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NEUTRON SKYSHINE FROM A 1-GeV ELECTRON SYNCHROTRON

Y. Uwamino
Institute for Nuclear Study, University of Tokyo
3-2-1, Midori-cho, Tanashi, Tokyo 188 Japan

T. Nakamura
Cyclotron and Radioisotope Center, Tohoku University
Aoba, Aramaki, Sendai 980 Japan

ABSTRACT

The three dimensional (surface and altitude) skyshine neutron distribution around the 1-GeV electron synchrotron (ES) of the Institute for Nuclear Study, University of Tokyo, was measured with a high-sensitivity dose equivalent counter.

Skyshine neutron transport calculations, beginning with the photoneutron spectrum and yielding the dose equivalent distribution in the environment, were performed with the DOT3.5 code and the two Monte Carlo codes, MMCR-2 and MMCR-3, using the DLC-87/HILO group cross sections. The calculated neutron spectra at the top surface of the concrete ceiling and at the point 111 m away from the ES agreed well with the measured results, and the calculated three dimensional dose equivalent distribution also agreed. The dose value increased linearly with altitude, and the slope was estimated for neutron producing facilities.

INTRODUCTION

A number of papers have been published on neutron skyshine from reactors and accelerators, and they deal with the skyshine neutron dose distribution only on the air-over-ground interface. Accelerators installed in densely populated areas are likely to have tall buildings and apartment houses near their site boundaries. In this case, it is essential to evaluate the altitudinal dose distribution in the air, in addition to the ground-level dose distribution around the accelerator facilities.

MEASUREMENT

The measurements were performed when electrons were being accelerated up to 1 GeV, the beam intensity was 5.1×10^{10} electrons/pulse, (i.e., 70 mA) and the acceleration was repeated 21.5 times per second. The whole synchrotron ring is fully surrounded by a 1-m-thick concrete side wall and a 0.75-m-thick concrete ceiling 3.2 m above the ground. An additional, outer concrete shield wall of 1.4 m to 2 m in thickness and about 4 m in height, as drawn in solid bold lines in Fig. 1, can be seen outside the ES building. The concentric circles in the figure indicate the distance from the ring center of the ES.

The neutron dose distribution on the upper surface of the concrete ceiling of the ES, which becomes the skyshine source leaking into the atmosphere, was measured with the Studsvik 2202D neutron dose equivalent counter. At one point, where the highest dose equivalent rate was observed, the neutron energy spectrum was measured with a multimoderator spectrometer incorporating an indium activation detector.[1]

The neutron dose distribution in the environment around the ES building was measured with a high sensitivity neutron dose equivalent counter designed and fabricated at INS,[2] in various directions around the ring center up to 523 m, in order to see the directional dependence and influence of buildings. The surface dose distribution was measured at points 1 m above the ground, drawn as solid circles in Fig. 1 (Nos. 1 – 14), and the variation of the dose equivalent rate with height from the ground was measured at points drawn as solid squares (Nos. H1 – H5) by lifting the counter with a crane. Moreover, the neutron energy spectrum was measured at the point, No. 6, drawn as a double circle, with a multimoderator spectrometer incorporating a ^{3}He counter.[1]

The response function of the Studsvik 2202D is given by the maker. The conversion factors from counts to dose equivalent values are 1.1×10^{-11} and 7.7×10^{-10} (Sv count^{-1}) for the high sensitivity counter and for the Studsvik 2202D counter, respectively. The response functions of the two types of multimoderator spectrometers were given by ANISN adjoint calculations, and checked by experimental results in the national neutron standard field. The reaction rates measured by these spectrometers were converted to the neutron energy spectra by the SAND-II[3] unfolding code with the aid of initial guesses of the spectrum described below.

