COST BENEFIT ANALYSIS OF THE RADIOLOGICAL SHIELDING OF MEDICAL CYCLOTRONS USING A GENETIC ALGORITHM

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Abstract

Adequate radiation shielding is vital to the safe operation of modern commercial medical cyclotrons producing large yields of short-lived radioisotopes. The radiological shielding constitutes a significant capital investment for any new cyclotron-based radioisotope production facility; hence, the shielding design requires an accurate cost-benefit analysis often based on a complex multi-variant optimization technique. This paper demonstrates the application of a Genetic Algorithm (GA) for the optimum design of the high yield target cave of a Medical Cyclotron radioisotope production facility based in Sydney, Australia. The GA is a novel optimization technique that mimics the Darwinian Evolution paradigm and is ideally suited to search for global optima in a large multi-dimensional solution space.

1 INTRODUCTION

The optimised shielding design of commercial medical cyclotrons producing large yields of medical radioisotopes requires a sound cost benefit analysis of the radiological, economical and the sociopolitical parameters [1]. The cost of radiological protection of a cyclotron facility is an explicit function of the intensity of radiation fields produced inside and outside the vault, cyclotron operational conditions, cost of shielding material, real estate cost and the depreciation rate of the cyclotron facility. The aim of the cyclotron shielding-designer is to achieve an optimised balance between the costs of radiological protection and radiological health detriment satisfying the ALARA [2] principle. The mathematical method of the accelerator shielding design has been discussed elsewhere [1, 3]. In a modern negative ion Medical Cyclotron almost 100% of the accelerated beam is extracted [4] from the cyclotron acceleration chamber and delivered to the target station located in a separate target cave for the production of large activities of radioisotopes. Hence, in this paper the principle of optimised shielding design of such a target cave (Figure 1) using a Genetic Algorithm is highlighted.

The Genetic Algorithm (GA) is a robust search tool suitable for finding the “Global Optimum” in a complex multidimensional “Search Space” where the analytical optimisation techniques may become futile [5].

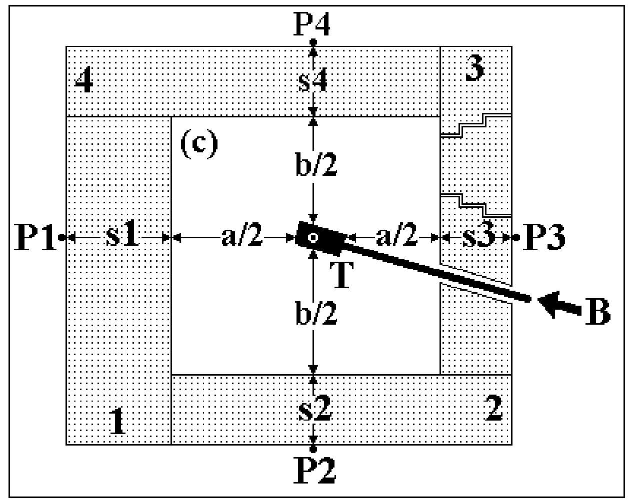

Figure 1: Schematic diagram of the target vault showing the important design parameters used in the GA based optimisation calculations.

The GA technique emulates the “Evolution Paradigm” proposed by Sir Charles Darwin, the great 19th century English biologist [6]. The pathway of the Genetic Algorithm search process is described in Figure 2.

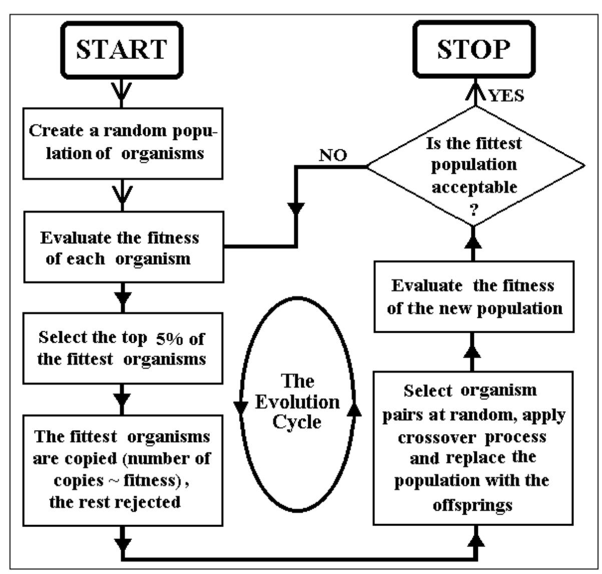

Figure 2: Flowchart showing the principle of Genetic Algorithm.

