SHIELDING CALCULATION OF NEUTRONS FOR THE RIKEN RING CYCLOTRON FACILITY

T.Shikata, N.Nakanishi, and S.Fujita
RIKEN (The Institute of Physical and Chemical Research)
Wako, Saitama, 351, Japan
and
T.Kosako
Research Center for Nuclear Science and Technology, The University of Tokyo
Bunkyo, Tokyo, 113, Japan

Summary

Aiming at the radiation shielding for the RIKEN ring cyclotron facility, the following calculation was carried out; (1) neutron attenuation properties of various materials with spherical geometry were studied in the energy range from thermal to 400 MeV, (2) two kinds of charts useful for the shielding design were obtained, (3) dose rate from neutron skyshine was roughly estimated.

Introduction

The RIKEN ring cyclotron will operate protons in the 200 MeV energy range, light heavy ions up to 135 MeV/u, and heavier ions in lower energy region(per nucleon) with increasing atomic number.

In this report, the approximation procedures for the shielding design will be described. Calculation was carried out by using the one-dimensional discrete ordinate code ANISN and the neutron-photon multigroup cross section library DLC-87/HILO for neutron energies from thermal to 400 MeV and photon energies from 10 keV to 14 MeV. Fluence-to-dose equivalent conversion factors for neutrons and photons recommended by the ICRP Publ.21 were used.

I. Some neutron shielding characteristics for lead, iron, concrete, heavy concrete, calcium carbonate, and paraffin.

Attenuation of neutron dose equivalent along the radius of a sphere is shown in Fig.1 for seven materials for nearly monoenergetic neutrons of group 1, group 12, group 35, and group 66 (group 1=400MeV-375MeV, group 12=140MeV-120MeV, group 35=10MeV-8.19MeV, and group 66=0.41eV-10^{-4}eV). Attenuations of dose equivalent for the capture gamma rays emitted simultaneously were also calculated. In general, the dose equivalent for neutrons is about two order larger than that for capture gamma rays for source neutrons with energy above about 50 MeV. However, this difference becomes to be small and then turn over ultimately as the energy of source neutrons decreases. For a composit sphere in which an iron sphere is superposed by other materials, drastic decrease of the neutron dose equivalent occurs at the interface of media, although only within rather a thin layer, in both cases of an iron-heavy concrete and an iron-paraffin. As shielding materials against neutrons with energy above several tenth MeV, it was ascertained that an iron was the most superior material and next a heavy concrete was.

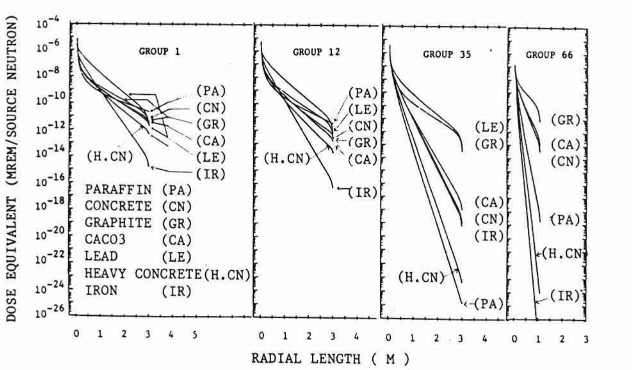

Fig. 1. Attenuation of neutron dose equivalent for various spherical materials.

II. Determination of neutron dose rate and the design of shield.

In the RIKEN ring cyclotron facility, many beam courses have been planned for different kinds of experiments. Therefore, the unified procedure of shielding design is desirable. On performing the calculation, two approximation procedures were adopted. Geometries of the calculation are shown in Fig.2. We have, at first, replaced the configuration of the experimental hall by the model consist of concentric spheres, which

