Session: RP in Medicine – Workers

Design Considerations and Validation of Tenth Value Layer Used for a Medical Linear Accelerator Bunker Using High Density Concrete

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Abstract
A bunker for the containment and medical use of 10MV and 6MV X-rays from a linear accelerator was designed to be added on to four existing bunkers. Space was limited and the walls of the bunker were built using Magnadense, a high density aggregate mined in Sweden and imported into the UK by Minelco Minerals Ltd. The density was specified by the user to be a minimum of 3800kg/m^3. This reduced the thickness of primary and secondary shielding over that required using standard concrete. Standard concrete (density 2350kg/m^3) was used for the roof of the bunker.

No published data for the tenth value layer (TVL) of the high density concrete were available and values of TVL were derived from those for standard concrete using the ratio of density. Calculations of wall thickness along established principles using normal assumptions and dose constraints resulted in a design with minimum primary wall barriers of 1500mm and secondary barriers of between 800mm and 1000mm of high density concrete.

Following construction, measurements were made of the dose rates outside the shielding thereby allowing estimates of the TVL of the material for 6 and 10MV X-rays. The instantaneous dose rates outside the primary barrier walls were calculated to be less than 6 x 10^{-6} Sv/hr but on measurement were found to be more than a factor of 4 times lower than this. Calculations were reviewed and the TVL was found to be 12% greater than that required to achieve the measured dose rate. On the roof, the instantaneous dose rate at the primary barrier was measured to be within 3% of that predicted using the published values of TVL for standard concrete.

Sample cubes of standard and high density concrete poured during construction showed that the density of the standard concrete in the roof was close to that used in the design whereas the physical density of Magnadense concrete was on average 5% higher than that specified.

In conclusion, values of TVL for the high density concrete derived from those for ordinary concrete and correcting only for physical density were found to be conservative and resulted in more material being used than

necessary in the primary and secondary barriers. The measured values of TVL for the high density concrete could be used in the future.

Introduction

Medical linear accelerator bunkers are designed in line with the principles laid down in NCRP49[1], IPEM75[2] and NCRP144[3]. The basic shielding calculation requires knowledge of the tenth value layer of the building material and publications exist giving the values in concrete, steel and a variety of other materials[1,2,3]. Barytes concrete was used for a number of installations some years ago, but it has fallen out of favour as the material is difficult to work with. New building materials become available from time to time and Magnadense concrete is one such product. Natural iron oxide (magnetite) is mined in Northern Sweden. This is used as an aggregate to form a high density concrete which reduces the required thickness of shielding and hence the footprint of a bunker.

No data has been published on the attenuation properties of such material. Therefore it was decided to use a conservative approach and scale the published TVL of concrete according only to physical density. On completion of the bunkers, dose rates were measured and found to be much lower than those predicted in the calculations. Blocks of Magnadense concrete were supplied and basic attenuation curves acquired to derive the TVL for this material for 6 and 10MV X-rays. The resultant values could then be used in the original calculation to work out the excess material used and its cost.

Method

The original calculations for shielding thicknesses were made using the criteria shown in Table 1.

Once the bunker had been constructed, a radiation survey was carried out using a fast scintillation detector (Szintomat 6134A) and the instantaneous dose rates at a number of points were recorded (Figure 1). These dose rates were measured with the linacs operating at 10 MV and 600 monitor units (mu) per minute (approximately 6 Gy/min). The maximum field size was selected and the collimators rotated to 45° to give the maximum field coverage of the back wall. Transmission through the walls and roof and the transmission and scattered radiation at the maze entrance were measured.

To directly determine the attenuating properties of Magnadense, dose rate measurements were made through increasing thicknesses of the material. To this end four specially made Magnadense blocks with dimensions 40×40×10cm were provided by Minelco. The measurements were taken using one of the newly-commissioned linear accelerators. All measurements were taken for exposures of 200 mu (2Gy) using beam energies of 6MV and 10MV. Two detectors were used to cover the range of dose rates expected, ranging from the orders of Sv/min down to tens of mSv/hr. For the lower dose rates the Szintomat model 6134A was used. The higher dose rates were measured using a 0.6cc Farmer ionisation chamber and dosemeter. Perspex was used to provide buildup in both cases.

The gantry was moved to a lateral position and the detectors positioned at the far end of the treatment couch, with the centres of their measurement volumes at a distance of 2m from the isocentre (providing a source-chamber distance of 3m). The set-up is shown in Figure 2. A small field size was selected to just cover the area of the Szintomat detector at the measurement distance. The blocks were placed adjacent to the exit port of the treatment head.

