Optimisation of the Radiation Shielding of Medical Cyclotrons using a Genetic Algorithm

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INTRODUCTION

Effective radiation shielding is imperative to safe operation of modern Medical Cyclotrons producing large activities of short-lived radioisotopes on a commercial basis. Like the containment shielding of Medical Linear Accelerators (1), the optimal shielding design of Medical Cyclotrons demands a careful balance between the radiological, economical and often the sociopolitical factors. One is required to optimize the cost of radiation protection and the cost of radiological health detriment (2). The cost of radiation protection depends explicitly on the nature of the ionising radiation field produced by the cyclotron, its operational condition, the cost of shielding material, the level of dose reduction, the projected net revenue from the from the sale of the radioisotopes, and the depreciation rate of the cyclotron facility. The mathematical methods of accelerator shielding optimisation (3, 4) within the guideline of ALARA (5) have been reported by various investigators.

The important radioisotopes produced by Medical Cyclotrons for present day diagnostic nuclear medicine include ^{201}Tl ($T_{1/2}$ = 73.06 h) and ^{67}Ga ($T_{1/2}$ = 78.26 h). These radioisotopes are generated by bombarding the thick copper substrates electroplated with enriched parent target materials with 30 MeV protons at ~ 400 μA beam current. The target bombardments result in the production of intense fields of high-energy neutrons and gamma rays. Therefore, in order to avoid the radio-activation of the cyclotron, the ancillaries and radiation exposure to cyclotron workers and members of the public, the high performance target irradiation stations of modern negative ion Medical Cyclotrons (6) are housed in separate target vaults made of high density concrete. Thus, the efficient shielding of the target vaults plays the most important role in the radiological safety of the commercial Medical Cyclotron facilities.

The conventional optimisation method for the functions of multiple variables, such as the cost benefit-analysis of Medical Cyclotron shielding design is too complex and prone to serious pitfalls. Hence, a new method based on the Genetic Algorithm (GA) was used to solve this problem. The GA is a mathematical technique that emulates the Darwinian Evolution paradigm, also known as the “Survival of the Fittest” strategy. It is ideally suited to search for a global optimum in a large multi-dimensional solution space, having demonstrated strength compared to the classical analytical methods. This paper highlights the application of an interactive spreadsheet macro program for the optimised shielding thickness calculation of the target vault of a Medical Cyclotron. The present optimisation method is based on a Genetic Algorithm search engine and runs on a Pentium 300 MHz Personal Computer in the Windows 98 platform.

MATERIALS AND METHODS

The Radiation Field near the Cyclotron Target

The nature of the radiation field produced in the vicinity of the cyclotron target, bombarded with protons should be well known prior to the shielding thickness calculation of the target vault wall. During routine isotope production, a well focussed proton beam (30 MeV, ~ 400 μA) is guided into the target vault through the beam tube A. The beam quality, which includes the proton current and energy distribution, is verified in the beam diagnosis chamber B before the beam is delivered to the water-cooled target irradiation station T. The target plate (copper substrate) attached to an aluminum shuttle S is pneumatically brought into the target station via the transfer duct D. The target is usually irradiated for about 15 – 20 hours. After the completion of the irradiation process the shuttle is transferred to the radiochemical hot cell for the separation process (Figure 1).

An isotropic field of predominantly evaporation neutrons with a peak energy of ~ 2.5 MeV is produced at a rate of 6.4×10^{10} [neutrons.μA^{-1}] during the proton bombardment of the thick copper (substrate) target plate (7). The gamma radiation field in the target vault originates from the nuclear reactions in the copper target, inelastic neutron scattering and neutron capture in hydrogen atoms of the water molecules present in the concrete shielding wall. The neutron (H_N) and gamma (H_G) dose equivalent rates at 1m from the copper target plate i.e.

the “source term” were measured experimentally (8) and found to be:

H_N [$Svh^{-1}\mu A^{-1}m^2$] = 1.4 ± 12 % (1a)

H_G [$Svh^{-1}\mu A^{-1}m^2$] = 0.11 ± 11% (1b)

