Pergamon

Appl. Radiat. Isot. Vol. 48, No. 4, pp. 453–457, 1997

0969-8043/97 $17.00 + 0.00

PII: S0969-8043(96)00268-0

Transmission of Neutron and Gamma Radiation Fields Along the Maze of a Cyclotron Vault

BHASKAR MUKHERJEE and SIMON PARCELL

ANSTO, Radiopharmaceutical Division, National Medical Cyclotron, PMB 12, Camperdown, NSW 2050, Australia

(Received 20 June 1996)

The neutron and gamma dose equivalent rates at various locations along the central plane of the four legged maze leading to the concrete vault of a 30 MeV Medical Cyclotron were measured. These measurements were performed during the bombardment of a water cooled aluminium target with a 30 MeV proton beam. The experimentally estimated neutron dose equivalent rates along the distance of penetration into the maze were fitted explicitly with a set of exponential functions. These functions were utilised to optimise the maze design calculations of similar cyclotron target caves.

Introduction

The installation of a 30 MeV negative ion (H^-) cyclotron (Model: Cyclone-30; Manufacturer: Ion Beam Applications, Belgium) at the Radiopharmaceutical Division of the Australian Nuclear Science and Technology Organisation (ANSTO) was completed in July 1991. In March 1992 the cyclotron commenced the routine production of the PET (Positron Emission Tomography) isotopes, $^{11}CO_2$, $^{13}NH_3$, and ^{18}FDG (in aqueous form) as well as the SPECT (Single Photon Emission Computed Tomography) isotopes, ^{201}Tl, ^{67}Ga and ^{123}I.

The Cyclone-30 cyclotron with the PET target station PT1 and the three SPECT target stations ST1, ST2 and ST3 are installed separately in two identical vaults (Fig. 1) with 2.3 m thick side walls and 2 m

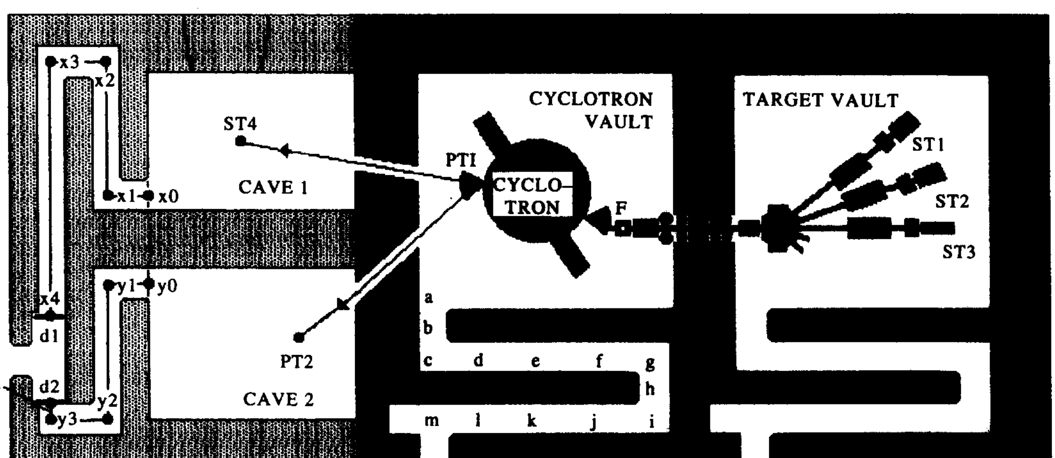

Fig. 1. Schematic diagram of the Medical Cyclotron complex of ANSTO showing the existing cyclotron and target vaults (dark shading) housing the PET (PT1) and SPECT (ST1–ST3) targets and the Faraday-Cup (F) bombarded with the 30 MeV proton beam. The locations of the neutron and gamma transmission factor evaluation along the maze are indicated by a–m. The dimension of the mazes of the proposed (light shading) Cave 1 (x0–x4) and Cave 2 (y0–y4) and position of the doors d1 and d2 lined with polyethylene plates are also shown.

