MEASUREMENT AND CALCULATION OF NEUTRON LEAKAGE THROUGH A LABYRINTH FROM A 35 MEV PROTON ACCELERATOR ROOM

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Abstract

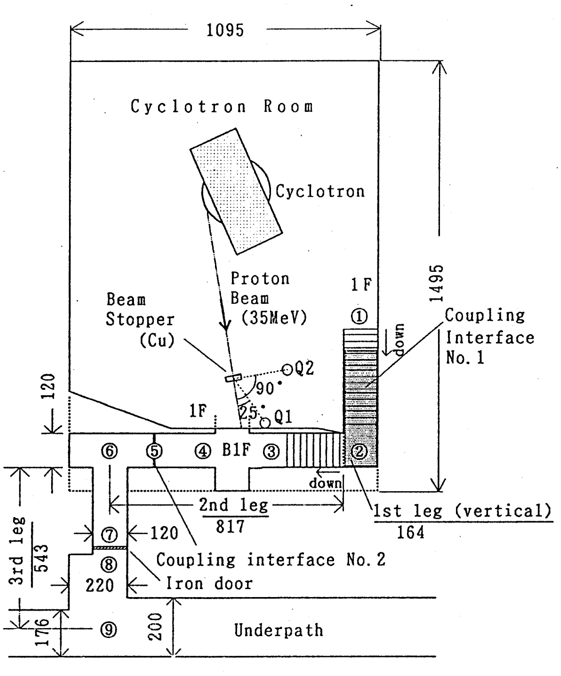
Energy spectra and dose equivalents of neutrons which were produced by 35 MeV protons in an accelerator room and leaked through a labyrinth with three legs from it, were measured by a multi-moderator spectrometer and a dose-equivalent counter.

Four simple formulas were intercompared with the measurements and the calculations by the three dimensional Monte Carlo code, MORSE-CG.

Consequently, it was clarified that ROLA-D Formula gave the best result for the dose equivalent of neutrons leaked through a labyrinth.

Introduction

An estimation of neutron streaming through a labyrinth in accelerator facilities is one of the most important and difficult problems for the shielding design calculation. A computer code based on the Boltzman transport equation is generally not applicable to the neutron streaming calculation, because of the complicated geometry of the labyrinth. Monte Carlo calculations have been applied to the streaming problem but required a long CPU time to attain good statistical accuracy. Simple formulas have, therefore, been used for the neutron streaming calculation in the shielding design.



unit of numerals : cm

①～⑨, Q1 and Q2 : detection points

Fig. 1 Plan view of the cyclotron room and the labyrinth at the Cyclotron and Radioisotope Center, Tohoku University (CYRIC).

In order to examine the accuracy of simple formulas, we measured both the energy spectra and the dose equivalents of neutrons in the source (accelerator) room and in the labyrinth and compared four simple formulas with the measurement.

Experiment

The neutron measurements were performed in the AVF cyclotron room and in the labyrinth connected to the room at the Cyclotron and Radioisotope Center, Tohoku University (CYRIC). Figure 1 shows the plan view of the experimental geometry. The cyclotron room has more than 2 m thick concrete wall and floor and a 1.8 m thick concrete ceiling. The labyrinth is surrounded with more than 2 m thick concrete, and consists of stairs and basement passage with two bends and an iron door. We separated the labyrinth into three legs and named them as 1st leg, 2nd leg, and 3rd leg as shown in Fig.1 for convenience. Figure 1 also shows the size of the labyrinth and the neutron detection points in numbers ① to ⑨ (which were set at 130 cm height from the floor) and in symbols Q1 and Q2 (120 cm high from the floor and 2 m away from the beam stopper).

Neutrons in the cyclotron room and the labyrinth were measured with a multi-moderator spectrometer composed of a 5.08 cm diam. spherical ^{3}He counter, filled with 10 atm. ^{3}He gas, i.e., Bonner Ball at the points ① to ⑨. The thicknesses of the spherical polyethylene moderators are 9, 5, 3, 1.5, 0 cm with the cadmium cover and 0 cm without the cadmium cover. The measured counts were unfolded to the neutron energy spectra by the SAND-II code. As the initial guess spectra for unfolding, those calculated by the ROLA-E code described later were used at every detection point.

