# A "COOK-BOOK-METHOD" OF SHIELDING DESIGN FOR COMPACT MEDICAL CYCLOTRONS

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The shielding design of high current commercial medical cyclotrons requires a number of nuclear data inputs, including the neutron-gamma source term and energy distribution, the neutron attenuation lengths and the dose equivalent rate attenuation characteristics. These shielding data were estimated through experimental investigations carried out in the existing cyclotron vault and beam room of the Australian National Medical Cyclotron. The optimised shielding design of two new target caves to house additional PET and SPECT targets at this facility was performed using the above experimental data. The empirical formulae and design recipes presented in this paper could be used to design shielding facilities for similar medical cyclotrons.

## 1. Introduction

The installation of the 30 MeV high current (maximum proton current: 400 μA) $H^-$-ion cyclotron (IBA Cyclone 30) of the Australian National Medical Cyclotron (NMC) was complete in July 1991. In March 1992 the NMC commenced routine production of the PET (Positron Emitting 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.

During the financial year 1994-95, 240 GBq of PET and 800 GBq of SPECT isotopes have been produced at the NMC and a three-fold increase of the isotopic yield is anticipated in the near future. The increased operation time of the cyclotron will cause a faster deterioration of the cyclotron targetry and thereby increase the probability of frequent cyclotron shutdown. In order to lower the production down time caused by targetry failure and to reduce the personnel radiation exposure of the cyclotron crew during the target maintenance work, installation of backup targets in two separate shielded caves adjacent to the existing cyclotron vault has been planned. In the design of these target caves the efficacy of the containment shielding including the maze dimension need to be well estimated.

The relevant nuclear data required for the shielding design of low energy high current medical cyclotrons like the Cyclone-30 of the NMC, was not available in current technical references[1]. Therefore, the optimum shielding thicknesses and the dimension of the mazes of the proposed target caves were calculated by utilising experimental data. These shielding experiments were carried out in the existing cyclotron vault and beam room[2]. This paper presents the simple empirical method utilised for this compact cyclotron shielding design and the related nuclear data.

## 2. Principle of Shielding Calculations

At the NMC, thick copper plates electrodeposited with enriched target materials are routinely bombarded with 30 MeV protons, which results in the production of an intense flux of fast neutrons. The main objective of an optimally designed shielding is to reduce the neutron and the associated gamma dose equivalent rates at the points interest to the acceptable level as recommended by the statutory authority[2]. The lateral thickness of the shielding configuration shown in Figure 1 was calculated by the modifying the empirical method given in the literature[3].

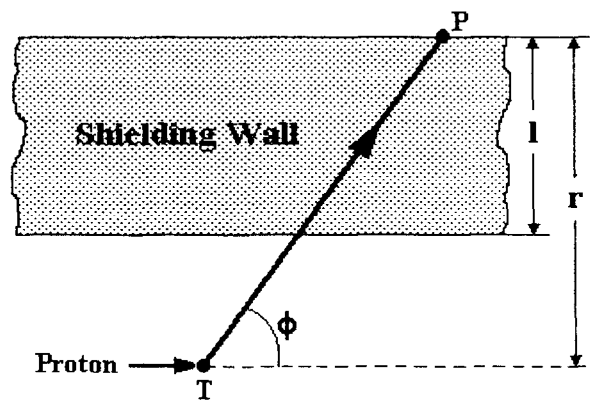


**Figure 1:** Diagram showing the principle of lateral shielding design.

The dose rate $D_P$ at the point of interest P from the neutrons produced by the proton bombardment of the target T is given as:

$$D_P = H(r/\sin\phi)^{-2}\exp(-l/\lambda\sin\phi) \qquad (1)$$

where, H = Neutron dose equivalent rate (source term) at 1.0 metre from the target T [$Svh^{-1}$]
l = thickness of the shielding wall, l > 1.0m
r = lateral distance between the target T and the and the point of interest P [m]
λ = neutron attenuation length of concrete [m]

Hence, for the lateral shielding ($\phi = 90^\circ$) the attenuated neutron dose equivalent rate could be calculated as:

$$D_P = H\exp(-l/\lambda)r^{-2} \qquad (2)$$

## 3. Estimation of Shielding Data

### *3.1 The Source Terms*

The neutron and gamma source terms ie. the dose equivalent rate at 1m from the neutron producing targets $S_w$ and $S_c$ were estimated experimentally (Figure 2). The experimental results are shown in details elsewhere[4, 5].

