OCCUPATIONAL RADIATION EXPOSURE AT THE SELF-SHIELDED IBA CYCLONE 10/5 CYCLOTRON OF THE A&RMC, MELBOURNE AUSTRALIA

HENRI TOCHON-DANGUY, JOHN I. SACHINIDIS, PAUL U, GARRY EGAN
Centre for PET, Austin and Repatriation Medical Centre, Heidelberg, VIC 3084, AUSTRALIA

BHASKAR MUKHERJEE
Safety Division, Australian Nuclear Science and Technology Organisation
PMB 1, Menai, NSW 2234, AUSTRALIA

A series of health physics measurements was carried out at the IBA CYCLONE 10/5 Medical Cyclotron of the Austin and Repatriation Medical Centre, Melbourne. The neutron attenuation factor of the cyclotron shielding was estimated using the Superheated Bubble dosimeters. The neutron and gamma dose rates at various public access and radiation worker's area in the vicinity of the cyclotron facility were evaluated during the ^{11}C, ^{18}F, ^{13}N and ^{15}O production conditions.

1. Introduction

In May 1992 at the Centre for PET of the Austin and Repatriation Medical Centre in Melbourne, Australia, the self-shielded compact CYCLONE 10/5 Medical Cyclotron (Manufacturer: Ion Beam Applications, Belgium) became operational[1]. The CYCLONE 10/5 accelerates the negatively charged hydrogen ($^1H^-$) and deuteron ($^2H^-$) ions to 10 and 5 MeV respectively. The accelerated ion beams are extracted by electron stripping using thin carbon stripper-foils and directed to one or, two diametrically opposed targets. The CYCLONE 10/5 has thereby dual beam capability for the production of two different radioisotopes simultaneously or an increased activity of a single one. There are currently six targets installed around the circumference of the cyclotron vacuum chamber. The design features of the CYCLONE 10/5 are described elsewhere[2]. Recently a series of health physics measurements with the following goals were carried out: (a) Estimation of the neutron attenuation factor of the cyclotron shielding using bubble dosimeters and (b) Assessment of the neutron and gamma dose rates at important locations in the cyclotron facility. The location of the radiation survey points are highlighted in Table 1. A Plan view (foot print) of the facility is shown in Figure 1. This report summarises the experimental procedure and results of the above health physics survey.

2. Materials and Method

2.1 Shielding Attenuation Estimation using Superheated Bubble Dosimeters

The shielding of the CYCLONE 10/5 is made of an annular stainless steel tank of a width of 60cm filled with 160 g/l potassium borate (K_3BO_4) solution. In addition to the self shielding the cyclotron is housed in a concrete vault of 60 cm wall thickness. The neutron attenuation factor of the lateral shielding wall was evaluated with superheated bubble dosimeters (Model: BD100R, Sensitivity Factor: 4.7 bubbles-μSv^{-1} at 20 °C, Manufacturer: Bubble Technology Industry Canada). The principle of the superheated bubble dosimeters and their applications are described elsewhere[3,4]. Two BD100R dosimeters were initialised and attached to the centre of the internal and external walls of the detachable sector-shielding as represented by points A and B respectively (Figure 1).

Table 1: Showing the brief description of the health physics survey points and the corresponding area classification of the cyclotron facility at the Austin and Repatriation Medical Centre Melbourne (Figure 1). Class 1 and 2 represent the radiation worker and members of the public area respectively.

Survey Point	Brief Description of the Health Physics Survey points	Classification
A	Bubble dosimeter at the internal surface of shield wall	n.a.
B	Bubble dosimeter at the external surface of shield wall	1
1	External surface of the exit door of the cyclotron vault maze	1
2	2m from the radiopharmaceutical production hot cells	1
3	Middle of the corridor (south of the cyclotron vault)	2
4	Middle of the corridor (west of the cyclotron vault)	2
5	Centre of the plant room (north of the cyclotron vault)	1
6	At floor level of the plant room (north of the cyclotron vault)	1
7	External surface of the cyclotron vault roof	2

The sector-shielding was moved back to place dosimeter A, then re-positioned and the ^{18}F production target (T2) bombarded with 10 MeV protons at 0.4 µA for 2 seconds. The shielding was pulled out, the Dosimeter (A) was removed and the sector brought back to its closed position. In two subsequent runs the target T2 was bombarded with 10 MeV protons at 0.4 µA and 4.0 µA for 20 and 110 seconds respectively. After the completion of the target bombardment the Dosimeter B was removed. The bubbles formed in both dosimeters were counted visually after a pause of 1 hour. During the entire irradiation procedure the dosimeters were kept at a constant temperature of about 22 °C. The neutron attenuation factor (a) for the shielding is calculated as follows:

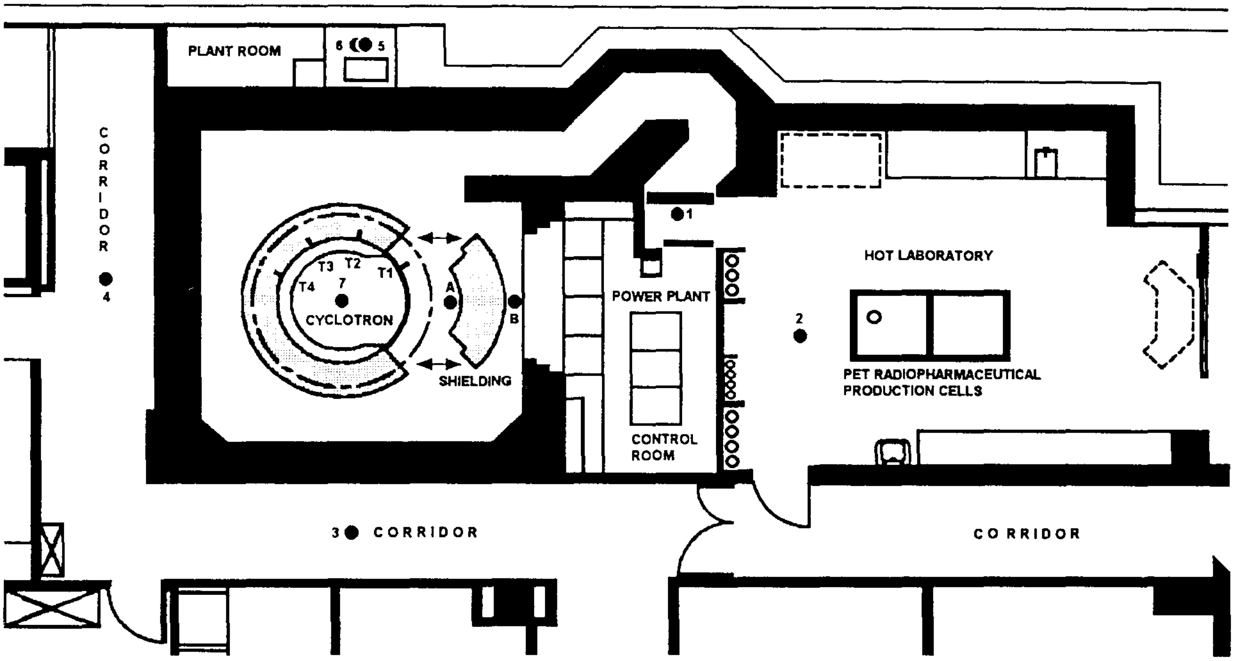

Figure 1: Showing the CYCLONE 10/5 Cyclotron, the Hot laboratory (including PET radiopharmaceutical production cells) and the location of the radiation survey points. T1, T2, T3 and T4 represent the location of the ^{11}C, ^{18}F, ^{13}N and ^{15}O production targets produced via the $^{14}N(p,\alpha)^{11}C$, $^{18}O(p,n)^{18}F$, $^{16}O(p,\alpha)^{13}N$ and $^{14}N(d,n)^{15}O$ reactions respectively

$$a = (N_B/(Q_1 + Q_2 + Q_3)) / (N_A/Q_1) \quad (1)$$

Where, N_A = Number of bubbles formed in Dosimeter A = 34

N_B = Number of bubbles formed in Dosimeter B = 3

Q_1 = Integrated beam current (for 1st run) = 0.4 μA × 2 s = 0.8 μAs

Q_2 = Integrated beam current (for 2nd run) = 0.4 μA × 20 s = 8.0 μAs

Q_3 = Integrated beam current (for 3rd run) = 4.0 μA × 110 s = 440 μAs

By substituting the numerical values in Equation 1 the neutron attenuation factor of the sector shielding was calculated to be 1.6×10^{-4}

2.2 *Neutron and Gamma Dose Assessment at Important Locations*

The neutron and gamma dose rates at critical locations in the facility were measured with a standard Leake type of Spherical neutron REM counter (Manufacturer: EG&G Berthold, Germany, Model: LB6411) and a Proportional counter type Gamma detector (Manufacturer: EG&G Berthold, Germany, Model: 1236). The detectors were interfaced to two general purpose digital radiation monitors (Manufacturer: EG&G Berthold, Germany, Model: LB123 UMO) and securely installed on a light aluminium trolley. The trolley was placed at the cyclotron vault entry (survey point 1) and the neutron and gamma dose rates were recorded for the $^{18}O(p,n)^{18}F$, $^{16}O(p,\alpha)^{13}N$, $^{14}N(p,\alpha)^{11}C$ and $^{14}N(d,n)^{15}O$ reactions. The average target current level for all four reaction modes was fixed at ~ 20 μA with a maximum uncertainty level of ± 0.8 %. The neutron and gamma dose rate and the corresponding target current are summarised in Table 2.

Table 2: Neutron (Dn) and gamma (Dg) dose equivalent rate and the corresponding target current (I) measured at the entrance of the CYCLONE 10/5 vault for various PET isotope production reaction using the targets T1, T2, T3 and T4.