The results are shown in a form of lethargy fluence per proton beam current in Fig.2. It reveals that the

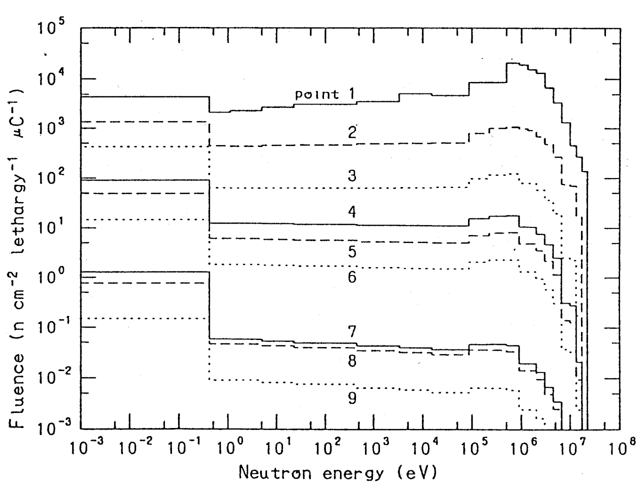


Fig. 2 Neutron energy spectra measured by the Bonner Ball in the cyclotron room and the labyrinth at CYRIC.

neutron spectrum becomes softer and the ratio of thermal neutron fluence to fast neutron fluence increases with penetrating through the labyrinth. For example, the ratios of the thermal neutron dose equivalent to total one are 1.3 % at the point ① in the cyclotron room, 5.7 % at the point ② in the 1st leg, 28 % at the point ⑥ in the 2nd leg, and 62 % at the point ⑨ in the 3rd leg.

Dose equivalent measurements were also made with the rem counter at the points ① to ⑨, in order to compare with the dose equivalent obtained by multiplying the measured energy spectrum and the flux-to-dose equivalent conversion factor. The comparison of dose equivalent values by the Bonner Ball and the rem counter is shown in Fig.3, as a function of the distance from the source along the labyrinth center line. The values by the rem counter at the points ③ to ⑨ are systematically higher than those by the Bonner Ball because of the discrepancy between the rem counter response and the flux-to-dose equivalent conversion factor, in the energy region below about 100 keV.

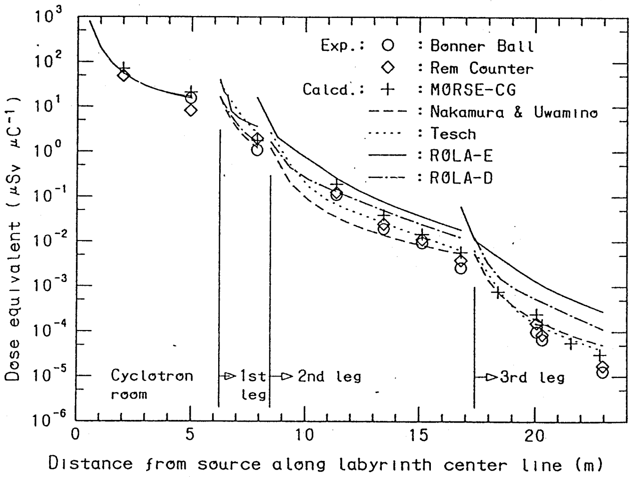


Fig.3 Dose equivalent distribution measured by the Bonner Ball and the rem counter compared with five different calculations (four simple formulas and the MORSE-CG).

Simple formulas

Two simple formulas developed by Nakamura and Uwamino[1] and by Tesch[2] were examined for their applicability by comparing with the measured results.

Two new simple formulas were also developed. The ROLA-E code was revised from Shin's formulas[3] [4] to calculate the dose-equivalent and the energy spectrum. The ROLA-D code is based on Nakamura & Uwamino's formula[1] and Goebel's universal attenuation curve[5]. An outline of each formula is described as follows.

