Shielding Design - MP569

Group 2

Ruiming Chen, Peter Hotvedt, Peter Li, Andrew McVea, Humza Ayub, Tommy Stasko

December 22, 2020

Abstract

Medical instrument shielding in medical physics is essential for the protection of both medical professionals and the general public from ionizing radiation. The level of shielding required depends heavily on various factors such as the type of radiation, the amount of time the modality is in use, and the materials used for shielding. In this work, a dual energy 6 MV/18 MV Varian Clinac 2100C model linear accelerator in a treatment room was evaluated to determine the amount of shielding necessary to reduce exposure levels to within the regulations outlined in NCRP-151 [1]. By using the dimensions of the treatment room and the specific operating procedures of this accelerator, the level of shielding required for the primary barriers, secondary barriers, and treatment vault door were determined using both the 6 MV and 18 MV energies. Our results for the primary barrier determined that thicknesses of concrete measuring 222.5cm for the ceiling, 181.9cm for the left wall and 180.6cm for the right wall with a barrier width of 4.87m is necessary to meet NCRP-151 exposure levels for these areas. Similarly, for the secondary barrier, a concrete thicknesses of 80.0cm for the back wall, 69.3cm for the front wall, 127.7cm for the left, 126.4cm for the right and 179.3cm for the ceiling are needed for protection from leakage and patient scattered radiation. Finally, for shielding to the door layers of 11.252 cm of Pb, 6.946 cm of Borated Polyethylene (BPE), and 1.9 cm of Pb were added giving a total thickness of 20.098 cm.

Contents

List of Tables

List of Figures

1 Introduction

Medical professionals are often at a high risk of radiation exposure. The sources of radiative risk often come from repeated imaging and treatment procedures, necessary for therapy and diagnosis. Therefore, it is essential to ensure the safety of these workers through radiation shielding measures such as proper room design and wall and door material choice. The process of radiation shielding involves adhering to the ideology of making received doses as low as reasonably achievable (ALARA) depending on the individual receiving the effective dose. These radiation dose limits vary significantly between radiation workers and the general public, but it is critical that both be met based on the design of the room housing the linear accelerator (linac).

When designing a room to house a linac for regular use, it is imperative that the proper safety standards are considered in each step of the process. The NCRP Report 151, titled "Structural Shielding Design and Evaluation for Megavoltage X- and Gamma-Ray Radiotherapy Facilities" covers in detail the defining features of a room designed for medical linac use, specifically, the shielding involved in primary and secondary barriers. Primary barriers are defined as the shielding surfaces in the direct path of a radiation beam, while secondary barriers are defined as any additional barrier in the space. Additionally, it should be noted that depending on the room, the door must also be considered on its own due to the varying positions of the barrier itself. Both the secondary barrier and the door are designed to specifically shield against any scattered radiation or leakage radiation during treatment.

For this project, some of the design parameters are already provided as foundational components in the problem statement. The machine in question is a dual energy 6 MV/18 MV Varian Clinac 2100C model that sits in a treatment room as shown in Figure 1. The distance to one of the primary barriers is given, while the remaining measures must be constructed based on important information about the testing room. The room itself borders both controlled settings, such as a control room, and uncontrolled settings, including a hallway on the same floor and offices on the floor above. Because of the location of the room, exposure limits for both radiation workers and the general public as outlined by 10CFR20 must be followed in order to ensure complete safety. The key factors to consider in this case are the uncontrolled locations. In particular, the hallway to the north of the vault and the offices above the vault both are classified as uncontrolled areas, which means that individuals in those spaces must not experience exposures that exceed the exposure limits as established by ICRP-103 of 1 mSv/year as they are members of the general public. All other areas surrounding this vault are controlled areas, so the exposure limits for these spaces can be regulated to occupational limits of 5 mSv/year.

In order to ensure the aforementioned rules and regulations are met, the exposure from the linac must be measured. Radiation exposure risk and effective dose can be determined from three key factors: the distance from the source at which an individual experiences this radiation, the duration the individual experiences the exposure, and the shielding between the source and the individual. These factors are all defined in the context of this problem as follows: the distance for this problem refers to a point, the worker, a certain distance away from the isocenter of the machine where it is assumed the worker is at least 0.3m from the barrier, and the time in this problem refers to the workload of the linac machine. Thus, the main parameter to determine is the proper shielding for the worker and the general public.

To properly shield the vault to adhere to the given exposure limits, a variety of different factors need to be considered. Barrier thicknesses for the primary barriers and secondary barriers need to be determined. Additionally, the door to the vault also needs to be designed to adhere to the safety considerations of this