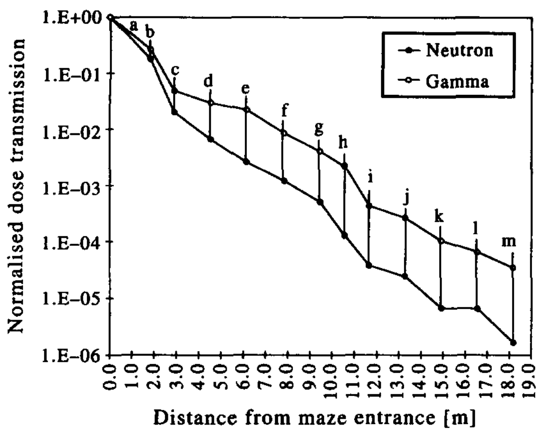

Fig. 2. The dose equivalent transmission of neutrons (●) and gamma rays (○) and the locations of the dose estimation (a–m) points are shown with the corresponding distance from the cyclotron vault maze entrance. The dose equivalent rates are normalised to entry point (a) dose.

thick roofs made of high density (2.4 g cm^{-3}) very low sodium content ($\approx 0.04\%$ ww) concrete (Mukherjee, 1990), in order to reduce the emanation of 1.36 MeV gamma rays from ^{24}Na, produced via $^{23}Na(n, \gamma)^{24}Na$ reaction. The vaults are accessed through two 1.1 m wide four legged mazes (Fig. 1). These multi-legged mazes were built to facilitate a trouble free passage of personnel and equipment to and from the vaults. The exit point exposure rate remains less than the permissible level without the deployment of massive and expensive shielded doors. The design parameters of the existing mazes were calculated (Mukherjee, 1990) by modifying the formulae originally developed for the high energy accelerators (Tesch, 1982). This paper summarises the experimental results of a real time dose equivalent rate measurement of prompt neutrons and gamma rays at various locations along the 1.1 m wide and 2.3 m high maze of a cyclotron vault. The neutron dose transmission data for each leg of the maze was fitted with a set of characteristic exponential functions. The coefficients of these exponential functions were used to optimally calculate the dimension of mazes of the new target caves Cave 1 and Cave 2 (Fig. 1) planned to accommodate a SPECT (ST4) and a PET (PT2) target stations respectively (Mukherjee, 1995).

Materials and Method

A light aluminium trolley carrying a neutron survey instrument (Model: NP-2, 'Snoopy'; Manufacturer: NRC Industries, U.S.A.) and gamma dose rate meter (Model: FH 40F2; Manufacturer: FAG, Germany) was moved to the entrance of the maze at location 'a' as shown in Fig. 1. The aluminium trolley was used to avoid the distortion of the neutron energy distribution near the neutron monitor due to inelastic