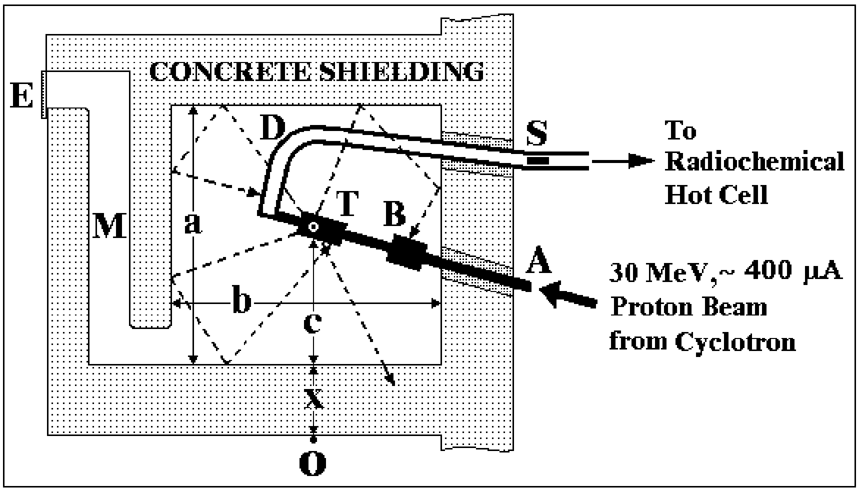

Figure 1: Schematic diagram of the shielding cave showing the target irradiation station and ancillaries and other relevant information used in the optimisation calculation

The fast evaporation neutrons emitted from the thick copper target plate undergo multiple scattering with the hydrogen atoms of the water molecules present in the concrete shielding and slow down to thermal energy level. These thermal neutrons bounce back into the vault and activate the target station, beamline components and the shielding concrete, as shown by the dotted lines in Figure 1. The thermal neutron fluence ϕ_n [$neutrons.cm^{-2}s^{-1}$] in the target vault is given as (9):

$\phi_n = \langle c \rangle Q/S$ (2)

where

<c> = fluence correction coefficient (9) = 4

Q [$neutron.s^{-1}$] = total number of neutrons produced in the target per second

S [cm^2] = total internal surface area of the vault

Shielding Thickness Calculation

By using the deterministic shielding thickness calculation method, the neutron dose equivalent rate D_N at the external reference point O (Figure 1) is calculated as (8):

$D_N = H_N I \exp(-x/\lambda)/(c+x)^2$ (3)

where

H_N = neutron source term (1a) = 1.4 [$Svh^{-1}\mu A^{-1}m^2$] ± 12 %

I [µA] = proton current impinging the target

x [m] = thickness of the concrete shielding (Figure 1)

c [m] = distance between the target and internal surface of the vault wall (Figure 1)

λ [m] = effective neutron attenuation length in the shielding concrete = 0.126 m (10)

With the vault wall designed for neutron shielding effectively attenuating the gamma radiation field produced in the vault, the gamma dose equivalent at the external reference point O (Figure 1) is primarily caused by neutron capture gamma rays produced in the shielding (11). Therefore, shielding thickness calculation exclusively for gamma rays becomes redundant. Following the most conservative assumption, the net gamma dose equivalent D_G (build up) at external reference point O (Figure 1) considered to be 50% of the neutron dose equivalent:

$$D_G\ [Svh^{-1}] = 0.5D_N \qquad (4)$$

Therefore, the total dose equivalent H_X at the external reference point O (Figure 1) is given as:

$$H_X = (D_N+D_G) = 1.5D_N \qquad (5)$$

By substituting the value of D_N from Equation 3 in Equation 5 and assuming the target (T) is located at the centre of the target vault (Figure 1) the total transmitted dose equivalent H_X [Svh^{-1}] at the external reference point O is calculated as:

$$H_X = 2.4I\exp(-x/\lambda)/(0.5\,a+x)^2 \qquad (6)$$

Entrance Maze

A multi-legged maze facilitates an effective passage of personnel and equipment into the target and cyclotron vaults. During the target bombardment, the high intensity prompt (by product) neutron/gamma radiation fields progressively undergo multiple scattering and consequent attenuation while propagating along the maze legs M. In a well designed maze the total neutron/gamma dose equivalent ultimately drops to the permissible level at the maze entrance door E (Figure 1). The attenuation characteristics of neutron and gamma rays along the maze depend of the shape, length, number of bends (legs) and the cross sectional area of the maze (12). The design calculation of the maze is beyond the scope of this presentation.