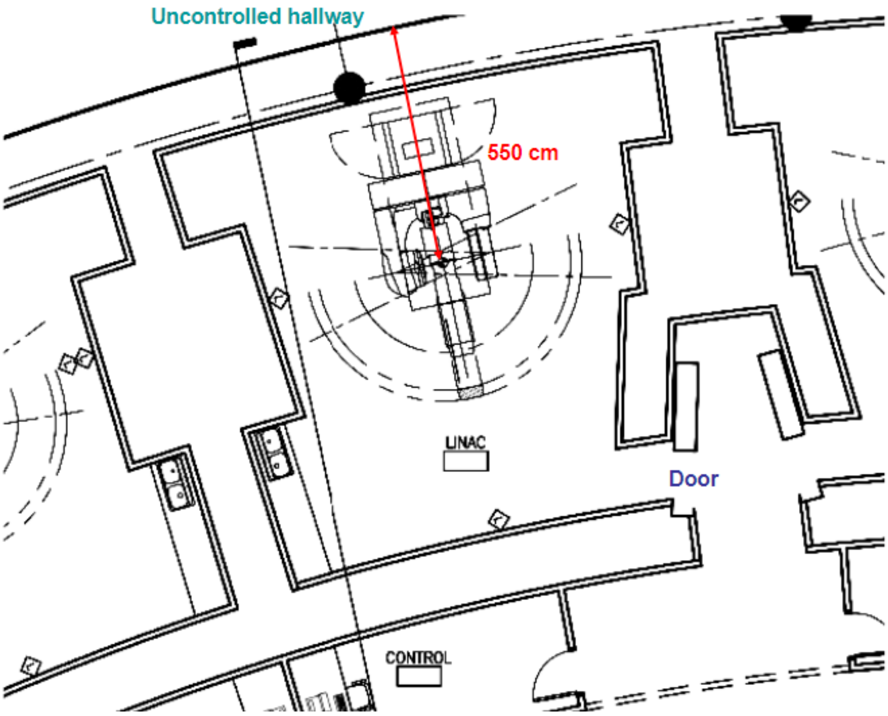

Figure 1: The incomplete blueprints of the vault provided in the problem statement.

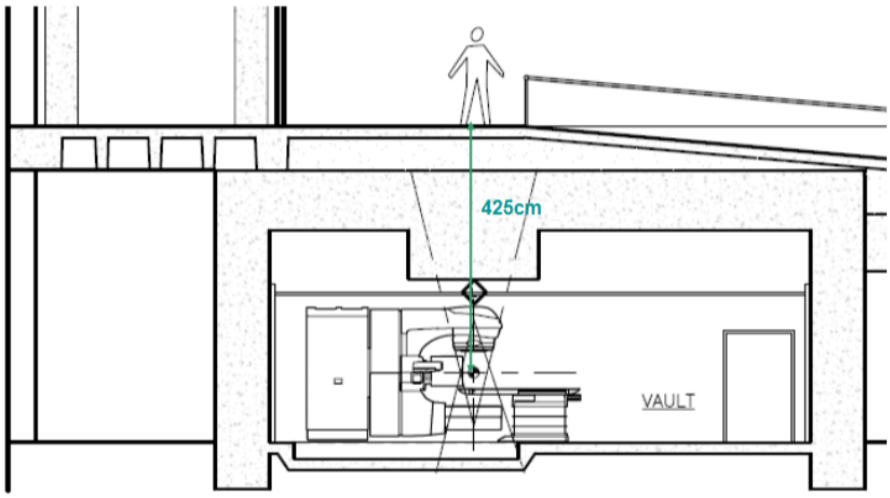

Figure 2: The incomplete vertical blueprints of the vault provided in the problem statement.

problem. The assumptions and operational parameters for this linac system are given in the problem statement and are presented in Table 1 below:

Table 1: A summary of the parameters for this linac vault

Maximum Workload	30 patients/day, 3 Gy/patient at isocenter, 5 days/week, 8 hours/day
Percentage of Workload at 6 MV	40%
Percentage of Workload at 18 MV	60%
Additional Workload from Physics and QA	100 Gy/week with same percentage split.
Maximum Dose Rate at Isocenter	6 Gy/min
Maximum patients treated per hour	6
Use factor distribution	Evenly on the two walls, ceiling and floor
Barrier (Walls/ceiling/floor) Materials	Concrete
Door Materials	Lead and Borated Polyethylene (BPE)
Isocenter field size	(40×40) cm^2
Machine used for IMRT?	No

The remainder of this document covers the derivations and calculations of the proper thicknesses for the primary barriers, secondary barriers, and door to the vault.

2 Primary Barrier Concerns

2.1 Primary Barrier Thickness

The parameters involved in primary barrier thickness calculations are shown in Table 2. The vault is assumed to be located in the basement, so that ground shielding calculations are not necessary. Use factor for all primary beam locations are assumed to be 0.25.

Table 2: Parameters for primary barrier thickness calculation.

Location	**Distance (d_{pri}) [m]**	**Occupancy Factor (T)**	**Use Factor (U)**	**Design Goal (P) [mSv/wk]**
Left Vault	7.35	0.5	0.25	0.1
Right Vault	7.60	0.5	0.25	0.1
Ceiling	5.55	1	0.25	0.02

The transmission factor B_T is calculated as

$$B_T = \frac{Pd_{pri}^2}{WUT}, \tag{1}$$

where d_{pri} is the distance from target to point protected (meters), 0.3 m behind the barrier; P is the shielding design goal, T is the occupancy factor, and U is the use factor. The primary barrier thickness t can then be solved using

$$B_T = 10^{-\left(1+\frac{(t-TVL_1)}{TVL_e}\right)}, \tag{2}$$

where TVL_1 and TVL_e are first and equilibrium tenth value layers. The number of TVLs ($nTVL$) for barrier thickness is calculated as

$$nTVL = \log_{10}\left(\frac{1}{B_T}\right). \tag{3}$$

B_T and t are calculated for 6 MV and 18 MV beams. TVL values, W used, and primary barrier results are shown in Table 3 and Table 4.

Table 3: Primary barrier thickness Calculations for 6 MV Beam.