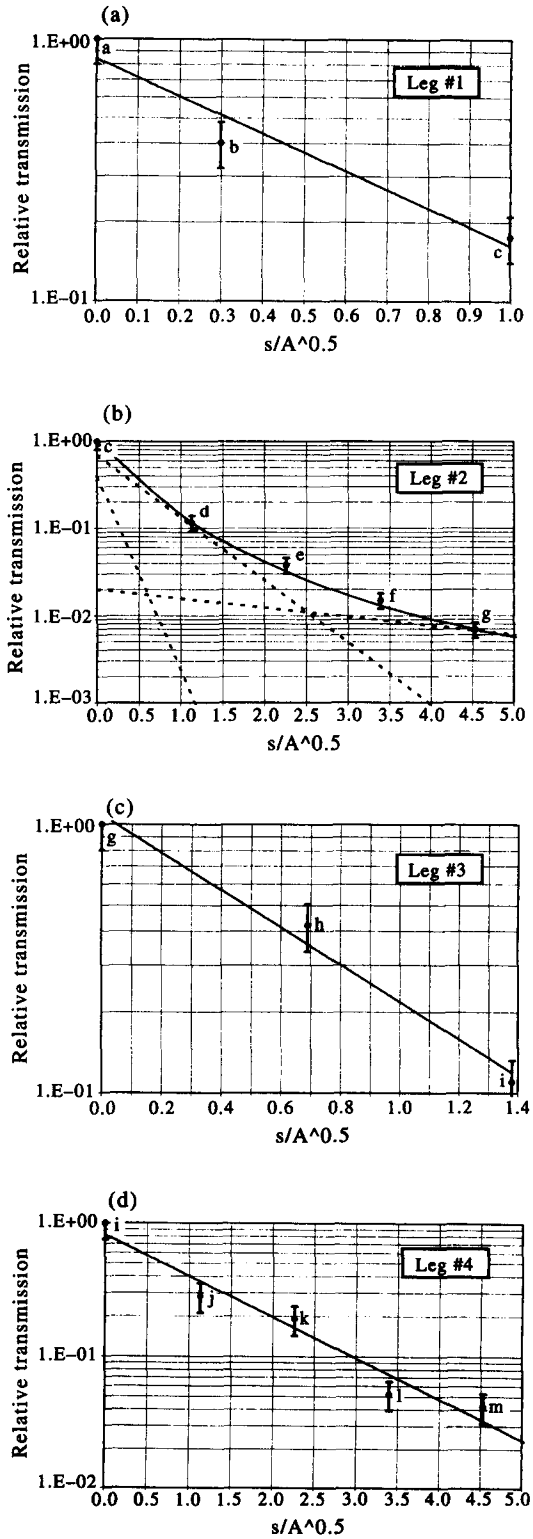

Fig. 3. The exponential fitting curves of the neutron attenuation characteristics of individual maze section—Leg No. 1 (a), Leg No. 2 (b), Leg No. 3 (c) and Leg No. 4 (d) are shown explicitly as a function of (s/A^0.5). The experimental errors ($\pm\sigma$) derived from the 10 randomly selected instrument readings are also shown. The square root of the cross sectional area (A^0.5) of the maze was 1.6 m.

Table 1. The exponential fittings of the four sections of the cyclotron vault maze derived from Fig. 2 are shown explicitly as a function of $s/\sqrt{A}$. The neutron dose equivalent rate (D_{rel}) at the selected spots located at distance (s) from the maze entrance was normalised to corresponding starting point dose of each maze section. The square root of the cross-sectional area ($\sqrt{A}$) of the maze was 1.6 m. The experimental errors represent one standard deviation ($\pm\sigma$) of at least 10 randomly selected instrument readings

Location	s [m]	$s/\sqrt{A} = x$	D_{rel}	Fitting function
a	0	0	1.00 ± 0.20	$D = 0.94 \exp(-1.64x)$
b	0.8	0.5	0.40 ± 0.08	for Leg No. 1
c	1.7	1.06	0.18 ± 0.04	
c	0	0	1.00 ± 0.15	$D = 0.67 \exp(-1.64x)$
d	1.8	1.03	0.120 ± 0.02	$+ 0.34 \exp(-5.12x)$
e	3.6	2.25	0.038 ± 0.006	$+ 0.02 \exp(-0.24x)$
f	5.4	3.39	0.013 ± 0.002	for Leg No. 2
g	7.2	4.53	0.007 ± 0.001	
g	0	0	1.00 ± 0.20	$D = 1.08 \exp(-1.60x)$
h	1.1	0.69	0.420 ± 0.08	for Leg No. 3
i	2.2	1.38	0.111 ± 0.02	
i	0	0	1.00 ± 0.25	$D = 0.82 \exp(-0.71x)$
j	1.63	1.02	0.282 ± 0.071	for Leg No. 4
k	3.26	2.05	0.190 ± 0.048	
l	4.89	3.07	0.052 ± 0.013	
m	6.52	4.10	0.042 ± 0.011	

scattering. The cyclotron vault was closed after activating the safety-interlock system and the Faraday Cup (F) consisting of a thick water cooled aluminium beam-stop (Target) was bombarded with a 30 MeV proton beam (Fig. 1).

The neutron and gamma dose equivalent rates were read directly from the instrument panel of the radiation monitors with a miniature TV camera fitted to the trolley. The intensity of the proton beam current during the target bombardment was recorded with the Health Physics Data Acquisition System (Mukherjee and Arnott, 1992). The experiment was repeated by placing the trolley on the spots b–m along the central plane of the four legged maze of the cyclotron vault as shown in Fig. 1. The neutron and gamma dose equivalent rates at spot 'a' (maze entrance) for an average proton beam current of 0.15 μA were measured to be 0.009 Svh^{-1} and 0.001 Svh^{-1} respectively. The gamma and neutron dose equivalents at the spots b–m were normalised to dose equivalents at the spot 'a' and are plotted with the corresponding central line distance from the maze entrance shown in Fig. 2.

Results and Discussion

The dose distribution characteristics in the cyclotron vault maze shown in Fig. 2 reveals the neutron and gamma transmission factors of 1.7×10^{-6} and 3.5×10^{-5} at the end point of the maze 'm' respectively. The higher transmission of gamma rays relative to neutrons resulted from the successive accumulation of 'neutron capture' gamma rays along the maze. These gamma rays were produced during slowing down (thermalisation) of the fast neutrons via multiple scattering and the resulting capture of the thermalised neutrons in hydrogen atoms of the water molecules present in the concrete maze wall.

