Shielding Design of the Cancer Therapy Facility using Compact Proton Synchrotron

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Abstract

In these days, due to the increase of proton or heavy ion cancer therapy facilities, the radiation shielding of intermediate energy accelerators is becoming an important problem.

Radiation shielding design of a cancer therapy facility using compact proton synchrotron was carried out. For shielding analysis, the one-dimensional discrete ordinate code ANISN and the skyshine calculation code SHINE-II were used. As an emission of neutron by proton beam losses, measured neutron yield spectra of 256MeV incident proton at LANL, and the high-energy cross section library DLC-119/HILO86 were used for the ANISN calculations.

Results from the calculation satisfy the limits from the domestic law of the radiation protection.

1 Introduction

The radiation shielding designs of recent accelerator facilities are becoming important for constructing the facility because either the particle energy or the beam intensity becomes higher. The shielding analysis plays an important role in the conventional facility design and reducing the total facility costs. To reduce the shielding design costs, the precise estimate of the neutron leakage, which corresponds to the significant part of the dose equivalent, is one of the key issues for the shielding design of those accelerators. This is due to the drastic change of cross sections of the materials around this energy region.

Mitsubishi Electric has been developing a cancer treatment facility based on the proton synchrotron. Low cost and compactness are important features for widespread use in the hospital environment. The layout of the facility is given in figure 1. Table 1 shows the specifications of the accelerator and the operating condition.

The radiation shielding design of the facility was carried out. The one-dimensional discrete ordinate code ANISN [1] with the multigroup cross section library DLC-119/HILO86 [2] was used for the bulk shielding calculation. Nakamura-Uwamino's formula [3] was used for the maze calculation. Also the skyshine calculation code SHINE-II [4] was used for determining the skyshine.

This paper describes the results of the calculation.

Table 1 Specifications of the accelerator and operating condition

Accelerating Particle	Proton
Particle Accelerating Energy	250 (MeV)
Operating current and time per week	max. 4388 (nA·min/week)
Beam tuning time per week	max. 335 (nA·min/week)

2 Bulk Shielding Design

Bulk shielding design of the facility was assessed at the points where dose equivalent limits should be determined. The entire facility was divided into the areas defined by the law, such as the controlled area, the area where workers have full time access, the hospital, and so on. The calculating points were defined at borders between the areas as shown in figure 1 as A1 – A5 and B1 – B7.

The expected radiation sources due to beam losses in the accelerator, the beam transport, and the delivery systems are given in figure 1 as S1 ~ S6. Radiation occurring from beam losses in RFQ and losses in synchrotron in processes such as injection, RF capture, and acceleration were considered as negligible.

Majority of radiation from the accelerator is caused by losses occurring in the course of extraction process at the deflector of synchrotron, given in S1, which was expected 5% of the overall beam current. This is caused by bombardment of protons on the septum made of iron. Losses occurring in the irradiation process during the treatments, given at S6, S7, and S8 in figure 1, were expected 100% of the beam current. The beam dump is designed to absorb the full beam. Therefore, losses at the beam stopper S2, and the beam shutters S3, S4, and S5 were expected to 100% of the beam current.

The shielding calculations were carried out assuming the operation is always at the maximum proton energy of 250 MeV.

Dose equivalent behind concrete shield can be simply estimated from the equation [5];

$$ H = \frac{H_0(\theta)}{r^2} \cdot J \cdot \exp\left(-\frac{d}{\lambda_{conc}(\theta)}\right) \tag{1} $$
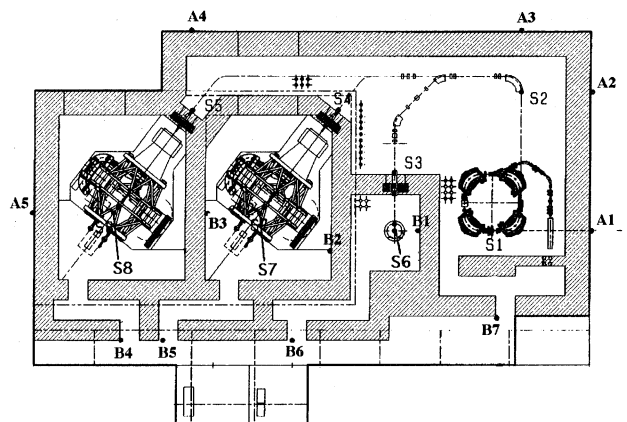

Fig.1 The layout of the cancer therapy facility using compact proton synchrotron

where :

H is the dose equivalent per week at the calculating point.(μSv/week);

$H_0(\theta)$ is the source term in the direction θ. (Sv $\cdot$ cm^2/nA/min);

J is the proton beam current per week. (nA $\cdot$ min/week);

r is the distance between the source and the calculating point. (*r>d*) (cm);

