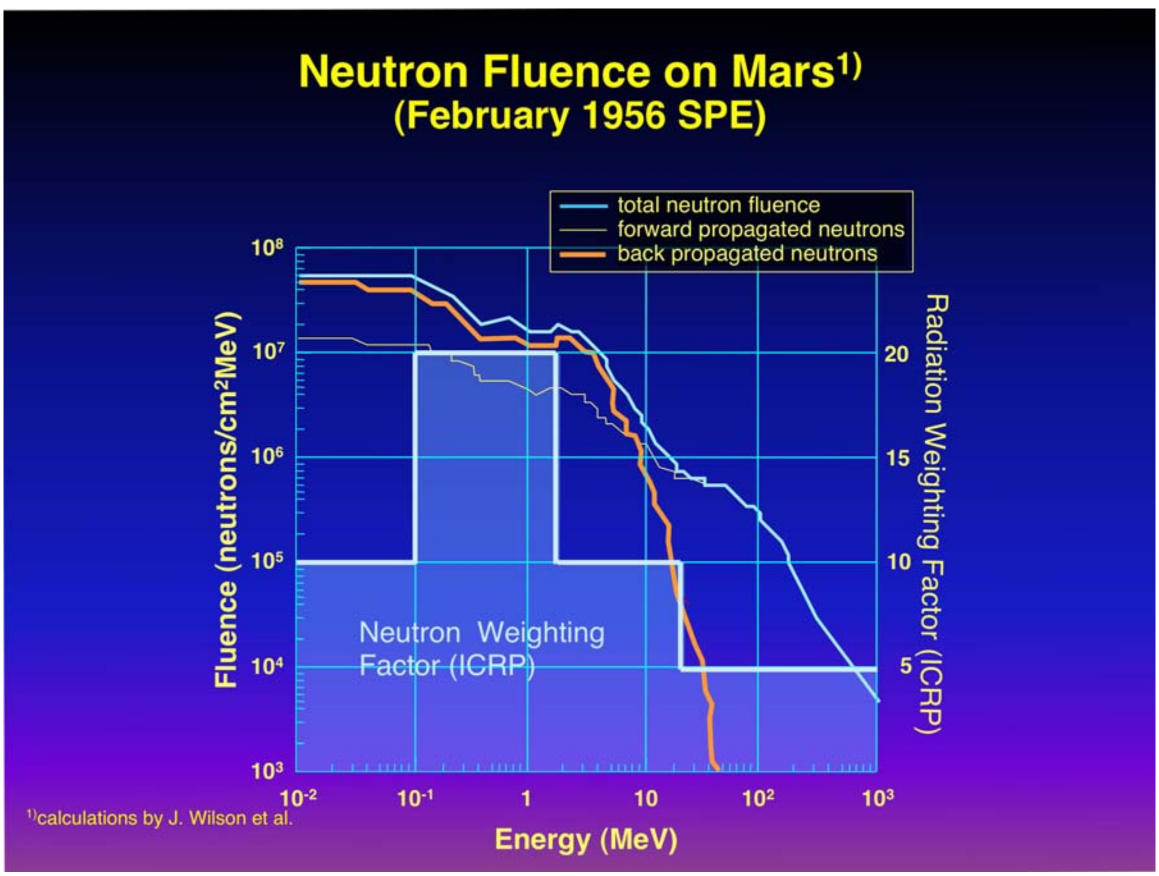

Figure 2. Neutron spectrum on the surface of Mars from the September 1956 solar particle event. The left-hand axis indicates the scale of the spectrum, and the right-hand axis indicates the scale of the radiation weighting factors that are a function of the

neutron energy. The lines indicate the various components of the neutron spectrum, and the histogram shows the weighting factors.

Note that if one is concerned about the surface spectrum inside a lunar habitat, neutrons above 20 MeV will be enhanced due to interactions of the primary radiation with the materials of the habitat. A secondary neutron spectrum inside a lunar habitat created by primary particle and albedo neutron interactions with structural and subsystem components will look similar to the spectrum shown in Fig. 2, except for a relative enhancement of the high-energy (above 20 MeV) neutrons. The shape and magnitude of the spectrum will vary as a function of structural configuration, structural mass, and location within the habitat. Outside of the habitat, on the surface of the moon, the spectrum of albedo neutrons will be dominated by neutrons below 3-5 MeV.