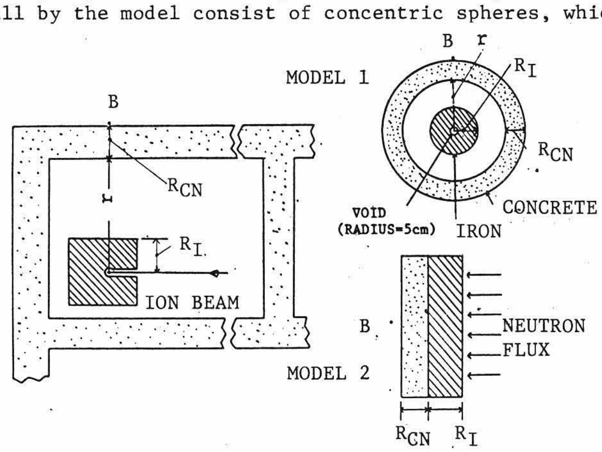

Fig. 2. Models for the calculation of shielding design.

Table 1. Energy and angular distribution of neutrons emitted by the reaction of 1000 ^{12}C ions with energy of 135 MeV/u on ^{56}Fe thick target (n/1000·ions·sr).

Energy (MeV) \ Angle	0° - 20°	20° - 40°	40° - 60°	60° - 120°	120° - 180°
0- 35					
35- 55	30	33	29.4	23.4	25.2
55- 75	122	49	22	11	18.1
75- 95	100	27	9.2	5	9.4
95-115	24	7.4	2.5	1.2	1.4
115-135	5.8	1.7	0.3	0.24	1.1
135-155	1.6	0.6	0.14	0.06	0.73
155-175	0.52	0.2	0.04	0.01	0.04

radii were taken to be the distances from the point neutron source to the interfaces of media in a specified direction. This model is suited to the design of a beam dump. The other is a double layer slab; one is a concrete slab, which mainly corresponds to a wall of the hall and the other is made of material to be used as a main part of more general local shield; neutrons are falling normally on it.

1. Design chart for the determination of the thickness of shielding materials with the concentric sphere model.

We have selected the neutron spectrum emitted by the reaction of ^{12}C(135 MeV/u,$6\cdot10^{12}$pps) on ^{56}Fe thick target as the neutron source in the calculation of the shielding design. This spectrum was estimated from the calculated results by Fernandez[1] for the reaction of ^{12}C(100 MeV/u,10^3 ions) on ^{56}Fe thick target; this shows plenty of energetic neutrons not only in the forward direction with respect to the beam direction but in 90^o and backward direction, than other available spectra calculated in different reactions.[2)3)] Our estimated spectrum is shown in Table 1. This estimated spectrum for $6\cdot10^{12}$ carbon ions of energy of 135 MeV/u is abbreviated hereafter as (C-Fe). In this table, the number of neutrons with energy less than 35 MeV is omitted, because they contribute little to the dose equivalent.

Calculated results are shown in Fig.3. We designate

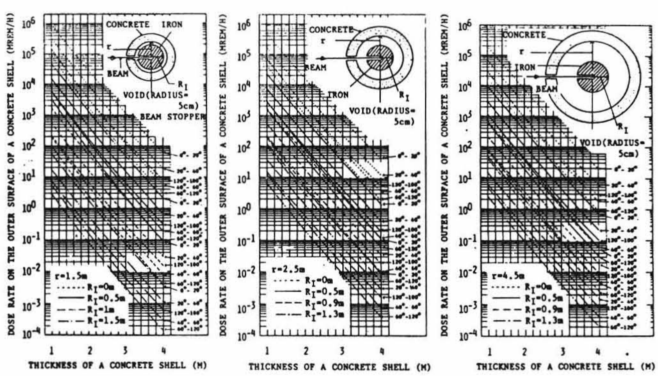

Fig. 3. Design chart 1. Dose rate on the outer surface of a concrete shell as a function of R_{CN}, with R_I (radius of an iron sphere) as parameter.

this figure as design chart 1 for the shielding design. If r is given, one can easily determine R_{CN} and R_I in any directions, which yield a tolerance dose at the surface of a concrete wall, by interpolation at any arbitrary thickness ratios R_{CN}/R_I.