$\lambda_{conc}(\theta)$ is the attenuation length in concrete in the direction θ. (cm);

d is the thickness of the concrete. (cm);

To calculate the transmission curve, the one-dimensional discrete ordinate neutron-photon transport code ANISN was adopted. The calculations were carried out with one-dimensional spherical geometry. The geometry consists of a vacuum layer with a radius of 4 m and a concrete layer of 2 m thick. Total neutron yield produced by 256 MeV protons bombarding stopping–length targets of iron and carbon, found in literature [6] was assumed to be the neutron losses from beam dumps points and isocenter of gantry. Neutrons and secondary photons are concerned in the calculation. Photons emitted from beam loss points were neglected. The neutron-photon multigroup, consisting of 66 neutron energy groups and 22 photon energy groups, coupled cross section library DLC-119/HILO86 was used for the calculation.

The calculated energy spectrum is converted to dose equivalent by multiplying the flux-to-dose equivalent conversion factor given by the recommendations of ICRP Publication 51 [7]. Finally, the factor 2, requested by the government, is multiplied to the conversion factor in order to estimate safely.

Figure 2 shows dose equivalent for each emission angle calculated by ANISN. The attenuation length of the shielding material is obtained by fitting the transmission curve of dose equivalent through the shielding with an exponential function. The H_0 and λ for each emission angle are give in table 2.

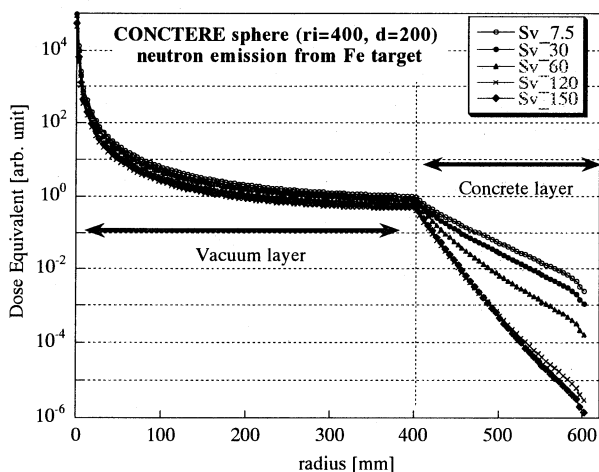Fig. 3 and 4 are comparisons of dose equivalents and

Table 2 Source term H_0 and λ in concrete for neutrons by 256MeV proton bombardment on iron and carbon

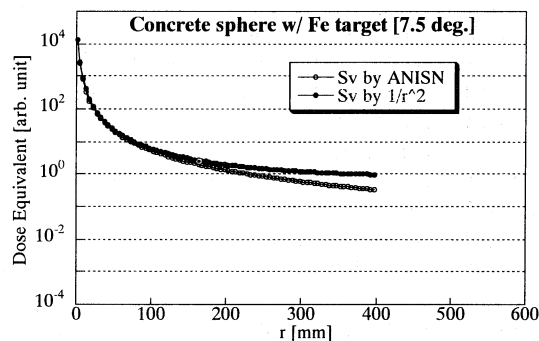| Angle (deg.)	C		Fe	
	H_0	λ (cm)	H_0	λ (cm)
7.5	21.2	52.2	35.0	42.6
30	18.5	46.5	26.9	37.4
60	8.3	33.4	15.0	27.0
120	3.2	20.2	12.7	18.3
150	2.5	18.5	15.9	17.1

H_0 is given by (Sv $\cdot$ cm^2/nA/min).

Fig. 3 Dose equivalents inside of the concrete sphere calculated by ANISN and a$1/r^2$ attenuation curve normalized at r=1
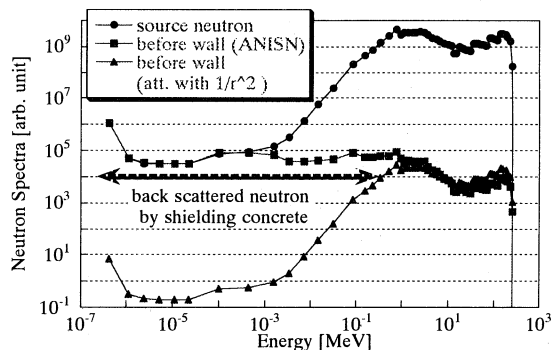

Fig. 4 neutron spectra calculated by ANISN and a$1/r^2$ attenuation curve normalized at r=1

neutron spectra inside of the concrete sphere calculated by ANISN and a$1/r^2$ attenuation curve normalized at r=1, respectively. As shown in Figure 3, the dose equivalent calculated by ANISN does not attenuate in inverse proportion to square of the distance r. Also, as seen in the low energy region of the neutron spectrum calculated by ANISN (Fig. 4), the component of thermal neutrons does not attenuate inverse proportionally but keeps almost constant value. Therefore, the dose equivalent calculated by ANISN remains a factor 2 ~ 2.5 larger than the one attenuates in inverse proportion to square of r.