Nuclear Reaction	Dn: [μSvh^{-1}]	Dg: [μSvh^{-1}]	I: [μA]
$^{18}O(p,n)^{18}F$ [T2]	0.021 ± 0.61%	0.238 ± 6.2%	20.1 ± 0.8%
$^{16}O(p,\alpha)^{13}N$ [T3]	0.027 ± 3.7%	0.170 ± 3.3%	20.3 ± 0.4%
$^{14}N(p,\alpha)^{11}C$ [T1]	not measured	0.130 ± 6.5%	20.1 ± 0.5%
$^{14}N(d,n)^{15}O$ [T4]	not measured	0.140 ± 3.8%	20.2 ± 0.4%

It is evident from the data presented in Table 2 that the $^{18}O(p,n)^{18}F$ reaction produces the highest gamma dose rate (0.238 μSvh^{-1}) at the cyclotron vault door (survey point 1). Hence, the above reaction was used as the reference case for the present health physics investigations.

The neutron and gamma dose rate levels at all health physics survey points, i.e. the critical work locations shown in Figure 1 were examined for the $^{18}O(p,n)^{18}F$ reaction mode at the target current level of ~ 20 μA. The aluminium trolley carrying the radiation detectors was moved to the locations of interest and the neutron and gamma dose rates as well as the target current value were recorded. The results are summarised in Table 3.

Table 3: Neutron (Dn) and gamma (Dg) dose rate and the corresponding target current (I) measured at the selected Health Physics survey locations in the vicinity of CYCLONE 10/5 cyclotron for the $^{18}O(p,n)^{18}F$ production reaction.

Health Physics Survey Location	Dn: [μSvh^{-1}]	Dg: [μSvh^{-1}]	I: [μA]
Cyclotron Vault Roof (7)	0.0065 ± 8.9 %	0.085 ± 6.8 %	20.2 ± 0.3 %
Plant room Ground floor (6)	0.480 ± 5.8 %	1.46 ± 3.8 %	20.1 ± 0.4 %
Plant room Centre 1.5m from floor (5)	0.188 ± 17.4 %	0.910 ± 2.0 %	20.1 ± 0.4 %
Corridor west of the Cyclo. vault (4)	0.143 ± 0.7 %	0.230 ± 2.4 %	20.1 ± 0.4 %
Corridor south of the Cyclo. Vault (3)	0.007 ± 1.9 %	0.240 ± 3.7 %	20.1 ± 0.4 %
Hot Cells Laboratory (2)	not detected	0.240 ± 2.2 %	19.9 ± 0.8 %
Cyclotron Vault Entry (1)	0.021 ± 0.6 %	0.238 ± 6.2 %	20.1 ± 08 %

3. *Assessment of Annual Occupational Exposure*

A minimum personnel radiation exposure in accordance with the ALARA (As Low As Reasonable Achievable) is imperative for safe operation of our PET Centre. The occupational radiation exposures to Cyclotron personnel (radiation worker) and other clinical and hospital staff (members of the public) of the Austin and Repatriation Medical Centre were calculated using the data presented in Table 3. To predict the annual occupational exposure the most conservative operation conditions, i.e. 750 hour/year cyclotron run time with an average 30 μA target current for $^{18}O(p,n)^{18}F$ reaction mode were considered. The predicted annual occupational exposure levels are summarised in Table 4.

Table 4: Annual occupational exposure at selected locations in the vicinity of the CYCLONE 10/5 Medical Cyclotron. The exposure levels were calculated for a 750 hours/year cyclotron operation with a 30 μA target current for the $^{18}O(p,n)^{18}F$ production mode. The occupancy factors for all cases were assumed to be 1.0.

Health Physics Survey Location (Figure 1)	Annual Occupational Exposure [μSv]		
	Neutron	Gamma	Total
Cyclotron Vault Roof (7)	18.1	236.6	255
Plant room Ground floor (6)	1343.3	408.6	5429
Plant room Centre 1.5m from floor (5)	526.5	2546.6	3073
Corridor west of the Cyclo. vault (4)	400.5	643.9	1044
Corridor south of the Cyclo. Vault (3)	19.9	678.4	698
Hot Cells Laboratory (2)	not detected	666.0	666
Cyclotron Vault Entry (1)	58.9	666.0	725

4. Summary and Conclusion

The neutron attenuation factor of the cyclotron shielding made of 160 g/l potassium borate (K_3BO_4) solution filled in annular stainless steel tank was experimentally evaluated using superheated Bubble dosimeters and found to be 1.6×10^{-4}. This value agreed well with the data provided by the manufacturer. It was however, important to check the efficacy of the shielding, as the Boron (the main agent of neutron attenuation) is progressively depleted via the $^{10}B(n,\alpha)^{7}Li$ reaction. The bubble dosimeters are inexpensive, small, and therefore found to be a very effective device to check the compact shielding of Medical Cyclotrons.

The projected annual occupational dose levels shown in Table 4 confirm that the present operational schedule of the CYCLONE 10/5 will not raise these dose levels above the mandatory exposure limit for the members of the public (1mSv/y) and radiation worker (20 mSv/y). In real situation however, the doses are much lower than the predicted values as the occupancy factors for all the cases are less than 1. The annual dose records[5] of the previous year showed the exposures of 1.08mSv and 0.78 mSv for radiochemist (750 working hours/y) and cyclotron engineer (150 working hours/y) respectively.

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