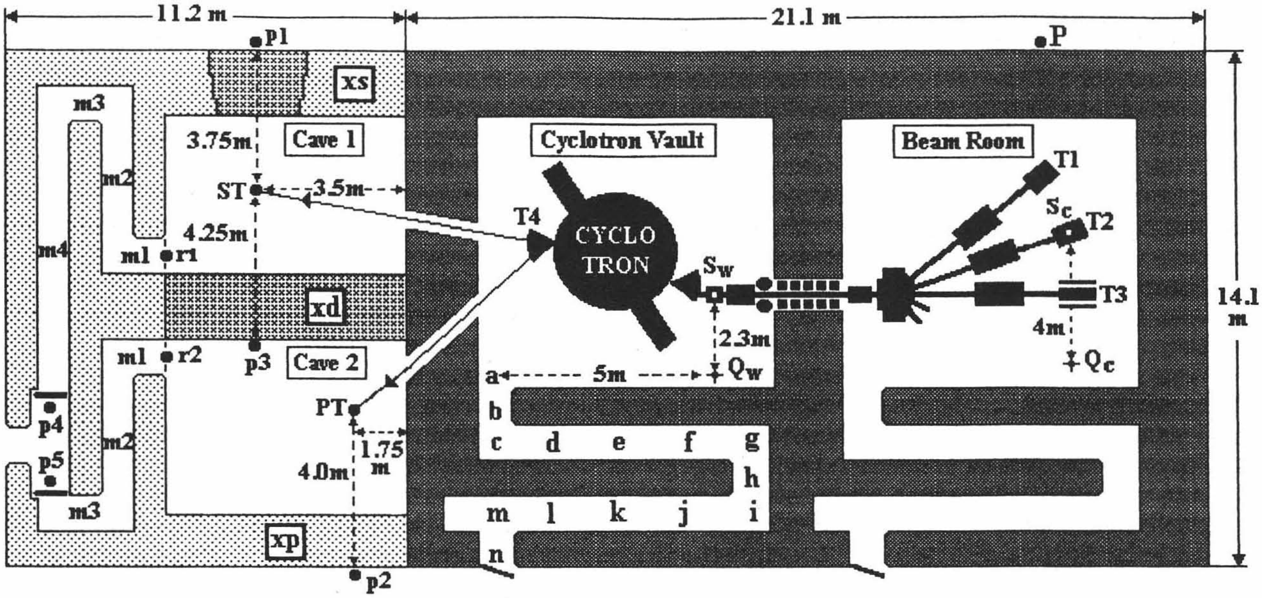


**Figure 2:** Schematic diagram of the NMC Shielding facility showing the existing cyclotron vault and beam room, the target irradiation stations (T1, T2, T3) and the proposed target caves (Cave 1 and Cave 2).

The source term H of neutrons and gamma rays produced by the proton bombardment of thick copper and water targets in the beam room and cyclotron vault are defined as the dose rate at 1m from the target per μA of proton beam current:

$$H = DI^{-1}x^2 \qquad (3)$$

where, D = neutron or gamma dose rate [$Svh^{-1}$]
I = proton beam current [μA] the values are recorded in the Health Physics Data Acquisition System[4]
x = distance between the target and the location of the detectors $Q_c$ and $Q_w$ [m], $x > 1$m

The neutron ($H_n$) and gamma ($H_g$) source terms for the thick targets are shown in Tables 1a and 1b respectively. The experimental uncertainties constituted one standard deviation (± 1σ) of 10 different observations.