In order to estimate the neutron attenuation characteristics of individual maze leg explicitly, the neutron transmission curve in Fig. 2 was unfolded into four components corresponding to Leg No. 1 (a–c), Leg No. 2 (c–g), Leg No. 3 (g–i) and Leg No. 4 (i–m) and are shown in Fig. 3(a–d) respectively. The starting point dose rate value of each component curve was normalised to unity and fitted either with a single or a linear combination of three exponential functions as shown below:

$$\text{Leg No. 1: } D = 0.94 \exp(-1.64x) \tag{1a}$$

$$\text{Leg No. 2: } D = 0.67 \exp(-1.64x) + 0.34 \exp(-5.12x) + 0.02 \exp(-0.24x) \tag{1b}$$

$$\text{Leg No. 3: } D = 1.08 \exp(-1.60x) \tag{1c}$$

$$\text{Leg No. 4: } D = 0.82 \exp(-0.71x)\,. \tag{1d}$$

Table 2. The neutron dose equivalent transmission factor (TF) at the important reference points (Fig. 1) along the mazes of the proposed Cave 1 and Cave 2 calculated using the exponential fitting functions [equation 1 (a–d)] are shown. The distance between the two adjacent reference points along the maze is indicated by s

Cave 1 (SPECT target)			Cave 2 (PET target stations)		
Reference point	s [m]	TF	Reference point	s [m]	TF
x0	0	1	y0	0	1
x1	1.5	1.8×10^{-1}	y1	1.5	1.8×10^{-1}
x2	3.3	6.3×10^{-3}	y2	3.3	6.3×10^{-3}
x3	2.0	9.2×10^{-4}	y3	2.0	9.2×10^{-4}
x4	5.9	5.5×10^{-5}	y4	0.5	6.1×10^{-4}