When the thickness of a wall is given, a part of an iron beam dump can be replaced by other materials. For example, as shown in Fig.4,one can obtain charts for designing a beam dump made of iron and heavy concrete for the configuration of the experimental hall illustrated in the same figure. Typical measuring points and tolerable radiation levels are also shown. Design chart 1, however, can be used appropriately near a wall where a beam dump may usually be set up. If the shielding design is required for a long source distance, the method to be described in the paragraph 2 should be utilized.

2. Design chart for the determination of the thickness of shielding materials with the double layer slab model.

The process of the shielding design is as follows. (1) Calculation of the dose equivalent outside a double layer slab (concrete-iron), when nearly monoenergetic neutrons with ≦400 MeV normally incident on it. (2) Derivation of the dose rate outside a double layer slab for the point (C-Fe) source. Calculated result is shown in Fig.5. We designate this figure as design chart 2. This chart is correct only in the case that neutrons can be assumed to travel in straight lines in the shield. (3) Some correction on the designed values estimated from the chart 2. The thickness of a local shield enclosing a neutron source, estimated from the design chart 2 for a given direction, requires some approximation correction so as to include the contribution from dose due to reflection of neutrons emitted in other directions in it. The correction will be perfect for an isotropic neutron source. Here, the method of correction in such case will be described. We can determine the thickness of a wall R_{CN} together with that of a local shield R_o from the design chart 2 for the source distance L and the direction θ. The schematic diagram pictured this circumstance is given in Fig.6. We obtained a couple of figures for the correction. One figure shows the dose rate on the outer surface of a slab with the thickness of R_o, D_p, as a function of the distance from the source to the slab l, with the thickness of a slab as parameter. The other figure shows the dose rate on the outer surface of a spherical shell D_s as a function of its inner radius l, with the thickness of a shell as parameter. We consider, for an example,

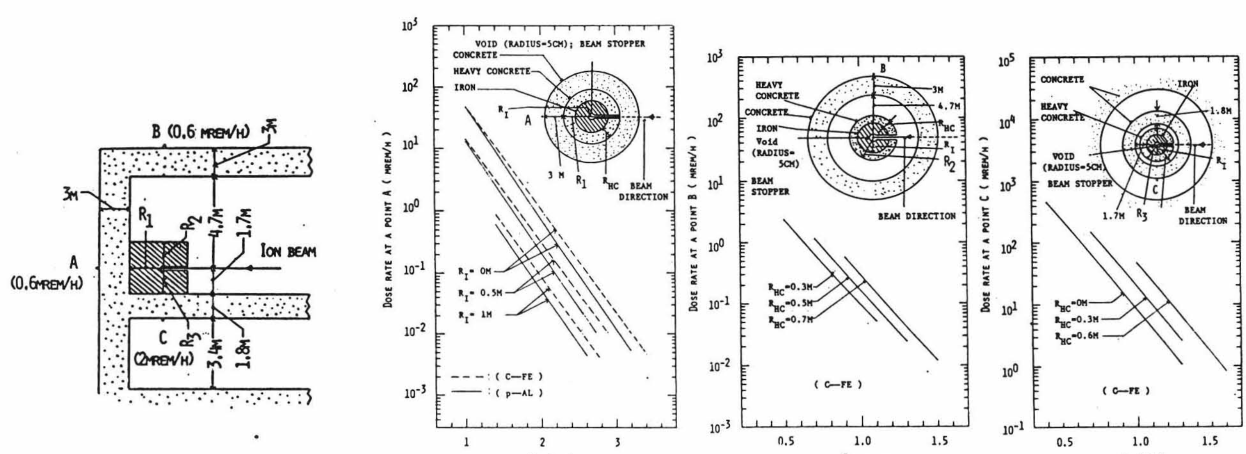

Fig. 4. A longitudinal sectional view of a typical experimental hall and charts for determination of the thickness, in direction of A, B, and C, of an iron-heavy concrete beam dump. Geometries for the calculation are also shown.