Location	**Work Load (W) [Gy/wk]**	**TVL$_1$ [cm]**	**TVL$_e$ [cm]**	**B$_T$**	**Thickness [cm]**	**nTVL**
Left Vault	220	37	33	2.0E-4	126.3	3.71
Right Vault	220	37	33	2.1E-4	125.4	3.68
Ceiling	220	37	33	1.1E-5	167.4	4.95

Table 4: Primary barrier thickness Calculations for 18 MV Beam.

Location	**Work Load (W) [Gy/wk]**	**TVL$_1$ [cm]**	**TVL$_e$ [cm]**	**B$_T$**	**Thickness [cm]**	**nTVL**
Left Vault	330	45	43	1.3E-4	169.0	3.88
Right Vault	330	45	43	1.4E-4	167.7	3.85
Ceiling	330	45	43	7.5E-6	222.5	5.13

The differences of thickness between 6 MV and 18 MV beams are 42.7 cm and 42.3 cm for the left and right vaults, and 55.1 cm for the ceiling. Both the left and right vault measurements are less than one TVL apart, so 1 $HVL = \log(2) \times TVL_e(18MV) = 12.9$ cm was added for each primary barrier thickness for the vaults. For the ceiling, however, since the two measurements are more than one TVL apart, 18 MV measurements are used for primary barrier thickness in this design. The final primary barrier thickness is shown in Table 16.

Table 5: Final Result of Primary Barrier Thickness Calculations.

Location	**Thickness [cm]**
Left Vault	181.9
Right Vault	180.6
Ceiling	222.5

2.2 Primary Barrier TADR

The weekly TADR for a primary barrier is the TADR at a given location averaged over a 40h work week:

$$R_w = \dot{D}_w = \frac{IDR \times W \times U}{\dot{D}_0}, \tag{4}$$

where IDR [Sv/h] is the instantaneous dose-equivalent rate, $\dot{D}_0$ [Gy/h] is the absorbed-dose output rate, W [Gy/wk] is primary-barrier weekly workload, and U is the use factor for each given location.

For an example calculation for the ceiling and the 18 MV beam, the instantaneous dose-equivalent rate can be calculated as

$$IDR = \frac{B_T \times \dot{D}_0}{d_{pri}^2} \tag{5}$$

$$IDR = \frac{(7.5 \times 10^{-6}) \times (360)}{5.55^2} = 8.77 \times 10^{-5} [Sv/h],$$

note that barrier transmission coefficients B_T used in TADR calculation were recalculated based on the final primary barrier thickness. The TADR can then be calculated as

$$R_w = \frac{(8.77 \times 10^{-5}) \times (330) \times (0.25)}{(360)} = 2.0 \times 10^{-5} [Sv/wk].$$

The new B_T, IDR, and TADR measurements for 6 MV and 18 MV beams are shown in Table 6 and Table 7.

Table 6: B_T, IDR, and TADR Calculations of the 6MV Beam.

Location	**B$_T$**	**IDR [Sv/h]**	**R_w [Sv/wk]**
Left Vault	4.1E-6	2.7E-5	4.1E-6
Right Vault	4.5E-6	2.8E-5	4.2E-6
Ceiling	2.4E-7	2.8E-6	4.3E-7

Table 7: B_T, IDR, and TADR Calculations of the 18MV Beam.

Location	**B$_T$**	**IDR [Sv/h]**	**R_w [Sv/wk]**
Left Vault	6.6E-5	4.4E-4	1.0E-4
Right Vault	7.0E-5	4.4E-4	1.0E-4
Ceiling	2.8E-6	8.7E-5	2.0E-5

In-any-one-hour time-averaged dose equivalent (R_h) specifies limits for the TADR. R_h is calculated as

$$R_h = \left(\frac{M}{40}\right) \times (R_w(18MV) + R_w(6MV)), \tag{6}$$

where M is ratio of the maximum number to the average number of patients treated in an hour. The average number of patients per hour is calculated as number of patients treated per day over number of working hours per day.

$$M = \frac{N_{max}}{\bar{N}_h} \tag{7}$$

$$M = \frac{6}{3.75} = 1.6$$

Calculations of R_h values for each primary barrier location are shown in Table 8.

Table 8: In-Any-One-Hour Time-Averaged Dose Equivalent Calculations.

Location	R_h [μ**Sv/h**]
Left Vault	4.2
Right Vault	4.2
Ceiling	0.8

This TADR value in-any-one-hour is lower than the 20 μSv TADR limit, so no additional shielding was added to the primary barrier.

2.3 Primary Barrier Width

NCRP recommends the primary barrier width be calculated as the size of the diagonal of the largest beam, which is calculated using the plane on the inner side of the secondary barrier [1]. Additionally, an extra 30 cm should be added to each side to account for beam scatter. The largest field size is assumed to be (40× 40) cm^2 at 100 cm source-to-surface distance. Therefore, the length of the diagonal of the maximum field size at isocenter is $\sqrt{40^2 + 40^2} = 56.6$ cm.