**Table 1a**: Neutron source terms for thick copper and water targets.

| Target | I [μA] | x [m] | $D_n$ [$Svh^{-1}$] | $H_n$ [$Svh^{-1}\mu A^{-1} m^2$] |
|---|---|---|---|---|
| Copper | 0.17 ± 0.003 | 4 | 0.015 ± 0.002 | 1.4 ± 0.17 |
| Water | 0.15 ± 0.003 | 2.3 | 0.009 ± 0.001 | 0.33 ± 0.04 |

**Table 1b:** Gamma source terms for thick copper and water targets.

| Target | I [μA] | x [m] | $D_g$ [$Svh^{-1}$] | $H_g$ [$Svh^{-1}\mu A^{-1} m^2$] |
|---|---|---|---|---|
| Copper | 0.17 ± 0.003 | 4 | 0.0012 ± 0.0001 | 0.11 ± 0.012 |
| Water | 0.15 ± 0.003 | 2.3 | 0.00113 ± 0.0001 | 0.04 ± 0.005 |

### *3.2 Dose Attenuations along the Maze*

The attenuation of prompt neutron and gamma dose rates at various locations along the 1.1m wide and 2.3m high cyclotron vault maze were measured in real time. A trolley carrying the neutron rem counter and gamma dose rate meter was moved to the mouth of the maze at spot "a" as shown in Figure 2. The cyclotron vault was sealed and the Faraday Cup ($S_w$) was bombarded with a 30 MeV proton beam. The neutron and gamma dose rates and the corresponding proton current were recorded using the method described earlier[5].

The experiment was repeated by placing the trolley on the spots b, c, d, e, f, g, h, i, j, k, l and m along the central plane of the 4 legged maze as shown in Figure 2. The neutron and gamma dose rates, normalised to the dose rate at spot "a" (maze entrance) are plotted against the corresponding central line distance from the maze entrance in Figure 3. The results in Figure 3 indicate a neutron dose attenuation of $7.9\times10^{-6}$ at the exit (m) of the maze. The relatively high transmission of gamma rays is caused by the neutron capture gamma rays from the hydrogen atoms of the water molecules present in the shielding concrete of the maze wall.

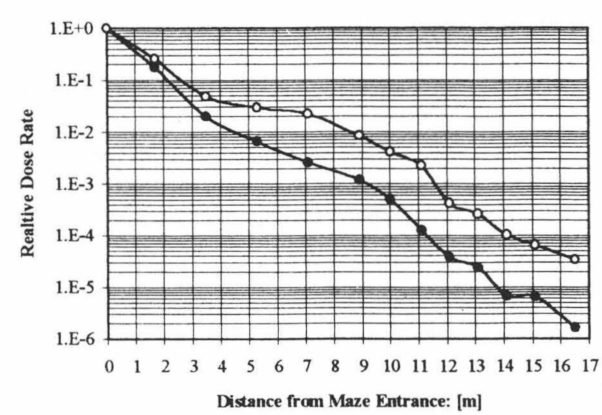


**Figure 3:** Relative attenuation of the neutron (full circles) and gamma (hollow circles) dose rates along the cyclotron vault maze derived from experimental results. The error bars are not shown in this graph.

In order to estimate the neutron attenuation property of each leg of the cyclotron vault maze exclusively, the neutron attenuation curve in Figure 3 was spliced into 4 curves corresponding to leg 1(a, b, c), leg 2 (c, d, e, f, g), leg 3 (g, h, i) and leg 4 (i, j, k, l, m) as shown Figure 2. Each attenuation curve was normalised to the starting point dose fitted with single or linear combination of two exponential functions and shown in column 5 of Table 2. The maze attenuation results for neutrons presented in Figure 3 were found to be in good agreement with the results published in the recent literature[6].

**Table 2:** Neutron attenuation characteristics of each individual leg of the cyclotron vault maze derived from Figure 3.

| Spot Nr. | d [m] | Leg Nr. | D (rel) | Fitting Function |
|---|---|---|---|---|
| a | 0 | | 1.00 | $D = 0.967\exp(-1.02d)$ $R^2 = 0.996$ |
| b | 1.8 | 1 | 0.40 | |
| c | 3.6 | | 0.18 | |
| c | 0 | | 1.00 | $D = 1.001\exp(-1.15d) + 0.030\exp(-0.22d)$ $R^2 = 0.998$ |
| d | 1.63 | | 0.12 | |
| e | 3.26 | 2 | 0.04 | |
| f | 4.89 | | 0.01 | |
| g | 6.52 | | 0.01 | |
| g | 0 | | 1.00 | $D = 1.033\exp(-1.02d)$ $R^2 = 0.998$ |
| h | 1.1 | 3 | 0.42 | |
| i | 2.2 | | 0.11 | |
| i | 0 | | 1.00 | $D = 0.885\exp(-1.11d) + 0.091\exp(-0.19d)$ $R^2 = 0.998$ |
| j | 1.63 | | 0.28 | |
| k | 3.26 | 4 | 0.11 | |
| l | 4.89 | | 0.05 | |
| m | 6.52 | | 0.04 | |