(p-Al) stands for the source neutrons ejected by the reaction p(200 MeV, 1μA) on ^{27}Al thick target.[4)]
R_I and R_{HC} stand for the radial thickness of an iron and a heavy concrete, respectively.

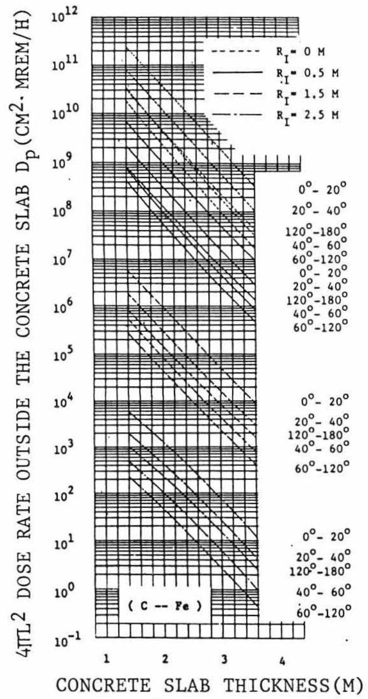

Fig. 5. Design chart 2. Dose rate multiplied by 4π (source distance)^2 as a fuction of a concrete slab thickness, with the thickness of an iron layer as parameter.

the spherical local shield with the inner radius of length l_0. Corrected thickness of a spherical shell with inner radius l_0 can be determined as the thickness of a spherical shell, on which surface the dose rate is equal to that on a slab of thickness R_0 apart l from the source, on condition that both surfaces are located at the same distance from the source. Of course D_{s0} is larger than D_{p0}. As a first step, R_1 is assumed to be the necessary thickness of a spherical shell; in this case the dose rate on the outer surface of a shell with inner radius l_0 has the same value as the dose rate D_{p0} on the outer souface of a slab with thickness R_0 apart l_0 from the source. Next, dose rate D_{p1} on the surface

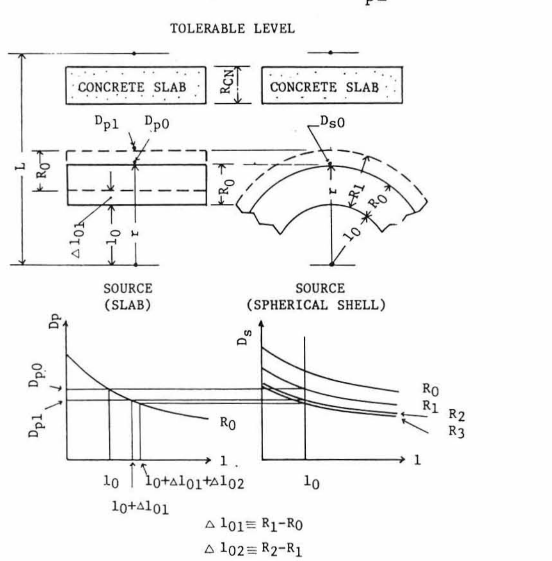

Fig. 6. Schematic figure for the explanation of the correction of the shield thickness obtained by using the design chart 2.

of a slab with thickness R_0 situated at the distance l ($=l_0+\Delta l_{01}, \Delta l_{01} \equiv R_1-R_0$) can be determined. Thus R_2 can be taken to be the spherical shell thickness, when the dose rate on the outer surface is D_{p1}. Then , the slab distance is shifted by Δl_{02} ($=R_2-R_1$), therefore l becomes to be $l_0+\Delta l_{01}+\Delta l_{02}$. The thickness of a spherical shell converges to a certain definite value by repeating in this way once or twice. In Fig.7, couple of figures for the correction for an iron local shield are given.

