LA-UR-14-20090
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Title:	MCNP6 Cosmic & Terrestrial Background Particle Fluxes - Release 4
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Intended for:	ANS Annual Meeting, 2014-06-15 (Reno, Nevada, United States)
Issued:	2014-03-05 (rev.1)

MCNP6 Cosmic & Terrestrial Background Particle Fluxes – Release 4

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INTRODUCTION

The galactic cosmic-ray (GCR) source option[1] was implemented in the all-energy, all-particle transport code MCNP6[2] in 2010. This source option along with other newly added features to MCNP6 have been used to produce increasingly accurate global cosmic and terrestrial background flux data files (background.dat).[3] This data file is read and sampled by MCNP6 whenever a user invokes the background source option. The most recent release of this file, Version 3, was produced in 2013. This paper will report on current progress toward enhancements that have been made to the modeling and simulation of these background spectra, which will be implemented in Release 4 of the background.dat file.

Cosmic radiation continuously bombards Earth with various particles, such as protons, α particles, and heavier nuclei, some of which are deflected by the Earth's shielding magnetic field. Particles that carry sufficient momentum can overcome the deflection and penetrate into the atmosphere. The sufficient momentum is dependent on the terrestrial coordinates due to the shape of the Earth's magnetic field and the Lorentz force's proportionality to the sine of the angle between the velocity vector of the incoming particle and the magnetic field direction.

As the particles propagate through the atmosphere, collisions with atmospheric molecules generate secondary particles such as neutrons, protons, photons, muons, pions, and other exotic particles. These secondary particles often have sufficient energy to undergo additional nuclear interactions, and so on, forming what is known as a cascade shower.

The tabulation of background particle fluxes on the surface of the earth is important for a variety of reasons, one of which is the design of nuclear material detection systems.

DESCRIPTION OF ACTUAL WORK

The simulations reported here used various models and data sources to represent atmospheric and terrestrial conditions as accurately as possible. These conditions were used to model the propagation of the initial GCR particles as well as all subsequently produced shower particles through the atmosphere and into the earth's surface.

Cosmic Source Spectra

MCNP6 provides two different formulations of GCR spectra: an older formulation, referred to as LEC (Lal with Energy Cutoffs), proposed by the Physical Research Laboratory (Ahmedabad, India),[4] and a modern formulation developed at the Bartol Research Institute (BRI, University of Delaware, Newark, DE)[5] in 2004. Details about these cosmic spectra options can be found in *MCNP Simulations of Background Particle Fluxes from Galactic Cosmic Rays.*[3] Whenever a user specifies a terrestrial location (via the LOC keyword on the SDEF card), the BRI formulation is invoked, providing automatic normalization of the source and Monte Carlo sampling of light and heavy GCR.

MCNP6 models solar modulation by interpolation of measured data (1965-2005) or parameterized data (for years outside the range), using a specified date (via the DAT keyword on the SDEF card) and a standard formulation.[6] It models geomagnetic modulation by truncating the energy sampling spectrum of protons, alpha, and the heavier particles in accordance to the BRI rigidity cutoff as described in reference 3. Other similar formulations can be found in the literature.[7,8]

Simulation Model

The atmospheric, ocean water, and soil models for Release 4 are relatively unchanged from the last release of the background.dat data file. Atmospheric composition was taken from the U.S. Standard Atmosphere, 1976 model[9] using temperature data from Wolfram Alpha[10] and elevation data from Google Elevation, API.[11] Soil composition from the model by Shue,[12] and naturally occurring radionuclide data from the USGS[13] and BNL.[14] Details on the models can be found in *MCNP6 Cosmic & Terrestrial Background Particle Fluxes – Release 3.*[15] The changes made to the model are the addition of heavy ions to the initial GCR spectrum, location dependent magnetic fields, the inclusion of all rare gases to the atmosphere, and the tracking of π^-, μ^+, and k^-. The magnetic field strength and direction are taken from the World Magnetic Model[16] for each location at 30 km with care taken to match the spatial orientation in the BRI source. The field strength at 30 km was chosen as a relative midpoint altitude in the model as it was found that there was only an average difference of 2.8% between the field strength at sea level versus 65 km. The inclusion of the magnetic field in the particle tracking required the use of a periodic boundary condition due to the asymmetry the field vectors introduced. Additionally, the geometry of the model was slightly enlarged from the previous release to a 2 km by 2 km prism going from 65 km down to 10 m below the elevation specified on the LOC card. A slab of concrete 15.24 cm thick was also placed on top of the ground to better simulate surfaces in metropolitan areas.

Simulation Details

The GCR source was positioned at the top of the atmosphere (65 km) and was specified to produce particles with velocity vectors that have a truncated-cosine distribution relative to the surface normal. Periodic boundary conditions were used to preserve the asymmetry caused by the addition of the magnetic field. The date was specified on the DAT keyword as 9/1/2013.