The secondary barrier surface for the right wall is 5.03 m from isocenter, and the secondary barrier surface for the ceiling is 2.45 m from isocenter, according to our secondary barrier thickness calculations. The line where these two surfaces meet is the $\sqrt{2.45^2 + 5.03^2} = 5.59$ m from isocenter. Beam divergence along the line where the two surfaces join is found using similar triangles.

$$\frac{1}{5.59 + 1} = \frac{0.566}{x}, \tag{8}$$

where x is the width of the beam at our point of interest. Solving this equation for x, we find that the width of the beam is 3.787 m at that line. As mentioned previously, NCRP-151 suggests that 30 cm be added to both sides of the beam to account for radiation that has scattered at small angles, which is still highly penetrating [1]. This added 0.6 m leads to a final primary barrier width of 4.387 m.

However, we must verify that the primary barrier intercepts at least 20° of scattered radiation at the surface of the secondary barrier. For a barrier of width 4.387 m, the maximum angle off the central axis contained completely within the barrier is $\arctan(\frac{2.1935}{6.69}) = 18.157°$. Therefore, this barrier width does not provide sufficient coverage.

To reach the required 20° of shielding, half of the barrier width must be $\tan(20°) * 6.69$m. This half-width is 2.435 m. Therefore, the full barrier width is 4.87 m. For ease of construction, the barrier width is uniform from the right wall, across the ceiling, to the left wall. This width may be beyond necessary for the ceiling and left wall, but it is easier to construct than a tapered primary barrier.

3 Secondary Barrier Concerns

3.1 Secondary Barrier Thickness

Parameters for secondary barrier calculations are shown in the table below. Several values not listed in the table are assumed to be constant. The use factor U is always 1 for secondary barrier concerns. d_{sca} is also assumed to be 1. Finally, F is conservatively assumed to be the area of a 40 x 40 cm^2 field in cm^2, which is 1600. For leakage calculations, d_L is equal to d_{sec}.

Table 9: Parameters for secondary barrier thickness calculation.

Location	Distance (d_{sec}) [m]	Occupancy Factor (T)	Design Goal (P) [mSv/wk]
Back (Uncontrolled Hallway)	5.8	0.2	0.02
Front (Control Room)	8.32	1	0.1
Left Vault	6.76	0.5	0.1
Right Vault	7.02	0.5	0.1
Ceiling	4.84	1	0.02

Now, consider scatter transmission for the 5 locations. For each location, we will need the scatter fraction (a) and tenth value layer for each energy. We can then calculate the scatter transmission using the following formula:

$$B_{T,sca} = \frac{P d_{sca}^2 d_{sec}^2}{aWUT} \frac{400}{F}. \tag{9}$$

For scattered radiation, the first tenth value layer is equal to the equilibrium tenth value layer. Therefore, the transmission found above is set equal to

$$B_{T,sca} = 10^{-\frac{t}{TVL}}, \tag{10}$$

where t is the thickness of the barrier. Using these equations and the data provided below, the thickness of the barrier for each energy was found. The front and back of the room calculations assumed a scattering angle of 90 degrees, while the other locations used a scattering angle of 20 degrees. This angle was chosen as the primary barrier intercepts scattered radiation of at least 20 degrees, making this a conservative estimate. Scatter fractions are found in **Table 28** in the Appendix. It is important to note that the scatter TVL for both energies were calculated using linear interpolation between data points found in NCRP-151. Scatter TVLs are found in **Table 29** in the Appendix.

Table 10: Secondary barrier thickness calculations for 6 MV beam scatter.

Location	Work Load (W) [Gy/wk]	Scatter Fraction (a)	TVL [cm]	$B_{T,sca}$	Thickness [cm]
Back	220	4.26E-4	17	8.97E-3	34.8
Front	220	4.26E-4	17	1.85E-2	29.5
Left	220	6.73E-3	31.33	1.54E-3	88.1
Right	220	6.73E-3	31.33	1.67E-3	87.0
Ceiling	220	6.73E-3	31.33	7.92E-5	128.5

Table 11: Secondary barrier thickness calculations for 18 MV beam scatter.

Location	Work Load (W) [Gy/wk]	Scatter Fraction (a)	TVL [cm]	$B_{T,sca}$	Thickness [cm]
Back	330	1.89E-4	19	1.35E-2	35.5
Front	330	1.89E-4	19	2.77E-2	29.6
Left	330	5.39E-3	40	1.28E-3	115.7
Right	330	5.39E-3	40	1.39E-3	114.3
Ceiling	330	5.39E-3	40	6.59E-5	167.2

Using the two source rule for these two energies, the appropriate thickness to accommodate both barrier transmission values was calculated. The following table displays the results.

Table 12: Secondary barrier thickness values for scattered radiation

Location	Thickness [cm]
Back	41.3
Front	35.3
Left	127.7
Right	126.4
Ceiling	179.3

However, when considering required thicknesses of secondary barriers, one must also account for leakage radiation from the head of the linac. Unlike scattered radiation, the first tenth value layer and the equilibrium tenth value layer are different for leakage radiation. Both of these values were gathered from **Table 30** in the Appendix. The formula to calculate barrier transmission is also different. The transmission can be calculated as follows:

$$B_L = \frac{Pd_L^2}{10^{-3}WT}, \tag{11}$$

where d_L is equivalent to d_{sec}, as mentioned previously. Then, the barrier transmission is as follows:

$$B_{T,L} = 10^{-\left(1+\frac{(t-TVL_1)}{TVL_e}\right)}. \tag{12}$$

This data is summarized for both the 6 and 18 MV beams below.

Table 13: Secondary barrier thickness calculations for 6 MV beam leakage.