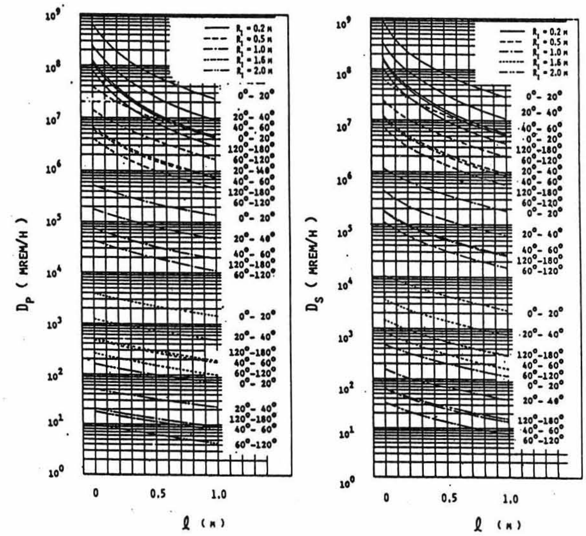

Fig. 7. Figures for the correction for an iron local shield obtained by using the design chart 2.

For an anisotropic source, the corrected thickness in any directions obtained by the correction method explained above will approaches to the value of safty side of the shielding design.

3. Examples of the shielding design.

As examples, an essential part of the experimental hall and allowable dose rates around the beam dump are shown in Fig.8. In these instances, a beam dump is set up near the wall. Required thickness of a beam dump in

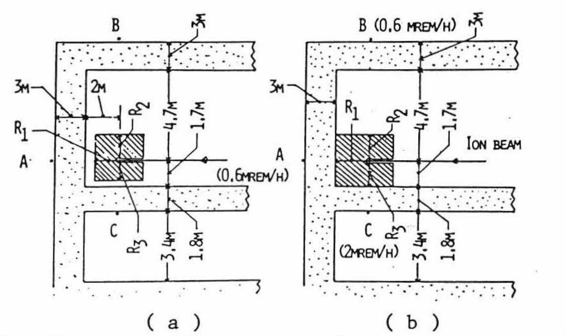

Fig. 8. Longitudinal sectional views of a typical experimental hall. These are illustrated as examples for the design of a beam dump.

direction A, B, and C obtained by different method mentioned above are shown in Table 2. This instance shows that the increment of thickness by the correction extends from 10 % to 20 % for an iron case but is limitted only from 5 % to 7 % for a heavy concrete case (space don't permit to illustrate the design chart and the figures for correction for heavy concrete local shield). Therefore, the iron-concrete double layer beam dump designed by the design chart 2, may be sufficient to be corrected only for an iron part, because the

Table 2. Examples of designed thickness of the shield illustrated in Fig.8.

	Observing point Tolerance level	A 0.6 mrem/h		B 0.6 mrem/h		C 2 mrem/h	
Fig.8-a	Thickness of concrete wall (m)	2	3	2	3	1.8	2.5
	Thickness of iron beam dump (m)						
	Design chart 1	R_1=1.63	R_1=1.14	R_2=1.01	R_2=0.58	R_3=1.12	R_3=0.77
	Design chart 2	R_1=1.46	R_1=0.96	R_2=0.88	R_2=0.42	R_3=0.98	R_3=0.63
	(corrected)	R_1=1.60	R_1=1.07	R_2=1.01	R_2=0.50	R_3=1.11	R_3=0.72
	Thickness of heavy-concrete beam dump (m)						
	Design chart 2		R_1=1.74		R_2=0.76		R_3=1.14
	(corrected)		R_1=1.83		R_2=0.80		R_3=1.22
Fig.8-b	Thickness of beam dump (m): Iron		1.0 / 0.50		0.3 / 0.41		0.87 / 1.04
	Thickness of beam dump (m): Heavy-concrete		0.4 / 1.25		0.5 / 0.30		0.60 / 0.30

increment of thickness by the correction becomes less important for low density materials.