## 4. Shielding Calculations

### *4.1 Shielding Design Requirements*

the following design requirements applied in the shielding calculations.

a) The new target caves should be constructed as a straight extension of the existing shielding containment of the cyclotron vault and beam room.

b) The new SPECT-Target (ST) should be located at 3.5m from the external shielding wall of the cyclotron vault and 3.75m from the external boundary of the proposed shielding wall, as shown in Figure 2.

c) The new PET-Target (PT) should be located 1.75m from the external shielding wall of the cyclotron vault and 4.0m from the external boundary of the proposed shielding wall, as shown in Figure 2.

d) A dividing wall should be erected midway between the two caves. The critical shielding assessment point $p_3$ should be located at a distance of 4.25m from the SPECT-Target (ST), as shown in Figure 2.

e) The maximum lateral dimension of the entire shielding facility should not exceed 11.2m.

f) The intensity of the routine proton beam current should not exceed 250µA for SPECT and 50µA for PET isotope production operations.

g) The maximum dose equivalent rate[2] (total) at the critical shielding assessment points on external surfaces of the shielding walls of Cave 1($p_1$) and Cave 2 ($p_2$) and the dividing wall ($p_3$) shall not exceed $5\mu Svh^{-1}$.

h) High density concrete with a ~ 4% water content[7] should be used in this shielding construction[8].

i) The dividing wall between the target caves and the wall plug should be constructed with $40\times20\times10$ $cm^3$ concrete slabs as shown in Figure 2.

j) The roofs of the caves should be made of 2m thick concrete as the existing cyclotron vault.

k) The ALARA principle shall prevail in all aspects of this shielding design.

### *4.2 Wall Thickness Calculations*

The optimum thickness x of the lateral shielding, required to reduce the transmitted neutron dose equivalent rate $D_T$ to an acceptable low level at the point of interest is calculated by modifying the equation 2:

$$D_T = H_n I\exp(-x/(\lambda_e/\rho))(d)^{-2} \quad (4)$$

where, $H_n$ = Neutron source term [$Svh^{-1}\mu A^{-1}m^2$] for the thick copper target, shown in Table 2a
$I$ = Proton beam current [µA]
$\lambda_e$ = Effective attenuation length of the shielding concrete[9] = 300 $kgm^{-2}$
$\rho$ = Density of shielding concrete = 2380 $kgm^{-3}$
$d$ = lateral shielding thickness [m]

The values of d for the external wall of Cave 1 (3.75m), Cave 2 (4.0m) and the dividing wall (4.25m) and I for the SPECT-Target (250µA) and PET-Target (50µA) as well as the neutron source term $H_n$ (Table 1a) were substituted in equation 4. The resulting neutron Dose Equivalent Rate Transmission is shown as a function of shielding thickness in Figure 4.

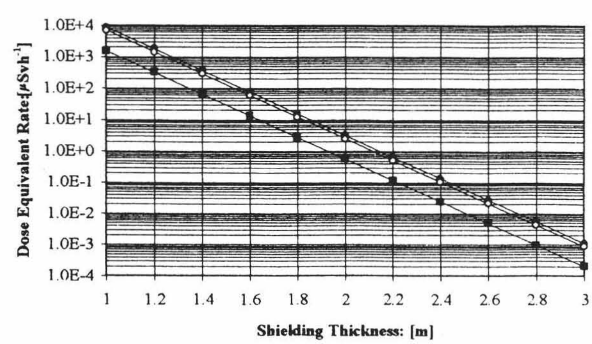


**Figure 4:** The Dose Equivalent Rate of neutrons are shown with the corresponding shielding thickness of the external wall of Cave 1 (solid circles), central wall (hollow circles) and the external wall of Cave 2 (solid rectangles).