Location	**Work Load (W) [Gy/wk]**	**TVL_1 [cm]**	**TVL_e [cm]**	**$B_{T,L}$**	**Thickness [cm]**
Back	220	34	29	1.53E-2	57.7
Front	220	34	29	3.15E-2	48.6
Left	220	34	29	4.15E-2	45.1
Right	220	34	29	4.48E-2	44.1
Ceiling	220	34	29	2.13E-3	82.5

Table 14: Secondary barrier thickness calculations for 18 MV beam leakage.

Location	**Work Load (W) [Gy/wk]**	**TVL_1 [cm]**	**TVL_e [cm]**	**$B_{T,L}$**	**Thickness [cm]**
Back	330	36	34	1.02E-2	69.7
Front	330	36	34	2.10E-2	59.1
Left	330	36	34	2.77E-2	55.0
Right	330	36	34	2.99E-2	53.8
Ceiling	330	36	34	1.42E-3	98.8

Once again, the two source rule is used to combine these results.

Table 15: Secondary barrier thickness values for leakage radiation

Location	**Thickness [cm]**
Back	80.0
Front	69.3
Left	65.2
Right	64.1
Ceiling	109.0

In every case, either the leakage or the scattered radiation calculated thicknesses were more than 1 TVL greater than the opposite. Therefore, no additional shielding needs to be added to any of the values calculated. The final secondary barrier thicknesses are shown below.

Table 16: Final Result of Secondary Barrier Thickness Calculations.

Location	Thickness [cm]
Back	80.0
Front	69.3
Left	127.7
Right	126.4
Ceiling	179.3

3.2 Secondary Barrier TADR

The weekly TADR for a secondary barrier is found in a similar way to the primary barrier, but with key differences. The IDR needs to be calculated for the patient scatter and leakage radiation for both the 6 and 18 MV beams and then combined to find the weekly and hourly dose rate. Using our barrier transmission factors from our barrier thickness calculations, we can solve the following equations for the instantaneous dose rates from patient scatter and leakage.

$$IDR_{ps} = \frac{\dot{D}_0 aFB_{ps}}{400d_{sec}^2} \tag{13}$$

$$IDR_L = \frac{\dot{D}_0 B_L}{d_L^2 \times 10^3} \tag{14}$$

where B_ps and B_L are the barrier transmission factors calculated from the barrier thicknesses for patient scatter and leakage respectively. These values for the 6 and 18 MV beam are reported below.

Table 17: The IDR values for the 6 MeV and 18 MeV Beam

Location	$IDR_{ps,6MV}$ [Sv/h]	$IDR_{ps,18MV}$ [Sv/h]	$IDR_{L,6MV}$ [Sv/h]	$IDR_{L,18MV}$ [Sv/h]
Back Hallway	3.61E-7	5.01E-7	6.44E-5	4.76E-5
Front Controls	7.44E-7	8.86E-7	6.18E-5	4.76E-5
Left Linac	1.78E-5	1.09E-4	2.23E-6	1.38E-6
Right Linac	1.82E-5	1.09E-4	2.26E-6	1.40E-6
Above Offices	7.84E-7	1.09E-5	1.61E-7	8.20E-8

Then combining these IDRs we can calculate the TADR over a week with the formula below.

$$R_w = \frac{IDR_L W_L}{\dot{D}_0} + \frac{IDR_{ps} W_{pri} U}{\dot{D}_0} \tag{15}$$

The TADR values are reported in the table below.

Table 18: The TADR values for the 6 MeV and 18 MeV

Location	$R_{w,6MV}$ **[Sv/wk]**	$R_{w,18MV}$ **[Sv/wk]**
Back Hallway	3.95E-5	4.41E-5
Front Controls	3.82E-5	4.45E-5
Left Linac	1.22E-5	1.01E-4
Right Linac	1.25E-5	1.01E-4
Above Offices	5.77E-7	1.01E-5

This can be converted then into μSv/hr from both the 6MV and 18MV beam using the following equation and our value for M calculated in the primary barrier TADR section.

$$R_h = \frac{M}{40}(R_w(18MV) + R_w(6MV)) \tag{16}$$

The determined values for the hourly TADR at each of the barriers are given below.

Table 19: The determined hourly TADR values

Location	R_h $[\mu Sv/hr]$
Back Hallway	3.35
Front Controls	3.31
Left Linac	4.54
Right Linac	4.56
Above Offices	0.43

The back hallway, front control, left, right linac, and ceiling barriers are already sufficient to have a dose rate lower than $20\mu Sv/hr$, so no extra shielding is necessary here. With this in mind the barrier thicknesses above are unchanged.

4 Door Shielding

The vault housing the linac in this design problem does not have a maze to act as a secondary barrier, therefore, a concerted effort must be made into designing the vault's door. Designing a door with a maze is relatively simple given the thinner design specifications, but because of the decision to operate without a maze, a much thicker and heavier door will need to be constructed. The door itself must be secured such that it operates on a motorized system that prevents any additional leakage radiation into uncontrolled areas. According to the design specifications of the problem, the door will be constructed of a slab of borated polyethylene sandwiched between two slabs of lead.

4.1 First Layer

The first layer of the door is designed to act as a secondary barrier, much like the rest of the room. Like other cases, there are three different radiation sources that must be taken into consideration as the door is designed. These sources include the leakage radiation, radiation from scattered photons, and photons created from neutron interactions, (n, γ) reactions. Each of these considerations will now be investigated in more detail.