III. Skyshine.

Neutron dose rate due to skyshine has been calculated recently with computer codes by Alsmiller et al.,[4] Nakamura and Kosako,[5] and Hayashi and Nakamura.[6)7] We have carried out roughly the estimation of the skyshine effect around the ring cyclotron facility. On one side of the nuclear facility, the level of the ground lies above the roof of the experimental hall, however, on the other side, the ground level lies below the roof. Therefore, the neutron dose rate due to skyshine was estimated for two cases by using the calculated results of Hayashi and Nakamura; 1) estimation with source height 15 m , and 2) estimation with source height 0 m, respectively. In the former case following analytical expression of dose equivalent was used,

$$D_n(r)=Q_n(E_s,\theta_s)\exp(-r/\lambda_n(E_s,\theta_s))/r,$$

where r is the source distance, E_s is the neutron energy, θ_s is the emission angle of neutrons, and Q_n and λ_n are give in reference 6. In the latter case, 'importance functions' obtained from the data offered by Hayashi and Nakamura[7] were used. Geometry for the transport calculation of neutrons is shown in Fig. 9. Effective thickness of the roof were taken into account. Neutrons emitted through the roof were collected at the center of the roof in case of the estimation of dose rate. Estimated results are shown in Fig. 10 together with those obtained by using Alsmiller et al.'s 'importance function'.

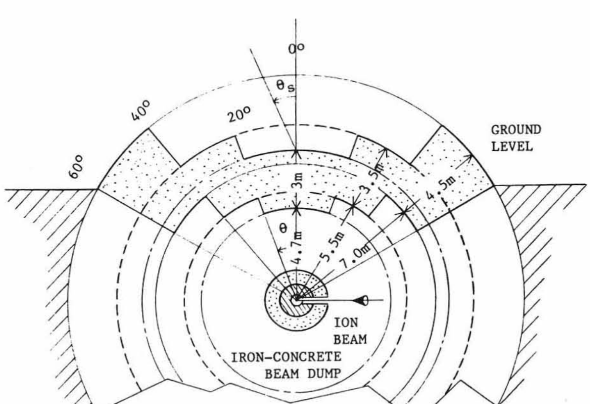

Fig. 9. Model for the estimation of neutron dose due to skyshine.

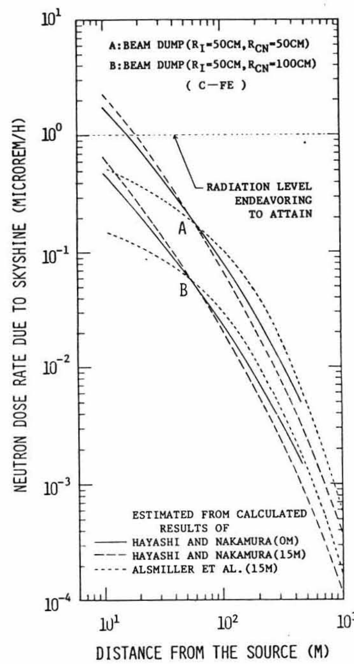

Fig. 10. Dose rate due to neutron skyshine around an experimental hall.

IV. Concluding remarks.

An iron and a heavy concrete were proved to be the most excellent shielding materials for neutrons with energy between several tenth MeV and 400 MeV. With these materials, approximation procedures for designing the thickness of a wall of the building together with a beam dump made of iron and iron-concrete have been obtained. Employing approximation procedures, beam dump will be designed at each beam courses from the ring cyclotron. Applying the calculated results of dose equivalent due to neutron skyshine by Hayashi and Nakamura, approximate estimation of dose rate due to skyshine around the RIKEN ring cyclotron facility was also carried out.

References

1) B.Fernandez: Cited in the report of J.Drouet and A.Leleux(D.CEN-S/SPR/SRI/78-342 GRA-066JD/A/5 mai (1978)).
2) T.A.Gabriel, R.T.Santoro, H.W.Bertini, and N.M. Larson: ORNL-TM-4334(1973).
3) R.G.Alsmiller: Given in the report of H.Smith,Jr. (IUCF Internal Report No.74-6(1974)).
4) R.G.Alsmiller,Jr., J.Barish and R.L.Childs: ORNL/TM-7512(1980).
5) T.Nakamura and T.Kosako: Nucl. Sci. Eng. 77,168 (1981).
6) K.Hayashi and T.Nakamura: Nucl.Sci. Eng. 91, 332 (1985).
7) K.Hayashi and T.Nakamura: Private communication.