For Cave 1 and the dividing wall, an optimum shielding thickness of 2.0m was interpolated from the Figure 4 (ie. $x_s = x_d = 2.0$m) to attenuate the relevant neutron dose equivalent rates down to 3.2μSvh$^{-1}$ and 2.5 μSvh$^{-1}$ respectively. Similarly, for Cave 2, a shielding thickness of 1.8m ($x_p$) was interpolated to achieve neutron attenuation of 2.7μSvh$^{-1}$. By using the gamma dose equivalent rate value per μA of proton beam current, ie., 0.007μSvh$^{-1}$/μA as shown in equation 5, the transmitted gamma dose equivalent rates were estimated as: 1.7μSvh$^{-1}$ (at $p_1$ and $p_3$) and 0.3μSvh$^{-1}$ (at $p_2$). The results are summarised in Table 3.

**Table 3:** The neutron, gamma and total dose equivalent transmission rates at various critical shielding assessment points and the extrapolated optimum lateral shielding thickness d

| Crit. Pts. | d [m] | Neutron DE [μSvh$^{-1}$] | Gamma DE [μSvh$^{-1}$] | Total DE [μSvh$^{-1}$] |
|---|---|---|---|---|
| $p_1$ | 2.0 | 3.2 | 1.7 | 4.9 |
| $p_2$ | 1.8 | 2.5 | 0.3 | 2.9 |
| $p_3$ | 2.0 | 2.7 | 1.7 | 4.4 |

*4.3 Transmission of Gamma Rays*

The gamma ray dose at the external surface of the shielding wall is primarily caused by the capture of thermal neutrons in the concrete. The gamma dose rate at the point P, opposite to target station T1 (Figure 2) was measured with a dose rate meter (Model: FH4-40F2, Manufacturer: FAG Kugelfischer, FRG). The gamma dose rate at the point P per 100 μA of proton current at the thick Cu-Target (by subtracting the natural background dose rate of 0.15 μSvh$^{-1}$ in Sydney) was calculated as:

$$Dg = 0.70\ \mu Svh^{-1}/100\ \mu A \qquad (5)$$

*4.4 Calculation of Maze Lengths*

As in the existing cyclotron vault and beam room, the proposed target Caves 1 and 2 will be provided with 3 legged mazes of 1.1m width (Figure 2). A simple calculation method based on the characteristic exponential fitting functions of individual maze legs, determined experimentally (Table 2). This method was used to estimate the neutron attenuation in the mazes instead of Monte-Carlo simulation[6]. The neutron dose equivalent rates at the entrances ($r_1$ and $r_2$) of the mazes were calculated using the inverse square law. The results are summarised in Table 4.

**Table 4:** Neutron dose equivalent rate attenuation along the mazes of the Caves 1 and 2 calculated using the exponential fitting functions.

| Cave 1 | | | Cave 2 | | |
|---|---|---|---|---|---|
| Spot Nr. | d [m] | DE [μSvh$^{-1}$] | Spot Nr. | d [m] | DE [μSvh$^{-1}$] |
| $r_1$ | 0 | $38.9\times10^6$ | $r_2$ | 0 | $3.1\times10^6$ |
| $m_1$ | 0.5 | $2.3\times10^6$ | $m_1$ | 0.5 | $1.8\times10^6$ |
| $m_2$ | 2.75 | $2.0\times10^6$ | $m_2$ | 2.75 | $1.6\times10^5$ |
| $m_3$ | 5.5 | $6.3\times10^4$ | $m_3$ | 5.5 | $5.0\times10^3$ |
| $m_4$ | 8.25 | $1.3\times10^2$ | $m_4$ | 8.25 | $2.0\times10^1$ |
| $p_4$ | 11.0 | $1.3\times10^0$ | $p_5$ | 1.0 | $1.2\times10^1$ |

## 5. Conclusion

This paper confirms that the simple empirical "cook-book" methods presented here could be used for the calculation of optimum shielding thickness of high (proton) current low energy compact medical cyclotrons after careful consideration of the source term characteristics and the maze structure. It had been taken into account that the "inverse square law" was valid only for the shielding thickness greater than 1metre[10] and the effective neutron attenuation length in concrete $\lambda_e$[9] was independent of the energy of the evaporation neutrons. With appropriate modifications, the neutron-gamma source terms (Tables 1a and 1b) and the neutron attenuation fitting functions of the maze legs (Table 2) presented in this paper could be universally used as important recipes for cyclotron shielding design.

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