Three readings were taken through attenuating thickness ranging from 0 to 400mm (0 - 4 blocks) and the mean values used. When the readings were within the measurement range of both detectors, readings were taken with each one in the beam in turn. This allowed conversion factors between the two meters to be determined.

The dose rates were plotted on a logarithmic graph against the thickness of Magnadense concrete in the beam and the TVL derived from this plot.

This value was then used in the original design calculations to estimate the required thickness of Magnadense concrete in the primary beam.

Table 1: Design criteria

X-ray energy:	*10MV photons*
Dose rate:	*6 Gy/min @ 1m*
Workload:	*15,000 fractions per annum* *3 Gy/patient* *60 patients/day* *30 mins/day beam on time* *Duty cycle dependent on proportion of Intensity Modulated Radiotherapy (IMRT) patients* *Primary beam duty cycle calculated from above* *Secondary beam on time increased with an IMRT factor of x 3 for 20% of patients*
Leakage:	*0.1% primary beam*
Tenth Value layer:	*Concrete 389mm (published density of 2350 kg/m^3)*[2] *Magnadense 241mm (relative to bulk density of 3800 kg/m^3)*
Dose and dose rate constraints:	
Outside bunker:	*Less than 300μSv (microSievert) per annum (except roof)*[4] *Less than 0.15μSv/hr time averaged dose rate (TADR)* *Less than 7.5 μSv/hr instantaneous dose rate (IDR)*
Roof:	*Less than 2 mSv/hr (IDR)*
Maze entrance:	*Less than 7.5 μSv/hr instantaneous dose rate (IDR)*

Figure 1: Bunker plans with dose survey measurement positions

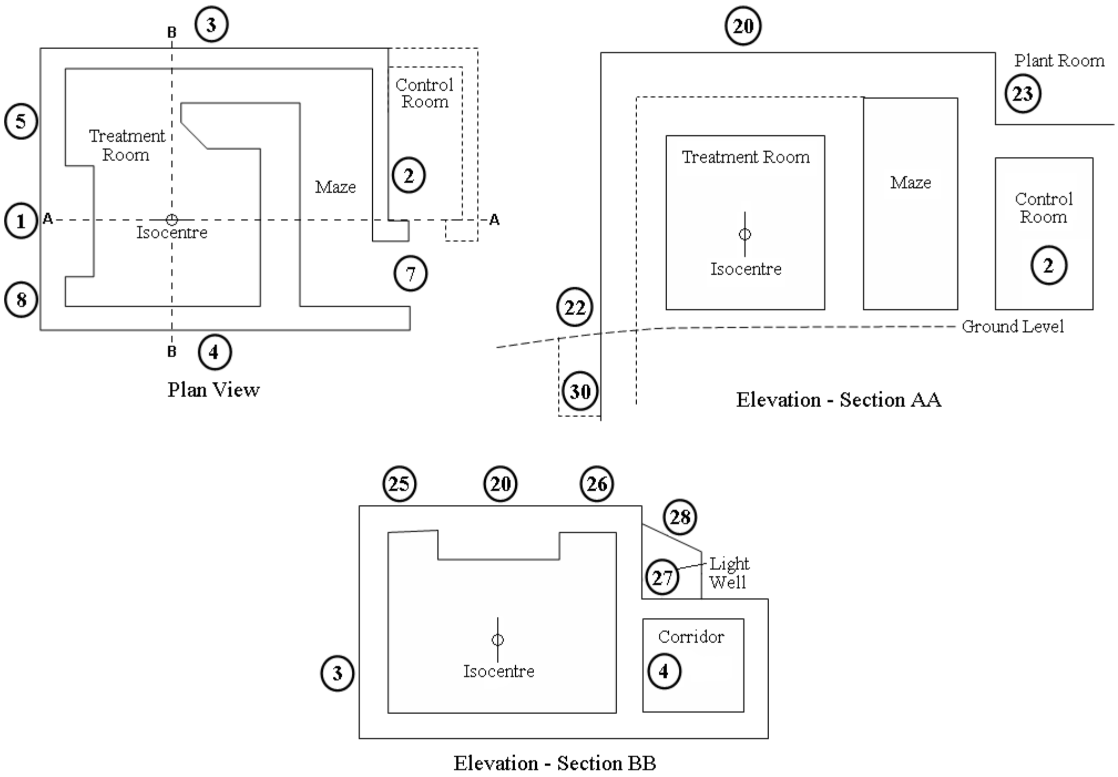

Figure 2: Experimental set-up

Results

Calculations of wall thicknesses required to achieve the dose and dose rate constraints set out in the design criteria gave the following requirements for the constructed bunker:

Nominal Wall thickness: primary barrier 1500mm Magnadense
(down to ground level, concrete below ground)
secondary barrier 1000mm Magnadense
(actual between 750 and 1500mm depending on calculation point)
Nominal Roof thickness : primary barrier 1500mm concrete
secondary barrier 750 mm concrete

Actual measurements of instantaneous dose rates, at points in line with the direct beam, are shown in Table 2. Also shown are the distances to the points of measurement, the constructed wall thicknesses, the calculated unattenuated dose rates and the IDRs calculated using these parameters.