CP600, *Cyclotrons and Their Applications 2001, Sixteenth International Conference,* edited by F. Marti

2 MATERIALS AND METHODS

2.1 The Shielding Calculations

The nature and intensity of the radiation fields produced in the target vault (Figure 1) during the bombardment of the target (T) by a well-focussed proton beam (B) shall be well estimated prior to the shielding calculation. In the present work the experimentally evaluated [7] neutron (H_N) and gamma (H_G) dose equivalent rates at 1 meter from a thick copper plate bombarded with 30 MeV protons [8] were used as the source terms:

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

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

By using the deterministic of the shielding calculation method the total (neutron + gamma) dose equivalent (H_X) at the external surface of the thick concrete shielding is calculated as [1]:

$$H_X = 2.4\ I \exp(-s/\lambda)/(d+s)^2 \qquad (2)$$

where

I [μA] = proton current impinging the target, s [m] = thickness of the concrete shielding (Figure 1)
d [m] = distance between the target and internal surface of the vault wall (Figure 1), λ [m] = effective neutron attenuation length in heavy concrete = 0.126 m [7]
Hence, the total dose equivalent rates at all 4 walls of the target vault (Figure 1) may be written as:

$$H_{P1}\ [Svh^{-1}] = 2.4\ I \exp(-s1/\lambda)/(0.5a+s1)^2 \qquad (3a)$$
$$H_{P2}\ [Svh^{-1}] = 2.4\ I \exp(-s2/\lambda)/(0.5b+s2)^2 \qquad (3b)$$
$$H_{P3}\ [Svh^{-1}] = 2.4\ I \exp(-s3/\lambda)/(0.5a+s3)^2 \qquad (3c)$$
$$H_{P4}\ [Svh^{-1}] = 2.4\ I \exp(-s4/\lambda)/(0.5b+s4)^2 \qquad (3d)$$

2.2 The Optimisation Calculations

The main goal of the optimisation process is to minimise the total cost, made up of the cost of shielding (radiation protection) and the cost of radiological health detriment (risk) [3]:

$$U(i, j, k) = X(i, k)+Y(j, k) \Rightarrow \text{Global Minimum} \qquad (4)$$

where,
U(i, j, k) = total cost [\$]
X(i, k) = cost [\$] of radiation protection including radiological shielding and real estate and
Y(j, k) = cost [\$] of radiological health detriment
The indices “i”, “j” and “k” represent the engineering, cyclotron operational and monetary parameters respectively.
The expression (4) is known as “objective function” and optimisation operation is fulfilled when the following necessary condition is satisfied:

$$H_e(x) \leq H_L,\ e = 1, 2, 3, \ldots.n \qquad (5)$$

where
$H_e(x)$ = effective dose equivalent [mSv/year] delivered to e^{th} individual at contact with the shielding thickness x [m] and H_L = permissible average collective dose equivalent limit [mSv/year] fulfilling the ALARA principle [2]. The net volume (V) of the shielding concrete (consisting of the volume of the individual walls V1, V2, V3 and V4) and the footprint (F) of the target vault (Figure 1) are given as:

$$V\ [m^3] = V_1+V_2+V_3+V_4 = (b+s2)s1c+(a+s3)s2c+(b+s4)s3c+(a+s1)s4c \qquad (6)$$
$$F\ [m^2] = (a+s1+s3)(b+s2+s4) \qquad (7)$$

where,
a = length of the vault [m], b = breadth of the vault [m] and c = height of the vault [m] (not shown in Figure 1)
Hence, the objective function as shown in expression 4 could be written as:

$$U(i, j, k) = X(i, k)+Y(j, k) =\{(V_1+V_2+V_3+V_4)w + (a+s1+s3)(b+s2+s4)u\}+\{\alpha\tau T(\rho_1\eta_1N_1H_{P1} +\rho_2\eta_2N_2H_{P2}+\rho_3\eta_3N_3H_{P3}+\rho_4\eta_4N_4H_{P4})\} \qquad (8)$$