Nakamura & Uwamino's formula

This formula gives the dose equivalent both in the source room and in the linked labyrinth.

The dose equivalent in the source room is given by

$$H(r)=k\left(\frac{1}{r^2}+\frac{4}{r^2+4s^2-2\sqrt{2}\,rs}\right) \tag{1}$$

where k : normalization constant,
r : distance from the source to the entrance of 1st leg,
$s=\sqrt{L_1L_2}/2$,
L_1, L_2 : diameter and length of a right cylinder replaced with the same volume as the source room.

The dose equivalent at each leg in the labyrinth is given by

$$H(r)=H(a)\frac{a^2}{r^2} \tag{2}$$

where a : a half of narrower size between width and height of the cross section of each leg,
$H(a)$: dose equivalent at the point A which is at the distance a backward from the entrance surface of the leg,
r : distance from the point A in each leg.

Tesch's formula

This formula gives the dose equivalent only in the labyrinth.

The dose equivalent in the labyrinth is given by

$$H(r_n)=H(a)\prod_{i=1}^{n}f_i(r_i) \tag{3}$$

where $H(a)$: dose equivalent at the 1st leg entrance,
i : leg number.

The function $f_i(r_i)$ is defined as follows,
for the 1st leg (i=1) where the source can be sighted directly from the exit,

$$f_1(r_1)=\frac{2a^2}{r_1^2} \tag{4}$$

where a : distance from the source to the 1st leg entrance,
r_1: distance from the source in the 1st leg,

otherwise,

$$f_i(r_i)=l_p\frac{exp\left(-\frac{r_i}{0.45}\right)+0.022A_i^{1.3}exp\left(-\frac{r_i}{2.35}\right)}{1+0.022A_i^{1.3}} \tag{5}$$

where l_p = 2 : at the 2nd leg if the condition of Eq.(4) is satisfied, or at the 1st leg if not,
= 1 : at the legs following the above,
r_i : distance from the entrance of each leg (m),
A_i : cross sectional area of each leg (m²).

ROLA-E code

Shin applied an albedo method to the neutron multiple-scattering in a spherical cavity[3] and the streaming in a cylindrical ducts[4], separately, and introduced simple analytical formulas to express the neutron energy spectra as follows.

The multiple-scattered neutron energy spectrum Φ at an arbitrary point in a spherical cavity wall which has a source at a center, is given by[3]

$$\Phi=\frac{4\boldsymbol{\alpha}}{\boldsymbol{I}-\boldsymbol{\alpha}}\cdot\frac{Q}{A} \tag{6}$$

where Q : neutron energy spectrum of an isotropic source,
A : inner surface area of the cavity wall,
α : albedo matrix for incident neutron energy and reflected energy on the cavity wall,
I : unit matrix.

The neutron energy spectrum Φ at the depth x from any leg entrance in the cylindrical duct is given by[4]

$$\Phi(x)=\Phi_0(x)+\gamma^2\boldsymbol{\alpha}_2\sum_{j=1}^{N}S_j\phi_j^{(2)}(x)+\gamma^8\boldsymbol{\alpha}_8\sum_{j=1}^{N}S_j\phi_j^{(8)}(x)\quad,\quad(7)$$

where x : dimensionless depth when the real depth is divided by a radius of the cylindrical leg,

$\Phi_0(x)$: spectrum due to the direct component,

γ : empirical factor multiplied to the albedo value,

$\alpha_2 = \alpha(I+\alpha+\alpha^2)$,

$\alpha_8 = \alpha^4/(I-\alpha)$,

α : albedo matrix for incident neutron energy and reflected energy on the duct wall,

S_j: source neutron energy spectrum at the angular mesh j on the entrance surface of each leg,

$\phi_j^{(i)}(x)$: neutron energy spectrum emanated from the source angular mesh j and reflected i times on the duct wall when the albedo value and the source intensity are unity.