Table 2 Comparison of calculated and measured dose rates outside the bunker

Point	*1*	*2*	*2*
Position	*Outer Wall (Left)*	*Control Room (Right)*	*Roof*
Distance from source (mm)	*5920*	*7850*	*4930*
Wall Thickness (mm)	*1500 magnadense*	*1500 magnadense*	*1500 concrete*
Unattenuated dose rate (Gy/hr)	*10.3*	*5.8*	*14.8*
Calculated IDR (μSv/hr)	*6.1*	*3.5*	*2063*
Measured max dose rate (μSv/hr)	*1.0*	*0.8*	*2000*

Sample cubes of standard and high density concrete poured during construction showed that the density of the standard concrete in the roof was close to that used in the design whereas the physical density of

Magnadense concrete was on average 5% higher than the specified value of 3800 kg/m^3.

The results from the measurements with the 100mm thick Magnadense blocks are shown in Figure 3 with the data plotted on logarithmic linear scales with exponential fits added. The equations of the trend-line and the R^2 fit values are also displayed.

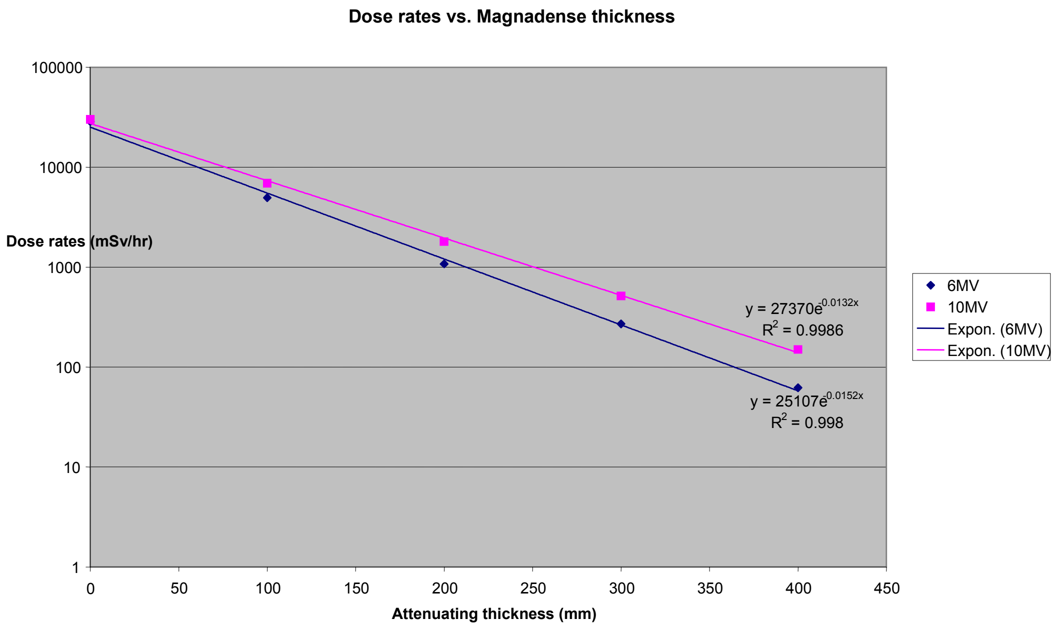

Figure 3: Plotted data with trendlines

According to the Beer-Lambert law, a logarithmic (base 10) plot of the measured dose-rates against thickness of Magnadense should yield a straight line with gradient -μ / ln10, where μ is the linear attenuation coefficient of the attenuating material. This is equal to the reciprocal of the TVL. The above data is therefore used to determine the TVL from the logarithms of the original data.

The experimental set-up provides some scope for error, with estimated errors of up to approximately 30% on the final TVL values. The principal source of this error is associated with the potential for human error in reading the Szintomat scale. The range of TVL values allowing for the experimental error is shown in Table 3 below.