Neutron Activation of Beamline Components

As it has been mentioned in the earlier section, the thermalised neutrons scattered from the vault wall hit the beam line components (Figure 1) and activate them via the (n, γ) reaction. The characteristics of the radioactive products produced in the target vault of a Medical Cyclotron were experimentally evaluated (13) and shown below (Figure 2):

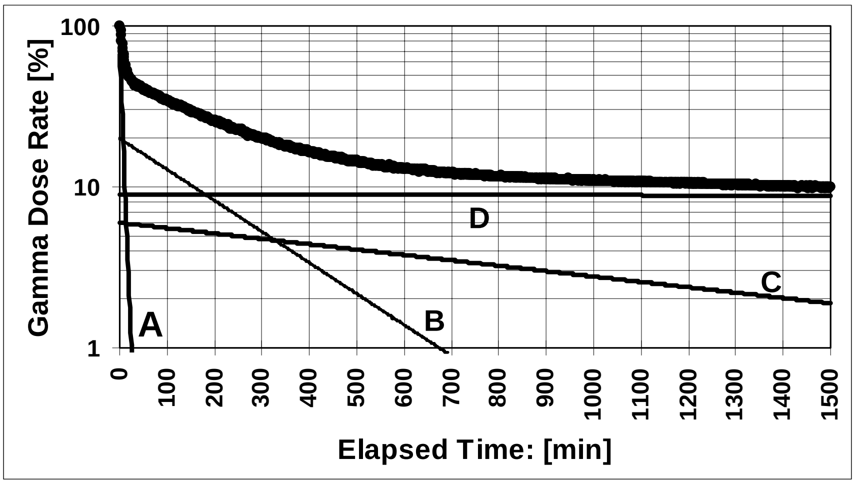

Figure 2: The gamma dose rate (normalised to 100%) in the target vault is presented as a function of elapsed time. The dose decay curve is unfolded into four exponential functions A, B, C and D representing the decay characteristics of four major radioactive species produced by thermal neutron activation.

The radioactive species indicated in Figure 2 were identified from their half-lives, derived from the slopes of the exponential functions A, B, C and D and found to be ^{27}Al ($T_{1/2}$ = 4 min), ^{56}Mn ($T_{1/2}$ = 156 min), ^{24}Na ($T_{1/2}$ = 15 h) and ^{59}Fe ($T_{1/2}$ = 44.6 d) respectively.

The longer lived radioactive species ^{24}Na and ^{59}Fe are produced as the activation products of ^{23}Na and ^{58}Fe present in the shielding concrete of the vault and structural steel of the target station respectively. Evidently, from the long-term waste management point of view, only the activated iron (^{59}Fe) plays a significant role and therefore, is considered as an important optimisation parameter. The saturation activity A_{SAT} [Bq] of ^{59}Fe is calculated as:

$$A_{SAT}\ [\mathrm{Bq}] = N\phi_n\sigma \qquad (7)$$

Where

N = total number of ^{59}Fe atoms in the steel structure

ϕ_n = neutron fluence rate [neutron.cm^{-2}s^{-1}]

σ = cross section of the $^{58}Fe(n, \gamma)^{59}Fe$ reaction = 1.15 barn (13) = 1.15×10^{-24} [cm^2]

The total number of ^{58}Fe atom (N) could be calculated from the weight of the steel structure and the isotopic abundance of ^{58}Fe.

$$N = 0.01\kappa L(W/A_{Fe}) \qquad (8)$$

Where

κ = isotopic abundance of ^{58}Fe = 0.31 %

L = Avogadro's number = 6.022×10^{23} atom.mol^{-1}

W = weight of iron components in the vault [kg]