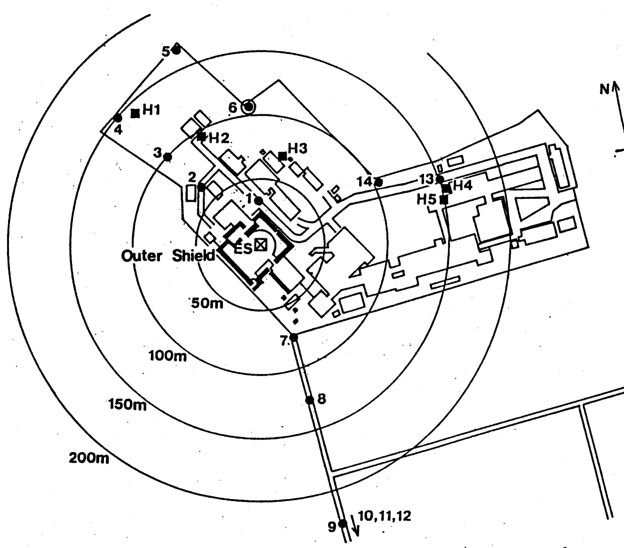

Fig. 1 The site of INS and the measurement points on the ground, plotted as solid circles, and the points above the ground, as solid squares.

CALCULATION

This skyshine experiment was simulated by two different procedures. The first procedure was divided into two steps: 1a) a transport calculation from the photoneutron source to the outer surface of the concrete shield with the two-dimensional discrete ordinates code DOT3.5, and 1b) a skyshine calculation of neutrons leaking from the upper concrete shield with the multi-group albedo Monte Carlo code, MMCR-2.[4] This calculation was insufficient to get the altitude neutron dose distribution in the atmosphere with good accuracy, since the upward polar angular intervals were limited to only eight, because the DOT3.5 calculation used S_{16} angular quadrature.

Another procedure was performed to improve the accuracy of the angular distribution as follows: 2a) the DOT3.5 calculation from the source to the surface of the magnet yoke, and 2b) the transport calculation from the yoke surface through the concrete shield to the atmosphere with a revised Monte Carlo code, MMCR-3.

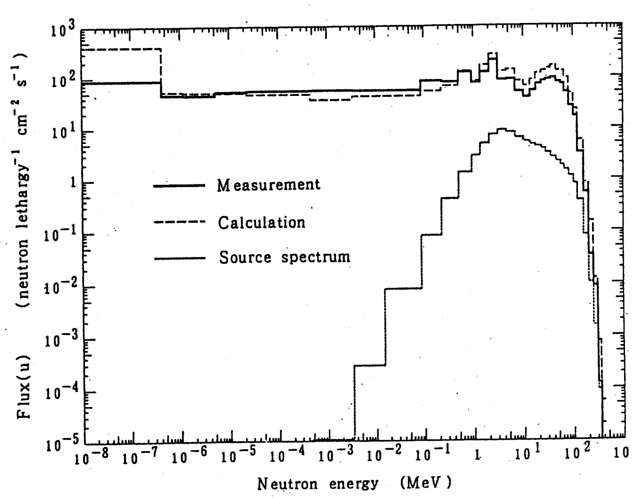

Fig. 2 The source photoneutron spectrum and the measured and calculated neutron spectrum at the outer surface of the concrete ceiling.

The neutrons were generated by photonuclear reactions of bremsstrahlung induced by 1–GeV electrons impinging onto the iron yoke. The neutron spectrum roughly consists of two distinct components: The low energy evaporation spectrum and the high energy direct–emission spectrum. For the high energy neutron components, Gabriel *et al.*[5] gives an analytical representation of the photoneutron energy spectrum resulting from electron incidence at 50 to 400 MeV energy on an infinite copper target. According to this representation, the shapes of the energy spectra are found to be similar to each other for incident electron energies higher than 200 MeV. Therefore, we approximated the neutron spectrum (15MeV$<E_n<$400MeV) from the iron yoke for 1–GeV electron incidence by the spectrum from a copper target for 400 MeV electron incidence given by Gabriel. The low energy evaporation spectrum (0$<E_n<$15 MeV) is adequately described by the Maxwellian distribution whith the nuclear temperature of 2.08 MeV.[6] The whole neutron energy spectrum could be estimated by smoothly connecting the high and low energy components. The source neutron spectrum from the iron yoke thus obtained is shown as a dotted line with arbitrary normalization in Fig. 2.