Table 3: TVL results from measurements

Beam Energy	TVL (mm)	Min TVL	Max TVL
6MV	150	103	199

10MV	*174*	*118*	*230*

The measured TVL of 174mm for 10MV was then used in the original calculation to calculate the instantaneous dose rates outside of the existing barrier thicknesses. The results are shown below in Table 4.

Table 4: Comparison of calculated dose rates using the measured TVL and actual dose rates, measured outside the bunker

Point	*1*	*2*
Position	*Outer Wall (Left)*	*Control Room (Right)*
Calculated IDR (μSv/hr)	*0.025*	*0.014*
Measured max dose rate (μSv/hr)	*1.0*	*0.8*

This data shows that the predicted dose rates, calculated using the experimentally measured TVL of 174mm, significantly underestimate the dose rate values measured during the survey.

The TVL value (at 10MV) required to achieve the measured dose rates is 215mm, using the same calculation method.

Summary

	Photon Energy	*TVL (mm)*
Scaled TVL used in original bunker design	*10MV*	*240*
TVLs measured empirically using Magnadense blocks	*6MV* *10MV*	*150 ± 45* *174 ± 52*
TVL calculated from dose survey	*10MV*	*215*

Discussion

The original design for the linear accelerator bunker used conservative attenuation factors for the magnadense concrete to ensure that the facility was safe. This has proved to be the case in line with results from barytes concrete constructions[5] but it was felt that the TVL should be measured for future projects, to enable more precise and cost-effective calculations. The TVL for concrete used was found to result in measured dose rates very close to those predicted by calculation.

The overestimate in the scaled TVL values can be attributed to the fact that the existing TVLs for concrete are scaled according to the physical densities of the materials alone. This does not take into account the increase in atomic number, Z, associated with the introduction of magnetite into the concrete mix. While the probability of Compton scattering taking place increases with density, it is independent of atomic number. However, the probabilities of the photoelectric effect and pair production occurring increase markedly with Z. This means that the use of Magnadense will increase the attenuation of the photon beam by an additional factor, not accounted for in the density-based scaling method.

The TVL measured using the 100mm blocks was found to underestimate the instantaneous dose rates predicted in the original calculations by approximately 23 % for 10MV photons.

However, the TVL measured in narrow beam attenuation conditions may underestimate the TVL in broad beam situations, as experienced in practical radiotherapy bunkers. The use of the value derived from our attenuation measurements in the original design would result in higher dose rates being measured outside the bunker than predicted in Table 4.

Errors in measurement arose from the thickness and density of the blocks and the statistical accuracy of the measurement. The principal source of error was the uncertainty associated in reading the results from a logarithmic scale via a viewing monitor. Such error could be reduced through the use of alternative equipment (e.g. a digital scale).

If the value of 215mm is used in the original design, the primary barriers can be reduced from 1500mm to 1320mm and the other to 1270mm, for measurement points 1 and 2 respectively. This results in a saving of £11,000 on the raw materials in the primary beam.

Further measurements are now planned to measure both the primary TVL under broad beam conditions, as recommended by Numark and Case[5], and the TVL's of Magnadense for secondary radiation.

Scatter coefficients from this material were assumed to be the same as those from concrete. This may not be the case and further work is also required to derive these more accurately so that scatter down the maze can be more accurately modelled.

Monte Carlo simulation of all bunker shielding and maze design is also planned.

Conclusions

The use of a conservative value for the tenth value layer of Magnadense concrete resulted in a safe design, but the resultant doses outside the facility are much lower than those adopted as the dose constraints for the design.

The values derived for the tenth value layer from measurements of attenuation through thin blocks of the material under narrow beam conditions are 23% lower than those used in the design, but the use of these values would have resulted in dose constraints being exceeded.

The use of 215mm for the tenth value of Magnadense concrete at 10MV (estimated from the dose survey results) is likely to result in a safe and cost effective construction. This figure will be further evaluated under broad beam measurement conditions, and the results presented.

References

1. *NCRP Report 49. Structural Shielding Design and Evaluation for Medical Use of X Rays and Gamma Rays of Energies up to 10 MeV (1976)*
2. *IPEM Report No. 75. Design of Radiotherapy Treatment Room Facilities 1997*
3. *NCRP Report 144 Radiation Protection for Particle Accelerator Facilities*
4. *L121 HSE. Work with ionising radiation. Approved code of practise and practical guidance on the Ionising Radiation Regulations 1999, London, HSE (2000)*
5. *Numark, N.J. and Kase, K.R. Radiation transmission and scattering for medical linacs producing X-rays of 6 and 15MV Health Phys 48:289-295 (1985)*

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