Consequences of albedo and surface neutrons

As with any radiation, neutron exposure will lead to biological and electronic effects. Because the spectrum of albedo and surface neutrons span the range from thermal energies up to several GeV, determining their effect using ground-based experiments will be difficult. If the spectrum is reasonably known, however, it may be possible to test for those effects using accelerator-based neutron sources here on Earth. The approach to testing can take different paths, based upon the type of neutrons produced at those accelerator facilities. Neutron accelerator facilities can be sorted into three major types: (1) Monoenergetic neutron sources, (2) Quasi-monoenergetic neutron sources, and (3) spallation, or "white energy" sources. Monoenergetic and quasi-monoenergetic sources are best for determining the consequences as a function of neutron energy. Spallation sources are ideal for mimicking an albedo or surface spectrum and determining the consequences from one particular broad-energy spectrum of neutrons.

Monoenergetic neutron sources

Monoenergetic neutron sources typically produce neutrons with a single energy below 20 MeV. The spread in energy is below 5%. The neutrons are usually created via ^{7}Li(p,n), ^{3}H(p,n), ^{2}H(d,n) and ^{3}H(d,n) reactions. Other reactions used are ^{9}Be(α,n), ^{14}N(d,n) and ^{15}N(d,n) reactions, although those have broader energy spreads. Table 1 below lists some examples of monoenergetic neutron sources

Table 1. Monoenergetic neutron sources in the U.S, Europe and Japan

Facility	Neutron energy (MeV)	Source reaction	website
National Physics Laboratory (UK)	0.08 – 5, 15.5 – 18	Sc(p,n), ^{7}Li(p,n), ^{3}H(p,n), ^{2}H(d,n), ^{3}H(d,n)	http://www.npl.co.uk/
FNL, Tohoku University, Japan	0.08 – 7.5, 13.5 – 18	Sc(p,n), ^{7}Li(p,n), ^{3}H(p,n), ^{2}H(d,n), ^{3}H(d,n)	http://www.cyric.tohoku.ac.jp/
Indiana University	Thermal – 5	^{9}Be(p,n)	http://www.iucf.indiana.edu/
Boeing (US)	14	d-T	http://www.boeing.com/assocproducts/radiationlab/index.htm
USNA (US)	2.5, 14	d-T, d-D	http://seutest.com/mwiki/index.php?title=USNA

These facilities have been used primarily for electronics testing. Typical neutron fluences at these facilities are between 10^4 to 10^5 neutrons per cm^2 at distances of 10 cm from the production target center. At the NPL in England, fluences are lower (10^3 neutrons per cm^2) because of greater distances between the source and irradiation point. The ambient dose-equivalents are a function of neutron energy, and range between 300 and 2000 mSv/hr^{-1}. Fission chambers are typically used to determine neutron fluence on target.

Quasi-monenergetic neutron sources

Quasi-monoenergetic sources produce a spectrum of neutrons with a peak energy similar to monoenergetic sources (widths on the order of 5% or less). Unlike monoenergetic sources, however, quasi-monoenergetic sources have a low-energy tail of neutrons that extend below the peak energy. The advantage of quasi-monoenergetic sources is that they have greater intensities (~10^6 neutrons/cm^2) at distances of several meters from the source location. Perhaps the biggest advantage is that quasi-monoenergetic sources are able to produce peak neutron energies well above 20 MeV. The disadvantage is the tail of neutron energies below the peak. The tail is a continuum of neutron energies, and can make up to 50% of the total fluence of neutrons. As a result, experiments at these types of facilities include measurements that try to determine the effects of the low-energy tail as well as the effects of the full spectrum of energies in order to separate the effects due only to the peak. Generally, the full spectrum (peak + tail) is produced at forward angles, whereas the tail spectrum is produced at all angles. Thus, a measurement at back angles will yield effects resulting only from the tail portion of the spectrum. Table 2 below gives information on several quasi-monoenergetic neutron facilities around the world.

Table 2. Quasi-monoenergetic neutron sources

Facility	Energy (MeV)	Flux	Website
RCNP (Japan)	392	$3x10^5$	http://www.rcnp.osaka-u.ac.jp/
CYRIC (Japan)	50-85 20-50	$1x10^6$ $1x10^7$	http://www.cyric.tohoku.ac.jp/
TIARA (Japan)	30-85	$1.2x10^5$	www.jaea.go.jp
TSL (Sweden)	25-180	$3x10^5$	http://www.tsl.uu.se/
UCL (France)	20-65	$1x10^6$	http://www.uclouvain.be/fynu
TRIUMF (Canada)	70-200	$1x10^5$	http://trshare.triumf.ca/~raso/www-pif/
UC Davis (US)	40-60	$6x10^5$	http://crocker.ucdavis.edu/

Spallation (white) neutron sources

Spallation neutron sources use high-energy particles (> 100 MeV/nucleon) striking heavy targets to produce a continuum of neutron energies. The spectral shape of the neutron spectrum depends on the angle of production. Because of the reaction dynamics for high-energy interactions, most of the high-energy component of the neutron field is focused in the forward direction. Neutron production can be quite high – as many as ten neutrons per incoming particle.