A_{Fe} = atomic weight of iron = 55.85

The neutron fluence rate ϕ_n [neutron.cm^{-2}.s^{-1}] given in Equation 2 could be expressed in terms of target current:

$$\phi_n = \langle c\rangle qI/S \qquad (9)$$

Where

q = neutron production rate of solid copper target (7) = 6.4×10^{10} [neutron.μA^{-1}]

I = proton beam current [μA]

By substituting the values of N (Equation 8) and ϕ_n (Equation 9) and the numerical values of κ, $\langle c\rangle$, q, L, σ and A_{Fe} in Equation 7 the saturation activity A_{SAT} of ^{59}Fe was calculated as:

$$A_{SAT}\ [\mathrm{GBq}] = 9.83IW/S \qquad (10)$$

Optimisation Calculation

The cost of radiation shielding constitutes the major share of the establishment cost of a commercial Medical Cyclotron facility. The main goal of the optimisation calculation is to reduce the total cost, made of the cost of shielding (radiation protection) and the cost of radiological health detriment (risk) to a minimum (3). In mathematical terms the present optimisation problem is described as follows:

$$U(i, j, k) = X(i, k)+Y(j, k) \qquad (11)$$

Where

$U(i, j, k)$ = total cost [$]

$X(i, k)$ = cost of radiation protection including radiological shielding, real estate and radioactive waste management [$]

$Y(j, k)$ = cost of radiological health detriment [$]

The expression (6) is known as objective function and optimisation operation fulfills the following criterion:

$U(i, j, k)$ => Global Minimum (12)

Satisfying the following necessary condition:

$H_e(x) \leq H_L$, e = 1, 2, 3, ….n (13)

Where

$H_e(x)$ = effective dose equivalent [mSv/year] delivered to e^{th} individual at contact with the shielding thickness x [m]

H_L = permissible average collective dose equivalent limit [mSv/year] fulfilling the ALARA principle (5)

The indices for engineering parameter, cyclotron operational parameter and the relevant monetary values are represented as "i", "j" and "k" respectively.

<u>Estimation of the Cost of Radiation Protection</u>

The net volume (V) of the shielding concrete, total surface area (F) and the total internal wall surface area (S) of the target vault walls are calculated as:

$V\ [m^3] = ((a+x).(b+x)-ab)h$ (14)

$F\ [m^2] = (a+x).(b+x)$ (15)

$S\ [m^2] = 2(ab+ah+ bh)$ (16)

Where

a = length of the target vault [m] (Figure 1)

b = breadth of the target vault [m] (Figure 1)

h = height of the target vault [m] (not shown in Figure 1)

x = shielding thickness [m]

The costs of shielding (C_S), real estate (C_E) and radioactive waste disposal (C_W) are calculated as follows:

$C_S\ [\$] = Vs$ (17)

By substituting the value of V from Equation 14 to Equation 17 one get:

$C_S\ [\$] = ((a+x).(b+x)-ab)hs$ (18)

Where
s = cost of 1 m^3 of shielding concrete [$]

$C_E\ [\$] = Fl$ (19)

By substituting the value of F from Equation 15 to Equation 19 one get:

C_E [$] = (a+x).(b+x)l (20)

Where
l = real estate rate of 1 m^2 of floor space [$]

C_W [$] = $A_{SAT}p$ (21)

By substituting the values of A_{SAT} from Equation 10 and S from Equation 16 to Equation 21 one get:

C_W [$] = 4.92IWp/(ab+ah+bh) (22)

Where
p = cost of waste disposal [$/GBq] for the activated ^{59}Fe

Therefore, the total cost for radiation protection X(i, k) is calculated as:

X(i, k) = (C_S+C_E+C_W) [$] (23)

By substituting the values of C_S, C_E and C_W from Equations 18, 20 and 22 in Equation 23 one get:

X(i, k) [$] = ((a+x).(b+x)-ab)hs+(a+x).(b+x)l+4.92IWp/(ab+ah+bh) (24)

Estimation of the Cost of Radiological Health Detriment

The monetary value of the radiological health detriment Y(j, k) is imperative to the optimisation analysis of radiological shielding design and expressed in mathematical terms as follows:

Y(j, k) = $\alpha\Lambda(x)$ (26)