4.1.1 Leakage Radiation

The leakage radiation contribution will first be considered. The leakage transmission factor is easily found from using Equation (12) from the secondary barrier calculation, using the distance to the door as the d term in the equation. This distance to the door can be estimated to be roughly 8m as based on distance to the primary barrier on the right wall. Given that the area behind the door is also assumed to be controlled, the radiation shielding goal for leakage radiation is 0.1 mSv/week. Furthermore, workloads have been previously given and the occupancy factor is given as 1/8 for doors according to the NCRP report. The general equation for the Leakage barrier transmission is given as Equation (17)

$$B_{T,L} = \frac{\left(1 \times 10^{-4}\right) \times (8m)^2}{10^{-3} \times W \times 1/8} \tag{17}$$

This barrier transmission can be used to find the thickness of the lead slab while using TVLs. In this case it is pertinent to ensure that the TVL estimate is incredibly conservative, so a completely safe upper bound would be to design the shielding to account for primary barrier scattering. If the door can shield against primary scattering, it will also be able to shield secondary scattering events. Therefore, when using this conservative TVL approach, a TVL value of 5.7 cm can be used. The summary of these calculations is given in **Table 20**

Table 20: The summary of information for the Leakage Barrier Transmission for the door

	6 MV	**18 MV**
$\mathbf{B}_{T,L}$	0.233	0.155
nTVL	0.633	0.809
Slab Thickness [cm]	3.609	4.613

The two found values in the thicknesses specifically differ, the two source rule can be incurred in this case. This involves taking the larger thickness and adding the product of one half-value layer (HVL) and the conservative TVL value.

$$t = 4.613cm + (log_{10}(2) \times 5.7cm) \tag{18}$$

$$t = 6.329\ cm$$

4.1.2 Scattering Radiation

The process for determining the contribution from scattering radiation is slightly more involved than the leakage contribution. Like before, the process from the secondary barrier is used, specifically using Equation (9). Given that the the minimum scattering angle is 50°, in this case, the a terms are found from interpolating values from **Table 28**. The general linear interpolation is done to find the a values for each case, and are shown as follows:

$$a_{6MV} = 1.20 \times 10^{-3}$$

$$a_{18MV} = 7.17 \times 10^{-4}$$

These values can be used in Equation (9) to yield Equation (19), a general equation for finding the Barrier Transmission for the scattered radiation.

$$B_{T,sca} = \frac{\left(1 \times 10^{-4}\right)}{aW(1/8)} \times 8^2 \times 1^2 \times \frac{400}{400}. \tag{19}$$

Like before, as well, the Barrier Transmission values can be used to determine the proper thickness to account for the transmission, again using the conservative TVLs accounting for the scatter fraction.

Table 21: The summary of information for the Leakage Barrier Transmission for the door

	6 MV	**18 MV**
$\mathbf{B}_{T,L}$	0.194	0.216
nTVL	0.713	0.665
TVL$_1$	2.208	2.479
Slab Thickness [cm]	1.574	1.649

The thicknesses required to shield against the scattered radiation is already less than what is needed to account for the leakage radiation, so it can be assumed that the scattered radiation is already properly shielded, assuming that the thickness to the first lead slab required to shield against the (n, γ) is thinner. If not, then it is necessary to again use the two source rule.

4.1.3 (n, γ) Reaction Radiation

The thickness of the lead slab also has to consider the contributions from radiation exposure from (n, γ) reactions. The 18 MV beam energy is the only process in which neutrons are generated, so only the parameters from the 18 MV exposures are considered here. The thickness contributions are dependent on the equivalent dose associated with the generated gamma rays from the reaction. This equivalent dose is given by the product as shown in Equation (20):

$$H_\gamma = K\phi_A W \tag{20}$$

where in this case, $K = 6.9 \times 10^{-16}$ [Sv-m^2] and refers to the ratio of the dose from the gamma rays produced by the (n,γ) reaction and the total neutron fluence around the door. Additionally, the ϕ_A needs to be determined explicitly, as shown in Equation (21).

$$\phi_A = \frac{Q_n}{4\pi d_{door}^2} + \frac{5.4Q_n}{S} \tag{21}$$

where in this case Q_n is equal to 0.96×10^{12} neutrons per Gray at the isocenter of this linac machine, and S is the total surface area of the room. It is assumed that the the surface area of the room includes the floor, ceiling, and, walls such that the vault is technically a cube. The total Surface area for the room is calculated as shown below:

$$S = 2(lw + wh + lh) \tag{22}$$

where l is the length of the room, w is the width of the room, and h is the height of the room. These values are found from subtracting the thicknesses of each barrier from the length from the isocenter and combining the proper lengths.

$$S = 366.15m^2$$

From this value, the total value of the fluence, ϕ_A can be determined.

$$\phi_A = 0.96 \times 10^{12} \left(\frac{1}{4\pi(8)^2} + \frac{5.4}{366.15} \right) \tag{23}$$

$$\phi_A = 1.535 \times 10^{10} \left[\frac{n}{Gy - m} \right]$$

The calculated flux can then be substituted into Equation 20 to find the equivalent dose

$$H_\gamma = \left(6.9 \times 10^{-16}\right) \times \left(1.535 \times 10^{10}\right) \times 330$$

$$H_\gamma = 3.496 \left[\frac{mSv}{week} \right]$$

From this equivalent dose, the barrier transmission can be found by dividing the weekly shielding goal by this equivalent dose.