The cross sections of iron, air and concrete used in this calculation were obtained from the DLC–87/HILO[7] data library. This library consists of 66 neutron and 21 photon energy group constants up to 400 MeV in a P_5 Legendre expansion.

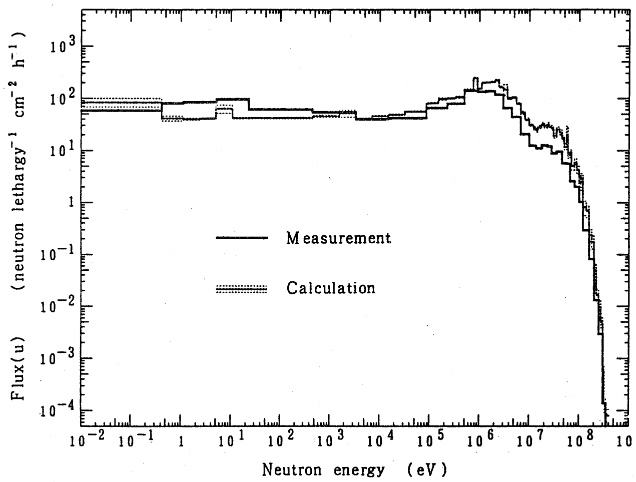

Fig. 4 The measured and calculated neutron spectra at the point 111 m away from the ES ring center.

RESULTS AND DISCUSSIONS

Neutron Dose Distribution at Ground Level

Figure 3 shows the neutron dose distribution measured at ground level around the ES, together with the statistical experimental errors. The abscissa is the distance from the ring center of the ES, r (m), and the ordinate is the neutron dose equivalent rate multiplied by r^2, i.e., $r^2H(r)$ in (m^2·μSv/h). The solid circles are the measured results with the high–sensitivity dose equivalent counter at the points 1 m above the ground, and the open circles are those at the points 4.3 to 20 m above the ground obtained by lifting the counter.

The solid–square shows the dose equivalent value, H, obtained by the following equation.

$$H = \int \Phi(E)\ K(E)\ dE \tag{1}$$

where $\Phi(E)$ is the neutron spectrum measured with the ^{3}He loaded multimoderator spectrometer shown in Fig. 4, and $K(E)$ is the flux–to–dose–equivalent conversion factor given by ICRP–21. The dose equivalent rate measured with the dose equivalent counter at the same point, No. 6 in Fig. 1, gives a 29% smaller value than that by the spectrometer. This comes from the underestimation of the contribution of high energy skyshine neutrons, because the response function of the dose equivalent counter becomes considerably lower compared with the ICRP–21 rem response function beyond 5 MeV.

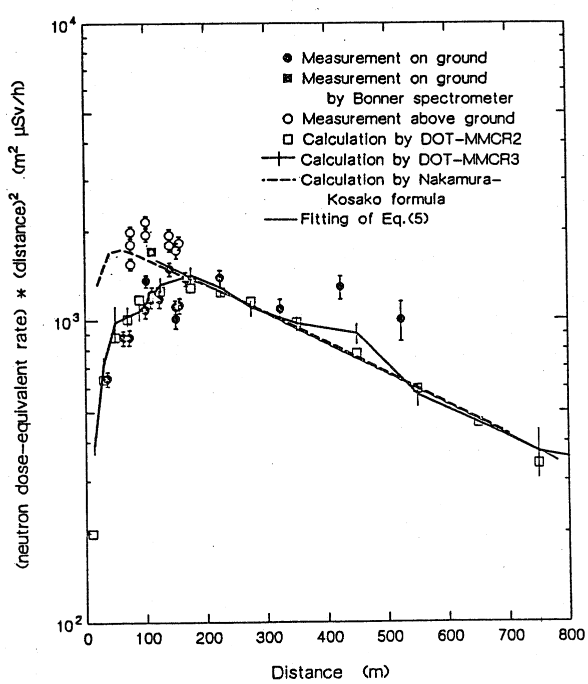

Fig. 3 The measured and calculated neutron dose equivalent distribution at ground level.