Where
α = cost of unit collective dose for radiation protection [$/person.Sv]

$\Lambda(x)$ = collective dose equivalent [µSv] for the shield thickness x [m]

By substituting the value of H_X from Equation 6 the collective dose equivalent $\Lambda(x)$ could be expressed explicitly as follows:

$\Lambda(x) = 2.4\rho\eta\tau NT (\exp(- x/\lambda)/(0.5a+x)^2)$ (27)

Where
ρ = ratio of the average permissible dose equivalent H_L and maximum dose equivalent H_X

η = occupancy factor

τ = 8760 [h/y]

N= number of exposed person

T = expected life of the shielding installation [y]

I = proton current at target [µA]

By substituting the value of $\Lambda(x)$ from Equation 27 to Equation 26 the total monetary value of the radiological health detriment is expressed as:

Y(j, k) [$] = $2.1\alpha\rho\eta NTI(\exp(- x/\lambda)/(0.5a+x)^2)\times10^4$ (28)

The monetary values of the radiation protection and radiological health detriment, design parameters and cyclotron operational conditions used in these optimisation calculations are presented in Table 1:

ITEM	**DESCRIPTION [Unit]**	**REMARKS**
α s l p	Cost of radiation protection [$/person.Sv] Cost of shielding concrete [$$m^{-3}$] Cost of real estate (surface area) [$$m^{-2}$] Cost of waste disposal [$$GBq^{-1}$]	Monetary Values (Index: k)
a b h λ T W	Length of the vault [m] Breadth of the vault [m] Height of the vault [m] Neutron attenuation length of concrete [m] Expected life of the shielding [y] Total weight of iron [kg]	Engineering Design Parameters (Index: i)
N η I H_L H_X ρ	Number of exposed person Occupancy factor Proton beam current [μA] Allowable Dose Equivalent [mSv] Maximum Dose Equivalent [mSv] H_L/H_X	Radiological and Cyclotron Operational Parameters (Index: j)
X(i, k) $\mathbf{H_{XR}}$ **x**	Total optimised cost of the shielding[$] Dose Equivalent rate at external reference Point [μSvh^{-1}] Concrete shield thickness [m]	Optimisation Goals

Table 1: Showing the monetary value of the radiation protection, engineering design, radiological and cyclotron operational parameters used in the optimisation calculation. The bold characters in column 1 represent the variables to be optimised using the Genetic Algorithm technique.

GENETIC ALGORITHM

Principle

The Genetic Algorithm (GA) is a powerful search tool suitable for locating the “Global Optimum” in a complex multidimensional “Search Space” where analytical optimisation techniques may suffer serious pitfalls (14). The GA technique has been used to optimise a wide rage of radiological and health physics related problems such as, the job allocation plan of radiological workers (15) and neutron spectra unfolding (16) using Bonner-spheres. The GA technique emulates the “Evolution Paradigm” (17) proposed by Sir Charles Darwin, the great 19th century English biologist (18).

The Genetic Algorithm search process is described as follows with the mathematical analogue of the corresponding GA term is shown in the parenthesis: (a) Random creation of a large *population* (set of prospective solutions) of organisms (*binary strings*). (b) The *fitness* (deviation from true value) of each organism in the population is validated. (c) A small fraction, (usually 1- 5%) of the *fittest organisms* (best solutions) is selected. (d) The selected fittest organisms are *cloned* (copied) according to the following the rule: “number of clones is proportional to fitness”. The rest of the remaining organisms are *discarded* (ignored). (e) Pairs of *parent organism* (initial solution pair) are chosen randomly from the cloned organism population and *mated* via *crossover process* (exchange of single or multiple “bits” between the selected binary strings). During the crossover process the *parent’s gene* (specific bits of the selected binary string) are manipulated to produce the *offspring pairs* (resultant solutions). (f) The previous *population* (solution set) is replaced by the new offspring population. (g) The fitness test of the current population is executed. (h) The *evolution process* (iteration run) is continued via the steps (b) – (g) until the *fittest population of organism* (Global-Optima or the best solution) is found.