$$B_{T,(n,\gamma)} = \frac{0.1}{3.496} \tag{24}$$

$$B_{T,(n,\gamma)} = 0.0286$$

From this barrier thickness, the amount of TVLs can be found, thus yielding the necessary thickness of lead for the front of the door.

$$nTVL = log_{10}\left(\frac{1}{B_{T,(n,\gamma)}}\right) \tag{25}$$

$$t_{(n,\gamma)} = nTVL \times TVL_{Pb} \tag{26}$$

where the TVL for Lead is 6.1 cm at 18MV. thus:

$$t = log_{10}\left(\frac{1}{0.0286}\right) \times 6.1$$

$$t = 9.415\ cm$$

Table 22: The summary of information for the Leakage Barrier Transmission for the door

	18 MV
$\mathbf{B}_{T,L}$	0.0286
nTVL	1.544
Slab Thickness [cm]	9.415

Alternatively, these (n, γ) contributions can be shielded by simply adding one half-value layer (HVL) to the leakage radiation thickness. This is simply given as:

$$t = 6.329 + log_{10}(2) \times 5.7 \tag{27}$$

$$t = 8.044\ cm$$

The thicknesses 9.415 cm and 8.044cm are comparable thicknesses, so the two source rule is necessary here to find the total necessary thickness. In this case, the TVL for lead, 6.1 is used along with the larger thickness.

$$t = 9.415 + log_{10}(2) \times 6.1$$

$$t = 11.252\ cm$$

Thus, the thickness of the first slab of lead that will ensure the shielding from leakage radiation, radiation from scattered photons, and radiation from photons generated in (n,γ) is 11.252 cm.

4.2 Second Layer

The second layer of the door is functionally useful in the door design as well, albeit through significantly different means. Whereas the first lead layer of the door attenuates both leakage photons and scattered photons, the borated polyethylene layers exists to moderate neutrons that are generated in the linac vault. The choice to use BPE is done for a couple different reasons. The BPE layer is functionally more efficient than concrete in moderating neutrons due to the presence of Boron present in the material mixture. Additionally, BPE is physically lighter in weight compared to concrete, so it makes for a reasonable door material choice when considering how the door moves. While the cost of BPE is notably higher than a slab of concrete, both of these cost are still less than ultimately constructing a maze, so the cost considerations in this case are less of an issue.

In order to ensure that the neutrons reaching this slab of BPE are properly moderated, the neutron flux generated from this linac machine needs to be found. Luckily, this process was previously covered in the (n, γ) reaction for the first slab and this value is consistent with the previously determined value for the neutron flux, and consequently, the equivalent dose. The only true difference from the previous method is now the TVL values differ for the new material choice. The process of finding the number of TVLs for BPE is given as equation (28),

$$nTVL = log_{10}\left(\frac{1}{B_{T,BPE}}\right) \tag{28}$$

$$nTVL = log_{10}\left(\frac{1}{0.0286}\right) = 1.544$$

Using the TVL of BPE of 4.5cm as listed in NCRP15 [1], the thickness for the BPE can be found to be

$$1.544 \times 4.5 = 6.946\ cm$$

4.3 Third Layer

After the slab of BPE, a second slab of lead is introduced to the door as a third and final layer. This layer is present in order to attenuate any gamma rays that were either not entirely shielded by the first two layers, or to attenuate the low-energy gamma rays (478 keV) that are generated in the BPE layer from an (n,γ) reaction from the BPE. Per NCRP15, for gammas with energies around 480 keV, adding 1.9 cm after the slab of BPE is an effective way to reduce the gamma intensity by a factor of 100. Thus, the third slab of the door is chosen to be 1.9 cm of Lead.

4.4 The Door Gap

While the door is properly designed and constructed, there remains an issue involving the space where the door and the wall meet. The issue stems from the fact that, in general, the radiation propagation is not perpendicular to the door itself, meaning that the corner will not entirely shield the exit. This is visualized by Figure 3

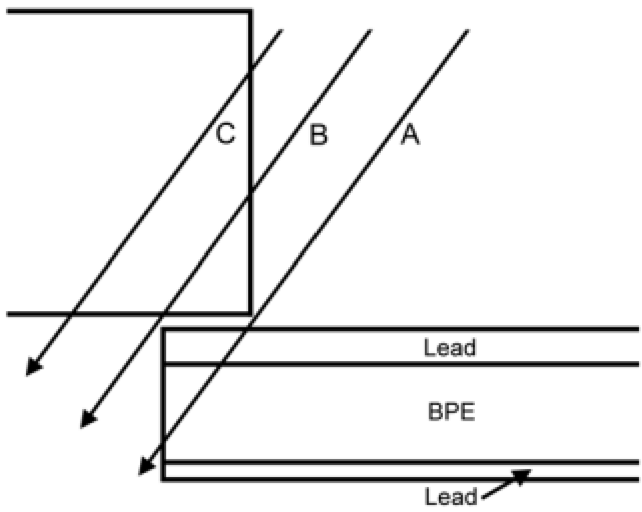

Figure 3: The incomplete shielding at the door

Luckily, this is a problem that the NCRP Report has a general solution for, that involves using additional Lead and BPE on the corners of the door frame itself. This design itself is shown by Figure 4. In this case, the high density concrete stop would be opposite the pocket where the door would slide when opening and would act as a stop for when the door is entirely closed.