Figure 4 shows the neutron energy spectrum at the 111 m point (No. 6 in Fig. 1). The bold line expresses the data measured by the ^{3}He loaded multimoderator spectrometer, and the dotted line calculated by the MMCR–2 code. The calculated result was normalized to the measured result, such that the integrated fluxes are equal. This spectrum is much softer in the MeV energy region than the skyshine source spectrum, the leakage spectrum from the upper concrete ceiling shown in Fig. 2, and approaches a $1/E$ spectrum below 1 MeV. The calculated spectrum is about double the measured spectrum in the MeV region and, conversely, about half in the eV region, but as a whole, the agreement between calculated and measured spectral shapes is good.

Altitudinal Neutron Dose Distribution

The altitudinal distribution of neutron dose equivalent rates is shown clearly in Fig. 5, where the ratio of the neutron dose equivalent rate at the height z from the ground to that on the ground, z=0, $H(z)/H(0)$, is plotted as a function of the angle of elevation, θ, from the outer surface of the ES ceiling. In Fig. 5, the results measured by the high sensitivity dose equivalent counter are shown as solid squares and those calculated by the MMCR–3 code as open circles. It can be seen from Fig. 5 that the ratio, R=$H(z)/H(0)$, can be fitted to a relationship which is linear in θ, as follows:

$$R = k\theta + 1\ , \tag{2}$$

Two k values, 0.103 and 0.083 deg^{-1}, where θ is in degrees, are obtained from the fit to Eq. (2) of the measured and calculated results, respectively. Considering that the measured data have significantly large fluctuations owing to the scattering from the nearby buildings and that the calculated data have large statistical errors, this difference seems acceptable.

The measured results are compared in Fig. 3 with the results calculated by the MMCR–2 code, which are drawn as open squares, and the MMCR–3 code, as a bold solid line with vertical bars to indicate the estimated error. Since the absolute value of the skyshine neutron source could not be obtained, the calculated results are normalized to the dose equivalent rates measured at the point 111 m away from the ES center (No. 6 in Fig. 1) with the dose equivalent counter. The two calculated results show good agreement with each other, although the MMCR–3 results indicate larger statistical fluctuation than the MMCR–2 results, since the calculation of deep neutron penetration in concrete was included in the skyshine calculation of the MMCR–3 code.

Those calculated results show good agreement with the measured results at 1 m above the ground in several directions around the ES. At two points, 423 and 523 m away from the ES center, however, the measured data give about 50 to 60% higher values than the calculated results.

Nakamura and Kosako[4] gave a simple analytical formula to estimate the skyshine neutron dose distribution at ground level for a monoenergetic neutron source, based on the MMCR–2 calculation. By using the energy and angular neutron spectrum leaking through the upper concrete shield, the neutron dose equivalent distribution in the field can be obtained.[8] The results are also shown as a broken line in Fig. 3, and are in good agreement with the MMCR–2 and MMCR–3 results beyond about 150 m. Beyond 200 m, all calculated results show the exponential attenuation of the neutron dose equivalent, if it is multiplied by the square of distance.