Application of GA in Shielding Optimisation

The main purpose of the present optimisation calculation is to evaluate the thickness of the concrete shielding wall to provide the "maximum radiological safety" at "minimum material and operational costs" by varying the engineering design parameters shown in Table 1. By using Equations 24 and 28 the "objective function" U(i, j, k) shown in Equation 11 could be expressed as a function of engineering design parameters and cyclotron operational parameters:

$$U(i, j, k) = ((a+x).(b+x)-ab)hs+(a+x).(b+x)l+4.92\,IWp/(ab+ah+bh)$$

$$+ 2.1\alpha\rho\eta NTI(\exp(- x/\lambda)/(0.5a+x)^2)\times 10^4 \qquad (29)$$

The "Global Minimum" of the objective function U(i, j, k) shown in Equation 29 was evaluated by using a Genetic Algorithm based on a commercially available Genetic Algorithm-Search engine EVOLVER (19). In Table 2 the classification and the tentative values of the input parameters used in the shielding optimisation study are summarised:

ITEM	**DESCRIPTION [Unit]**	**VALUE**	**CATEGORY**
α:	Cost of radiation protection [$/person.Sv]	400,000	Monetary Cost
s	Cost of shielding concrete [$$m^{-3}$]	300	
l	Cost of real estate (surface area) [$$m^{-2}$]	1000	
p	Cost of radioactive waste disposal [$$GBq^{-1}$]	100	
λ	Neutron attenuation length of concrete [m]	0.126	Physical Parameters
T	Expected life of the shielding [y]	20-50	
a	Length of the vault [m]	5 - 10	
b	Breadth of the vault [m]	5 - 10	
h	Height of the vault [m]	5 - 10	
W	Weight of iron parts [kg]	50 - 200	
N	Number of exposed person	10 -50	Operational Parameters
η	Occupancy Factor	0.2 - 1.0	
I	Proton beam current [μA]	100 - 400	
ρ	Allowable Dose Equivalent / Maximum Dose Equivalent	0.2 - 1.0	

Table 2: Showing the category and typical values of the monetary cost, physical and operational parameters of a generic Medical Cyclotron facility used in the Genetic Algorithm based optimisation calculation. All cost parameters refer to at 1996 US$. The weight of iron parts excludes the iron reinforcement of the shielding concrete)

The present optimisation calculation was executed in the Microsoft Excel V7.0 spreadsheet environment. The spreadsheet also served as the input to the Genetic Algorithm search engine EVOLVER (19). A Personal computer with a 300 MHz Pentium Processor and a 128 MB RAM was used. The calculation steps are described as follows:

Step 1) Specify the groups of cells assigned for the monetary cost (α, s, l, p), physical parameters (λ, T, a, b, h, W) and operational (N, η, I, ρ) parameters in the Excel spreadsheet

Step 2) Specify the groups of cells assigned for the variables (optimisation parameters), i.e. the shielding thickness x, dose equivalent rate at external reference point H_{XR} and the cost of the vault X(i, k) in the spreadsheet

Step 3) Set the necessary boundary condition for the "Hard constraint" as follows:

x AND X(i, k) > 0 (positive real number) (30)

Step 4) Set the optimisation condition (Equations 12 and 29) for the "Goal" as follows:

U(i, j, k) => Global Minimum

or,

X(i, k) => Minimum AND Y(j, k) => Minimum (31)

Step 5) Substitute the numerical values of the monetary costs, physical and operation parameters from Table 2 to the allocated cells (Step 1)

Step 6) Substitute an a-priori value of shielding thickness (x = 0.5 m) in the variable cell (Step 2)

Step 7) Initiate the Genetic Algorithm search engine EVOLVER to search for the "best solution" The total number of iteration loops (*generations*) was set at 1000 (19).