We have considered this as effect of the back scattering from the concrete wall and applied a correction factor of 3 to the result of eq.(1). Thus, the dose equivalent estimate is given by eq. (2).

$$H' = 3 \cdot H \qquad (2)$$

These results are given in Table 3.

Fig. 2 Dose equivalent plot of one-dimensional concrete sphere model for ANISN.

Table 3 Dose equivalent of each calculating point

pt.	H' (μSv/week)	pt.	H' (μSv/week)	pt.	H' (μSv/week)
A1	69.6	B1	0.2	B6	274.5
A2	0.6	B2	96.2	B7	0.2
A3	30.9	B3	530.7	C1	6.5 *
A4	4.0e-3	B4	289.5	C2	206.7 *
A5	232.6	B5	11.0		

* given in μSv/3months

3 Attenuation of Radiation from Access Mazes

The neutron and secondary photon dose equivalent at the exits of the maze were calculated. There are a number of formulas for estimating the attenuation of the radiation in access maze. Here, Nakamura–Uwamino's formula, derived from simple equations, was chosen.

The dose equivalent at the maze entrance was estimated first and then the attenuation in each leg of the maze was estimated by the formula. Finally at the maze exit the attenuation of the slow neutron component by a door made of 10-cm-thick polyethylene with 2-wt. % boron was taken into account.

Contribution of the secondary photon can be assumed to be 1/10 of the neutron dose equivalent according to the DOT3.5 calculation [3]. The factor, 2, requested by the government was applied as well as in the case of bulk shielding. Table 4 shows the results of the attenuation in the maze.

Table 4 Dose equivalent at the entrance
and the exit of the mazes

Calc. Point	$H_{entrance}$ (μSv/week)	H_{exit} (μSv/week)
B4	8.3×10^4	12.5
B5	8.0×10^4	21.2
B6	4.1×10^4	0.4
B7	2.4×10^4	0.3

4 Skyshine

The neutron and secondary photon dose equivalent caused by skyshine effect was calculated by the skyshine calculation code SHINE-II. First, in order to estimate the leakage neutron and secondary photon from the roof of the facility, the angular flux of radiation from the concrete sphere of 2 m thick was calculated by ANISN.

Second, the neutron and secondary photon dose equivalent by skyshine was calculated by SHINE-II. Two calculating points were defined;
· C1 is the point at the border of the facility. The distance from the nearest beam loss point is 75 m.
· C2 is the point at the border of the hospital. The distance from the nearest beam loss point is 45 m.
Table 5 shows the results of the calculation.

Table 5 Results of the skyshine calculation by SHINE-II

Calculating pt.	$H_{skyshine}$ (μSv/3months)
C1	0.07
C2	0.31

5 Summary

Overall dose equivalents for all the calculating points are given by table 6. Contributions by the radiation via the maze and the skyshine are around 10~50 % and lower than 10 % of the directed transmission, respectively.

The calculating points, denoted by A1 ~ A5, B1 ~ B7, and C1 ~ C2 are located at the border of the controlled area, at the area of the area where workers have full time access, and the border of the facility, respectively. Dose equivalent limits for these borders by the law are 300 μSv /week, 1mSv /week, and 1.3mSv/3months, respectively.

Since all results satisfy the limit, our analysis supports that the shielding design of the facility is appropriate.

Table 6 Overall dose equivalent of calculation points.

pt.	H' (μSv/week)	pt.	H' (μSv/week)	pt.	H' (μSv/week)
A1	69.6	B1	0.2	B6	274.9
A2	0.6	B2	96.2	B7	0.5
A3	30.9	B3	530.7	C1	6.6 *
A4	4.0e-3	B4	310.7	C2	207.0 *
A5	232.6	B5	23.5		

* given in μSv/3months

References

[1] RSICC COMPUTER CODE COLLECTION ANISN-ORNL, CCC-254, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

[2] RSICC DATA LIBRARY COLLECTION HILO86, DLC-119 HILO86, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

[3] Y. Uwamino, T. Nakamura, "Shielding Design and Detection of Neutrons from Medical and Industrial Electron Accelerators", Radioisotopes, Vol. 35, 2 (1986)

[4] K. Hayashi et al. "DUCT-II and SHINE-II : Simple Design Code for Duct-Streaming and Skyshine", JAERI-M 91-013 (1991)

[5] H. W. Patterson and R. H. Thomas, "Accelerator Physics", Academic Press, 1973

[6] M.Meire, et al., "Neutron Yields from Stopping- and Near-Stopping-Length Targets for 256-MeV Protons", Nucl. Sci. and Eng., Vol. 104, 1990

[7] International Commission on Radiation Protection (ICRP) Publication 51