We joined Eqs. (6) and (7) for calculating the neutron energy spectra consistently from the source room to the access way (duct and labyrinth). For that purpose, the neutron current incident to the duct entrance from the source room was given as follows,

$$S_j=\frac{1}{2}\{cos(2\theta_j)-cos(2\theta_{j+1})\}\frac{I}{I-\boldsymbol{\alpha}}\cdot\frac{Q}{A}+S_d\ ,\qquad(8)$$

where θ_j : angular mesh boundary of neutrons incident into the duct entrance,

S_d : neutron current directly incident into the duct entrance from the source

$$=\frac{Q}{4\pi r^2}cos(\theta_d),\quad if\ \theta_j<\theta_d<\theta_{j+1}\ ,\qquad(9)$$

$$=0\qquad\qquad,\ if\ not,$$

where r : distance from the source to the duct entrance,

θ_d: angle between the direct source neutron and the normal to the duct entrance surface.

By combining Eqs. (6) through (9), we developed the ROLA-E code. This code can calculate the neutron energy spectra and the dose equivalents both in the source room and in the labyrinth. The albedo data of Eqs. (6) and (8) were cited from the DLC-57 data library (SAIL).

ROLA-D formula

Two formulas by Nakamura & Uwamino and by Tesch tend to underestimate the dose equivalent in the labyrinth in some cases. ROLA-E is also not usable when the source neutron spectrum is unknown.

We therefore developed a new simple formula "ROLA-D" for calculating the dose equivalents both in the source room and in the labyrinth. The equation in the source room is the same as Eq. (1) of Nakamura & Uwamino's formula and in the labyrinth, Goebel's universal attenuation curves were used[5]. We fitted these universal curves to a progression of three exponential functions and obtained the following formula for the dose equivalent H(x) in any leg,

$$H(x)=H_d+H(0)\sum_{i=1}^{3}k_i exp(-m_i x),\qquad 0<x<11\ ,\qquad(10)$$

where $x=r/\sqrt{A}$,

$k_1=1-k_2-k_3$,

$H(0)$: dose equivalent at the entrance of each leg, and for the 1st leg, given by Eq. (1),

r : distance from the leg entrance,

A : cross sectional area of the leg,

H_d : direct component from the source, if the 1st leg exit is in the direct sight of the source, H_d is given as

$$H_d=\frac{k}{d^2}\ ,\qquad(11)$$

otherwise $H_d = 0$,

where k : normalization factor same as in Eq. (1),

d : distance from the source.

The values of the fitting parameters m_1, m_2, and m_3 are 5.0, 0.87, and 0.34, respectively, both for the average curve and for the upper limit curve. The values of the fitting parameters k_2 and k_3 are 0.18 and 0.0045 for the average curve and 0.3 and 0.015 for the upper limit curve, respectively.

Calculations and comparison with experiment

The calculations by using these formulas were performed for the experimental geometry in the AVF cyclotron room and in the labyrinth connected to the room at the CYRIC. The dose equivalent values calculated by the above four formulas are shown in Fig. 3 with the measured values.

In Fig. 3, the dose equivalents by the four simple formulas in the cyclotron room were close to each other. In the attenuation profile of the dose equivalent through the three-leg labyrinth, Tesch's formula gave the steepest slope. Nakamura & Uwamino's formula, ROLA-D, and ROLA-E followed it, in order of decreasing slope.

Here, we have to point out that these four formulas can simulate the dose distribution only in a straight leg perpendicularly joined to a preceding leg. However, the actual legs of the labyrinth in the CYRIC are not straight. This brings the situation that the comparison between the experiment and the simple formulas has some ambiguity in the accuracy. To clarify this problem, a Monte Carlo calculation was done to simulate both the actual experimental geometry as faithfully as possible and the straight one corresponding to the formulas. In the result, the dose equivalent by MORSE-CG at the exit of the labyrinth with the straight legs was $1.11\times10^{-4}\,\mu Sv\ \mu C^{-1}$ close to the value by ROLA-D.

Conclusion

Among above four simple formulas, ROLA-D gave the most resonable dose equivalent which was closest to the MORSE-CG result on the safer side.

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