The shape of the neutron spectrum can be adjusted by using targets of different mass, varying the angle at which the irradiation takes place, and by placing absorbers (such as polyethylene) to decrease the number of low-energy neutrons. The spectrum produced at forward angles by heavy targets is close to the spectrum of terrestrial neutrons. Figure 3 below shows the double-differential spectra at the WNR facility (LANSCE) at Los Alamos National Laboratory. Note that the units are number of neutrons per MeV per steradian per incoming proton (neutrons are produced by bombarding targets with 800 MeV protons). Multiplying the spectra by the energies at each bin will produce spectral shapes very similar to the shapes in Fig. 1.

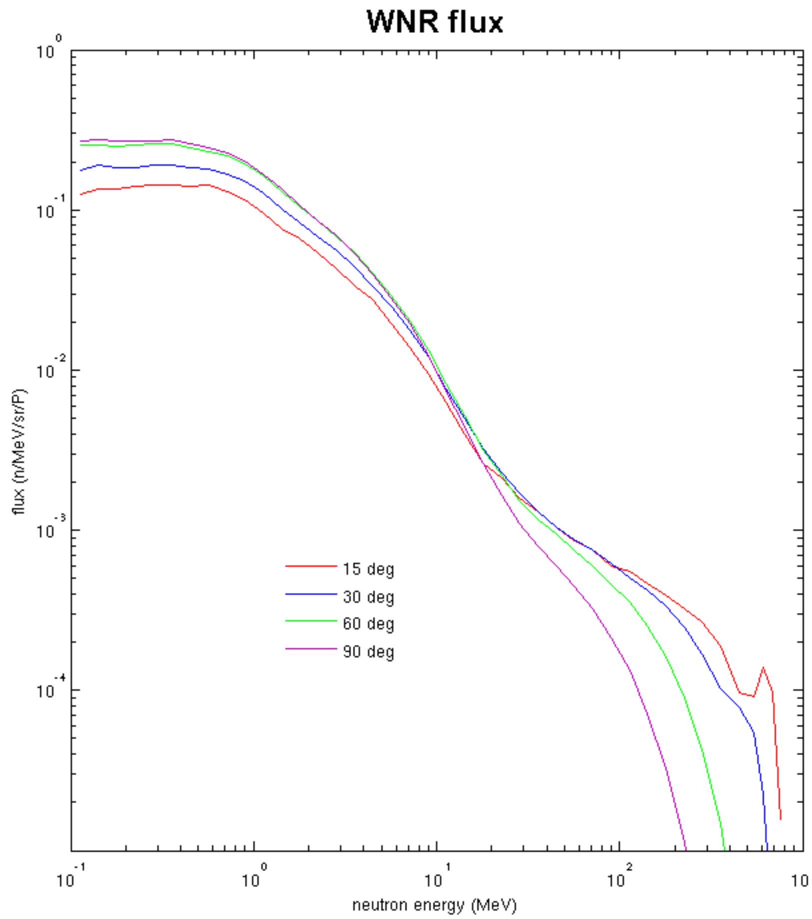

Figure 3. Neutron energy spectra at the WNR facility at Los Alamos National Laboratory.

Table 3 shows a list of some of the spallation neutron sources around the world. Most facilities were developed without much emphasis on biological experiments. However, these facilities now recognize their importance to the field of radiobiology and are actively seeking users in that field. For example, LANSCE (Los Alamos Neutron Science Center) will be hosting a Neutrons in Biology conference October 25 – 28, 2009, with the idea of attracting more biology users of the facility.

Table 3. Spallation neutron sources

Facility	Location	website
LANSCE	Los Alamos, NM, USA	http://lansce.lanl.gov/
SNS	Oak Ridge, TN, USA	http://neutrons.ornl.gov/facilities/facilities_sns.shtml
TRIUMF-NIF	Vancouver, Canada	http://trshare.triumf.ca/~raso/www-pif/
RCNP	Osaka, Japan	http://www.rcnp.osaka-u.ac.jp/

For more information, please see:

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