where,

w = cost of shielding concrete = \$300.00/m^3, u = cost of real estate = \$1000.00/m^2, α = cost of unit collective dose for radiation protection = 400000.00[\$/person.Sv], ρ_1, ρ_2, ρ_3 and ρ_4 = allowable dose equivalent/maximum dose equivalent (may vary from 0.2 to 1.0 depending of the nature of the exposed population group), η_1, η_2, η_3 and η_4 = occupancy factor for the individual shielding wall (may vary from 0.2 to 1.0 depending of the nature of the exposed population group), τ = cyclotron operation factor = 8760 hours/year, N_1, N_2, N_3 and N_4 = number of exposed people (may vary from 10 to 50), T = projected life of the shielding (may vary from 20 to 50 years)

Considering all relevant cyclotron operation factors, engineering parameters, monetary costs and radiological health detriment the “Globally Optimised” thickness of each individual shielding wall (s1, s2, s3 and s4), the dose equivalent rates at external wall surface (H_{P1}, H_{P2}, H_{P3} and H_{P4}) and the cost of the shielding X(i,k) were calculated [1]. The optimisation of the objective function (equation 8) was executed using a commercially available Genetic Algorithm search engine EVOLVER [9] in the Microsoft Excel V7.0 spreadsheet environment. The important results of the optimisation calculation are shown in Table 1 for a proton beam of 400 μA.

3 SUMMARY AND CONCLUSION

This paper highlights the feasibility of a Genetic Algorithm (GA) based optimisation technique for the shielding design of a vault housing a high performance cyclotron target. Unlike conventional optimisation methods, that tackle only a few variables, the GA can manipulate a large number of variables and search for a global solution (Global Optima). The main goal of an ideal radiological shielding is to provide the highest achievable radiological safety to members of the public and radiation workers at the lowest construction, operational and radiological health detrimental costs. The Genetic Algorithm technique was found to be an ideal

Table 1: Presenting the summary of the optimised shielding calculation of a cyclotron target-vault using a Genetic Algorithm. The thickness of each shielding wall was calculated by considering the level of radiological protection required for the relevant exposed individual group. The cyclotron operation parameters are also indicated. The table is explained in the text.

	Exposed Group 1 **Wall No. 1** N = 20 T = 25 y I = 400 μA H_L = 1.0 mSv/y η = 0.2		**Exposed Group 2** **Wall No. 2** N = 20 T = 25 y I = 400 μA H_L = 1.0 mSv/y η = 0.2		**Exposed Group 3** **Wall No. 3** N = 20 T = 25 y I = 400 μA H_L = 20 mSv/y η = 1.0		**Exposed Group 4** **Wall No. 4** N = 20 T = 25 y I = 400 μA H_L = 1.0 mSv/y η = 0.2		
ρ = H_L/H_X	**s1 [m]**	**H_{P1} [Svh^{-1}]**	**s2 [m]**	**H_{P2} [Svh^{-1}]**	**s3 [m]**	**H_{P3} [Svh^{-1}]**	**s4 [m]**	**H_{P4} [Svh^{-1}]**	**X (i, k) [kUS$]**
0.2	2.39	3.81E-07	2.33	6.34E-07	2.46	2.04E-07	2.72	2.24E-08	144.3
0.4	2.47	1.84E-07	2.33	6.24E-07	2.89	5.29E-09	2.45	2.30E-07	149.0
0.6	2.32	6.38E-07	2.65	4.03E-08	3.00	2.17E-09	2.60	5.15E-07	158.2
0.8	2.73	2.17E-08	2.84	8.07E-09	2.86	7.26E-09	2.35	5.15E-07	162.3
1.0	3.00	2.17E-09	3.00	2.17E-09	2.54	1.01E-07	3.00	2.17E-09	178.7

candidate for the solution of such a multivariable optimisation problem. The present GA optimisation routine operates within a user-friendly spreadsheet environment. The GA program is highly flexible, as the engineering parameters, material cost and the cyclotron operational conditions may be conveniently varied in the spreadsheet to evaluate the optimisation for a myriad of scenarios considering the level of radiological protection for individual population groups [10] in the vicinity of the target vault.

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