The search process (Step 7) was continued until the "best solution", or the minimum value of the objective function (Equation 31), i.e. the "GLOBAL MINIMUM" was found. The optimised values x [m], H_{XR} [μSvh^{-1}] and X(i, j) [$] appeared in the appropriate cells. The optimisation was carried out for two exposure modalities: a) Members of he Public (Annual permissible dose equivalent: H_L = 1 mSv/y, Occupancy factor: η = 0.2) and b) Radiation Worker (Annual permissible dose equivalent: H_L = 20 mSv/y, Occupancy factor: η = 1.0). The results summarised in Table 3 show the optimised shielding thickness x [m], dose equivalent rate H_{XR} [μSvh^{-1}] at the external reference point O (Figure 1) and the radiation protection cost X(i, j) [$] as function of ρ, the ratio of the permissible and maximum dose equivalent rates (H_L/H_X).

	Members of the Public N = 20 T = 25 y W = 100 kg I = 400 μA H_L = 1.0 mSv/y η = 0.2			**Radiation Workers** N = 20 T = 25 y W = 100 kg I = 400 μA H_L = 20 mSv/y η = 1.0		
ρ H_L/H_X	**x [m]**	**H_{XR} [μSvh^{-1}]**	**X(i, k) [$]**	**x [m]**	**H_{XR} [μSvh^{-1}]**	**X(i, k) [$]**
0.2	2.89	3.8 E-03	3.803 E+05	2.45	9.1 E-02	3.656 E+05
0.4	2.96	2.1 E-03	3.823 E+05	2.56	5.8 E-02	3.677 E+05
0.6	2.97	1.7 E-03	3.835 E+05	2.63	3.2 E-02	3.704 E+05
0.8	2.98	1.6 E-03	3.841 E+05	2.68	2.1 E-02	3.724 E+05
1.0	2.99	1.5 E-03	3.851 E+05	2.71	1.7 E-02	3.734 E+05

Table 3: Presenting the summary of the shielding thickness optimisation of the target vault of a Medical Cyclotron using the Genetic Algorithm. A proton current of 400 μA at 30 MeV impinging on a thick copper target was considered to be the routine cyclotron operating condition. The calculations were performed for the members of the public and radiation workers. The table is explained in the text.

SUMMARY AND CONCLUSION

This paper highlights a Genetic Algorithm optimisation method for the radiological shielding design of the high density concrete vaults housing cyclotron targets to produce high yields of medical radioisotopes. The phenomenological neutron and gamma attenuation models were used for the shielding thickness evaluation. The thermal neutron field produced inside the vault during the target bombardment was calculated using the physical property of the target material, beam current and energy. The primary fast neutrons, generated during the bombardment of the target undergo multiple scattering with the vault wall and thereby becoming thermalised and bouncing back into the vault space (Figure 1). The integrated thermal neutron fluence was used to estimate the saturation activity of the long-lived ^{59}Fe (half-life: 45 days) produced via the thermal neutron capture of ^{58}Fe present in various structural materials including the beamline and target irradiation station components located in the vault.

The main attribute of an ideal radiological shielding is to provide the highest achievable radiological safety to members of the public and radiation workers at the lowest establishment and detrimental costs. The establishment cost depends on cyclotron operational conditions (beam current and energy) and includes the cost of shielding material (usually high-density concrete), real estate cost (floor area of the vault), and the waste disposal cost of the activated components. The detrimental cost primarily depends on the cost of radiation protection, occupancy factor, the number of exposed persons and the projected working life of the facility. It is therefore, a daunting task of the cyclotron-shielding designer to balance between a wide range of diverse entities, such as the physical, engineering, economic and sociopolitical aspects, like the radiation exposure to the members of the public.

The Genetic Algorithm technique was found to be an ideal candidate for the solution of the above multivariable optimisation problem. Unlike convention optimisation methods, where a single solution (Local Optima) is calculated in a sequential mode one at a time, the Genetic Algorithms (GA) search for a global solution (Global Optima). The GA search process is initiated by selecting a large population of tentative solutions. The best solution, or the Global Optima is selected through the subsequent “fitness test”, “selection” and “crossover” processes applied to the initial population of solution. The present GA based optimisation program runs in a user friendly spreadsheet environment. The GA program is highly flexible, as the engineering parameters, material cost and the operational conditions may be conveniently manipulated in the spreadsheet to compare the optimisation results for different scenarios. The Genetic Algorithm is a powerful optimisation tool and could be used for a cost effective and safe design of radiological shielding of cyclotron based medical radioisotope production facilities.

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