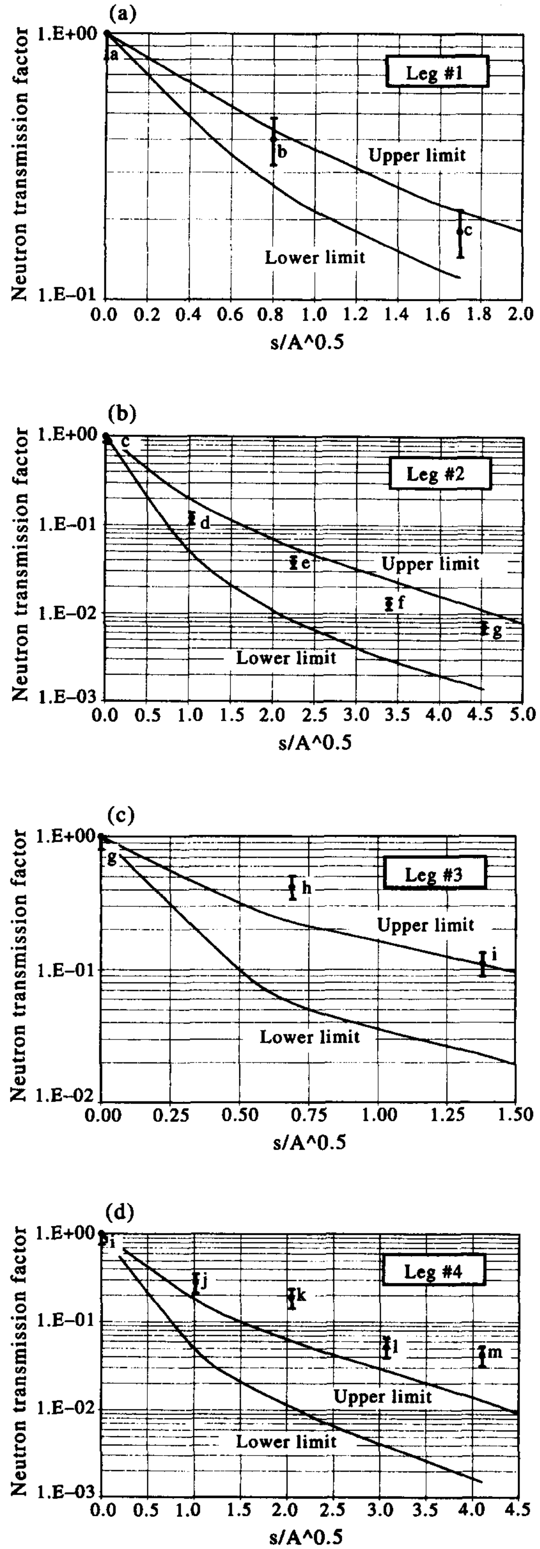

Fig. 4. The neutron transmission factors of the 1st (a), 2nd (b), 3rd (c) and 4th (d) leg of the maze of the cyclotron vault estimated with a rem-counter (Snoopy) are explicitly shown as a function of (s/A^0.5) and compared with the universal maze transmission curves. The neutron transmission factors of the 1st and 2nd legs fit satisfactorily within the upper and lower limits of the universal neutron transmission curves (IAEA, 1988).

The important parameters of the unfolded maze transmission curves are summarised in Table 1. In Fig. 4(a–d) the neutron transmission factors from the present investigation are compared with the universal maze transmission curves (IAEA, 1988; Ishikawa *et al.*, 1992) based on the data reported by various authors (Stevenson and Squier, 1973; Goebel *et al.*, 1975; Gollon and Awschalom, 1971) and found to be in good agreement.

By using the exponential functions given in equations (1a)–(1d) the maze dimensions of Cave 1 and Cave 2 were calculated. The exit point neutron dose equivalent transmission factor (TF) for Cave 1 (at x4) and Cave 2 (at y4) was derived as 5.5×10^{-5} and 6.1×10^{-4} respectively. The values of the dose equivalent transmission factor at selected reference points along the maze of Cave 1 (x1–x4) and Cave 2 (y1–y4) with the corresponding length of the maze leg (s) are shown in Table 2.

By assuming the neutron source strength (i.e. the dose equivalent rate) at the maze entrance point of Cave 1(x0) to be 10 Svh^{-1} and the same of Cave 2 (y0) to be 1 Svh^{-1} the exit point dose equivalents were calculated as 550 and 610 μSvh^{-1} respectively. It is evident that the exit point dose equivalents were optimally regulated by adjusting the lengths of the 4th maze legs, i.e. 'x3–x4' and 'y3–y4' of Cave 1 and Cave 2 respectively. For a further reduction of the exit point neutron dose equivalent the deployment of 20 cm thick linings of commercially available borated polyethylene sheet on the maze doors d1 and d2 has been planned. The overall reduction of the radiation exposure due to neutron capture gamma rays could be achieved by overlaying the maze walls with an epoxy based paint loaded with boron carbide powder. The experimentally estimated maze transmission factors for cyclotron produced neutrons presented in this paper could be universally used to optimise the maze design for similar medical cyclotron facilities.

Acknowledgements—We wish to thank Mr Brian Holland, Senior Health Physicist, ANSTO and Dr Tomas Kron, Chief Physicist, Mater Misericordiae Hospital, Newcastle, N.S.W. for valuable comments and suggestions and Mr Christopher Jamieson, Manager, Radiopharmaceutical Division, ANSTO for his interest in this work.

References

Goebel, L., Stevenson, G. R., Routti, J. T. and Vogt, H. G. (1975) *Rep. LABII- RA/Note*/75-10. CERN, Geneva.

Gollon, P. J. and Awschalom, M. (1971) *Rep.* 71–16, Vol. 2. CERN, Geneva.

IAEA (1988) Radiological safety aspects of the operation of proton accelerators. Technical Report Series No. 283. IAEA, Vienna.

Ishikawa, T., Kumazaki, M. and Makamure, T. (1992) Measurement and calculation of neutron leakage through labyrinth from 35 MeV proton accelerator room. *Nucl. Sci. Tech.* **29**, 97–109.

Mukherjee, B. (1990) ANSTO SAC Approval No. 90/97, p. 20.

Mukherjee, B. (1995) *Proc. XIV Int. Conf. on Cyclotrons and their Applications*, p. 330. Cape Town, South Africa.
Mukherjee, B. and Arnott, D. W. (1992) *Proc. XIII Int. Conf. on Cyclotrons and their Applications*, p. 252. Vancouver, Canada.
Stevenson, G. R. and Squier, D. M. (1973) An experimental study of the attenuation of radiation in tunnels penetrating the shield of an extracted beam of the 7 GeV proton synchrotron NIMROD. *Hlth Phys*. **24,** 87–103.
Tesch, K. (1982) The attenuation of the neutron dose equivalent in a labyrinth through an accelerator shield. *Part. Accel*. **12,** 169–175.