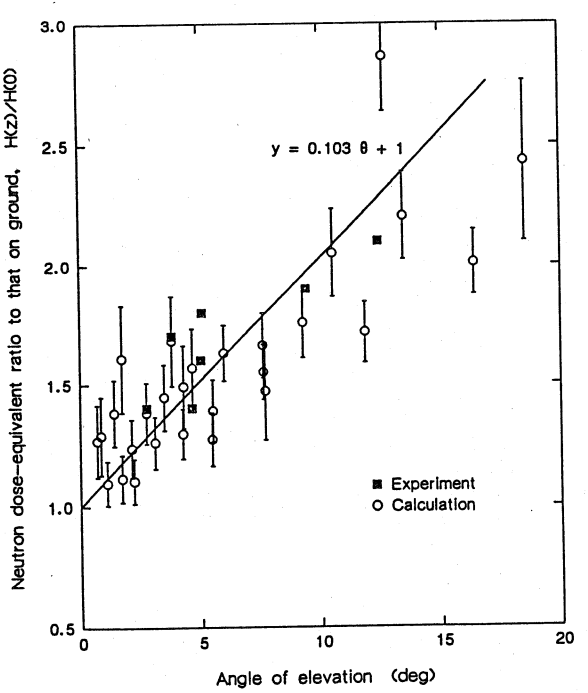

Fig. 5 The altitudinal variation of the measured and calculated dose equivalent rate. The solid line is a least-square fit to the experimental results.

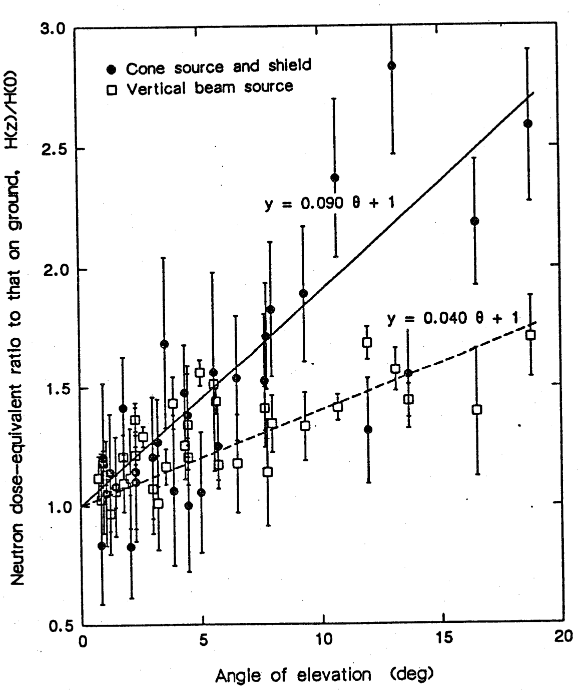

Fig. 6 The altitudinal variation of the calculated dose equivalent rate. The solid circles correspond to a 14-MeV cone source shielded with a thick concrete building, and the open squares correspond to a 14-MeV upward monodirectional source without shielding.

In order to investigate the variation of k with the energy E_S and emission angle θ_S of the source neutron, the skyshine calculation for a monoenergetic 14 MeV neutron source was performed with the MMCR-3 code. Two types of calculational geometries were selected here; one was exactly same as that of ES. The other was the cylindrical air-over-ground geometry without concrete shield around a point source, which emitted neutrons only vertically upward, placed 1.2 m above the ground. The calculated results under these two calculational conditions are shown in Fig. 6, with the same ordinate and abscissa as those in Fig. 5. By fitting those results to Eq. (2), two k values of 0.090 and 0.040 deg^{-1} were obtained for the former (a cone source with the surrounding concrete shield) and for the latter (a vertically-directed beam source), respectively. The former k value is considered to be in good agreement with the k value in Fig. 5 within errors.

It has already been shown in many experiments and calculations that a leakage neutrons at the shield surface have a $1/E$-type slowing-down spectrum and a nearly isotropic angular distribution, for moderated neutrons which dominantly account for dose, in any case after penetrating through a thick concrete or soil shield, almost independently of the source neutrons. From these observations, the altitudinal neutron dose distribution given by this skyshine experiment may be applicable to the estimation of an environmental dose distribution around an accelerator facility in general.

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