The MODE card included nucleons (n, q, h, g), light ions (d, t, s, a), pions (z, /,*), kaons (k,?), photons (p), muons (|,!), and heavy ions (#). An upper energy cutoff of 1 TeV/n was used with an average value of 28 TeV/n used for the heavy ions, along with the default CEM and LAQGSM physics modules.

The cosmic particle flux was computed at 2054 terrestrial locations to match the University of Delaware, BRI sky-maps.[5] The locations provide a 10^{o} longitudinal resolution and latitudes every 10^{o} from 90^{o} to 60^{o}, every 5^{o} from 60^{o} to 50^{o}, and every 2^{o} from 46^{o} to 0^{o} with the southern hemisphere having a mirrored grid. The simulations ran ten million GCR incoming particles for each terrestrial location. The photon and neutron flux across the lowest air cell, from ground level to 2 meters above ground, was tallied and properly normalized as well as ten equal atmospheric depths from 65 km to ground level. The terrestrial sea water gamma flux was computed for a single composition of water,[9] while the terrestrial soil gamma flux was computed for all grid locations within the continental U.S. (39 grid points). The average of all U.S. locations was used for the soil gamma flux at all locations outside the contiguous U.S. The terrestrial photon flux is extremely variable in location and therefore the background.dat file can be easily modified to incorporate user-supplied spectra for their specific location.

RESULTS

The MCNP6 Release 4 GCR simulations were benchmarked by comparing the ground-level neutron flux of the nearest grid-point (38^{o}N 120^{o}W), adjusted to the proper date and elevation, to measured data taken in 2006 at Sandia National Laboratory, Livermore, CA.[17] In Fig. 2, the neutron flux per lethargy is shown for the measured data along with the grid-point simulation as well as a full

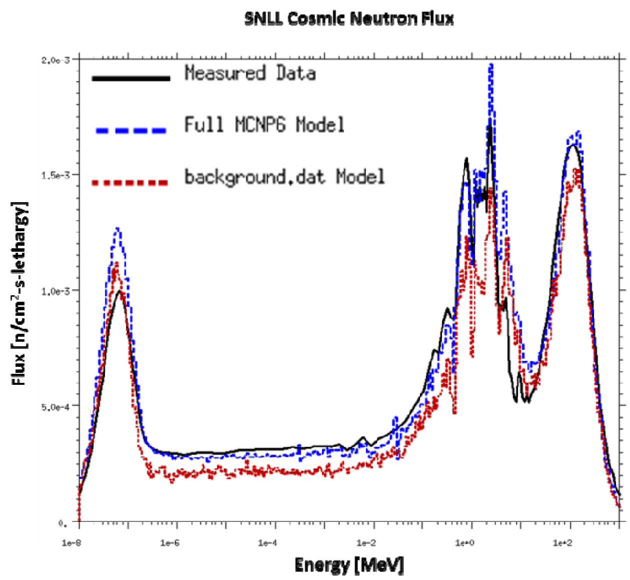

Fig. 2. Measured (black) neutron flux spectra for Nov. 6, 2006 at SNLL (37.7^{o}N, 122.7^{o}W), Livermore, CA. Simulations used 38^{o}N, 120^{o}W with elevation and date adjusted on the SDEF card. The full MCNP6 model (blue) incorporated all building and structural materials, while the background.dat simulation (red) included only soil and concrete on the ground.

MCNP6 model that includes a very accurate representation of the site where the measured data was taken. Both simulation results have a spectral shape that is very similar to the measured data. In the high energy peaks of the spectrum the full model matches more

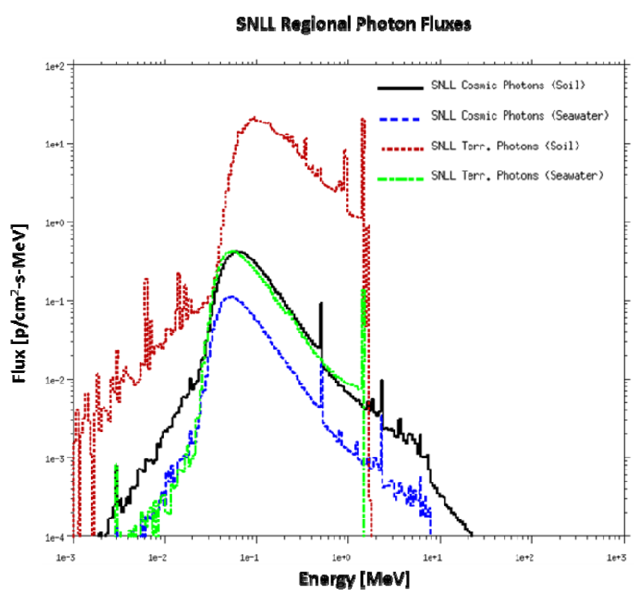

Fig.3. The four sources of photon surface spectra at or near Sandia National Laboratory – Livermore, CA: Cosmically induced over soil (black), cosmically induced over seawater (blue), terrestrially produced from soil (red), and terrestrially produced from seawater (green).

closely, though both are within the stated error bars of the measured data. The grid-point model is ~15% low due to several approximations, such as omission of buildings and structural materials and use of an average temperature and pressure. The full MCNP model is only ~2% high so the building and structural materials are the larger of the affecting factors. The cosmic and terrestrial induced photon spectra at the same location along with the nearest longitude over water (130°W) are shown in Fig. 3.

The 2054 cosmic simulations provided ground/sea-level flux spectra for neutrons and photons at each terrestrial location. Fig. 4 and Fig. 5 indicate the variation in these spectra for various locations on Earth, in particular their variation with elevation. In general, elevation is the most significant factor in the magnitude of a location's spectrum, (i.e., increase with higher elevation) and less significantly with latitude (i.e., increase toward the equator – at least within the U.S.). The statistical errors associated with the major peaks in these spectra are on the order of a few percent.

The cosmic and NORM spectra were combined at each grid location to produce an isotropic neutron and photon background flux within Release 4 of the background.dat file. This data can be automatically sampled by MCNP6 when a user invokes the PAR=[bg|bn|bp] and LOC source options. The LOC option will use the nearest grid location in the background.dat file to the user's latitude/longitude input. The next release of MCNP6 will also include an elevation scaling factor for

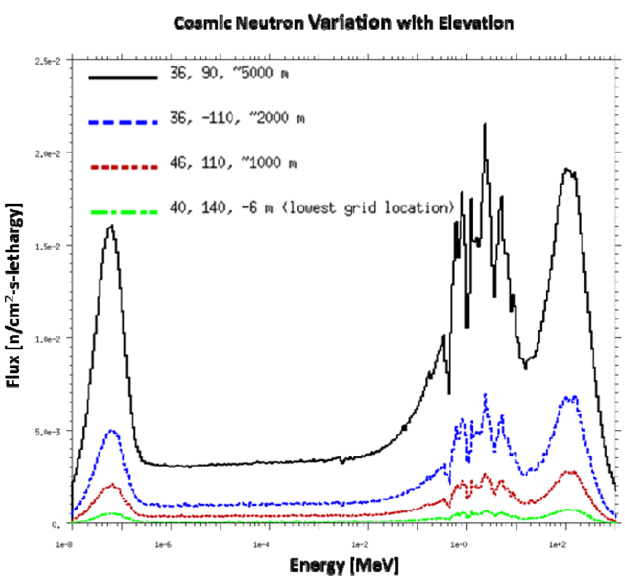

Fig. 4. Neutron lethargy spectra for several locations that vary in elevation, Tibetan region of China (black, 36°N 90°E, elevation 16,476 feet), northeast of Flagstaff, AZ (blue, 36°N 110°W, elevation 6,551 feet), western Mongolia (red, 46°N 110°E, elevation 3,275 ft), and Hachirogata, Japan (green, 40°N 110°E, elevation -20 ft).

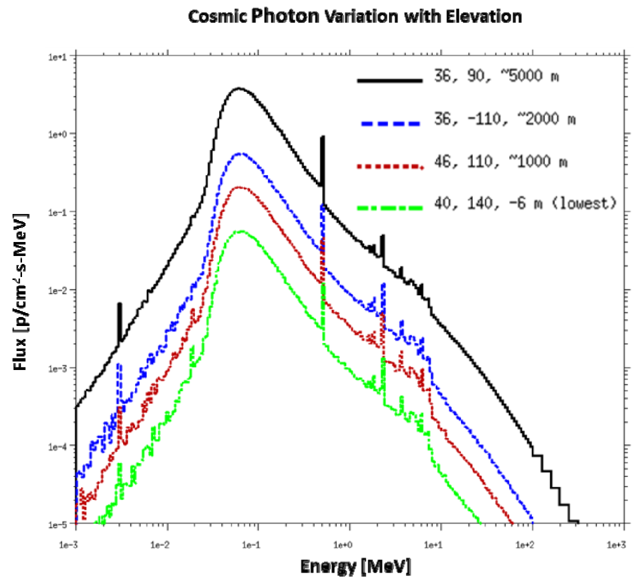

Fig. 5. Cosmic photon differential spectra for the locations specified in Fig. 4.

the integral flux of the spectra requested by the PAR keyword. The last entry on the LOC keyword is the user-specified elevation, and the difference to the nearest grid-point elevation will determine the scaling (see Gordon et al.[18]).

CONCLUSIONS

MCNP6 was used to produce ground/sea-level neutron and photon cosmic and terrestrial background fluxes on a 2054 point grid around the earth. This simulation capability is shown to produce neutron spectra that are in good agreement with measured data. These spectra have been incorporated into Release 4 of the background.dat file which will be included with the second Production Version of MCNP6 (scheduled for release in 2014).

ENDNOTES

This work has been supported by the U.S. Department of Homeland Security, Domestic Nuclear Detection Office, under competitively awarded contract/IAA HSHQDC-12-X-00251. This support does not constitute an express or implied endorsement on the part of the Government.

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