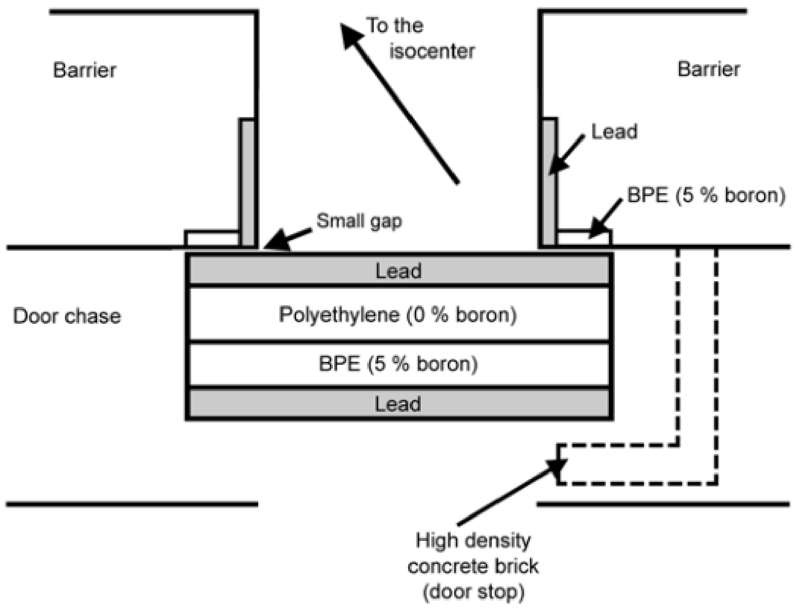

Figure 4: The NCRP recommended design to account for the corners

The thicknesses of these slabs of Lead and BPE can also be found based on a similar methodology as before, using dose rates at the door and minimizing them as much as reasonably achievable. From the previous work, it was found that the equivalent dose was 3.496 $\left[\frac{mSv}{week}\right]$. In this case, the worst case scenario corresponds to the ray labelled 'B' in Figure 3, as that is the shortest distance the radiation would have to travel to escape the chamber.

Additionally, a few factors must be considered and/or assumed to make this proper calculation. It is first assumed that that the main source of radiation will come the isocenter of the room where the operations will be taking place. The scattered radiation contribution is not going to be modelled nearly as easily and will be much smaller in magnitude when compared to the isocenter contributions. Furthermore, given the geometry of the room, it is reasonable to assume that the angle of incidence will be a maximum of 50°.

For the door that is 6 feet (183 cm) long and a distance between the two jambs that is 4.5 feet wide (137 cm), with a 50 degree scattering angle, the shortest distance the radiation will need to penetrate is $23/sin(50°)$ or approximately 30 cm. To determine the additional lead that needs to be placed in that corner in addition to the concrete, the total dose that is received on the other end of the corner needs to be determined. This can be done using the attenuation of radiation with a TVL of 36 cm as given by **Table 30** for photon energies up to 18 MV.

$$H_{tr} = H \times 10^{-30/TVL} \tag{29}$$

$$H_{tr} = 3.496 \times 10^{-30/36} = 0.513 \left[\frac{mSv}{week}\right]$$

This dose rate is still well above the goal dose rate of 0.1 mSv/week, so there needs to be additional lead shielding on this corner. This is done by using a similar workflow as before:

$$t = log_{10}\left(\frac{H_{tr}}{P}\right) \times TVL \tag{30}$$

$$t = log_{10}\left(\frac{0.513}{0.1}\right) \times 6.1 = 4.332cm$$

This thickness is relatively similar to the leakage thickness necessary, so, once again, the two source rules can be applied to find the total thickness.

$$t = 6.329 + log_{10}(2) \times 6.1 = 8.165\ cm$$

This is the thickness of the lead that should be present in the jamb of the door to ensure that the dose rate is below the required goal. Additionally, a slab of BPE must be placed at the end of the concrete portion facing the door. This is to act similarly to the door and moderate any additional neutrons that have passed through the concrete barrier. In this case, the thickness of this BPE slab is the same of that in the door, as the door BPE thickness was designed to be an upper bound on moderation and, as such, the same thickness is guaranteed to function here as well. These measures should be implemented on both jambs in this case to ensure safety on both sides of the door.

5 Summary

The final shielding thicknesses and TADR for the primary and secondary barrier are shown in Table 23 and Table 24.

Table 23: Primary barrier thickness and TADR

Location	Thickness [cm]	R_w(6 MV) [Sv/wk]	R_w(18 MV) [Sv/wk]	Rh [μSv/h]
Left Vault	181.9	4.1E-6	1.0E-4	4.2
Right Vault	180.6	4.2E-6	1.0E-4	4.2
Ceiling	222.5	4.3E-7	2.0E-5	0.8

Table 24: Secondary barrier thickness and TADR

Location	**Thickness [cm]**	**R_w(6 MV) [Sv/wk]**	**R_w(18 MV) [Sv/wk]**	**Rh [μSv/h]**
Back	80.0	4.0E-5	4.4E-5	3.4
Front	69.3	3.8E-5	4.5E-5	3.3
Left	127.7	1.2E-5	1.0E-4	4.5
Right	126.4	1.3E-5	1.0E-4	4.6
Ceiling	179.3	5.8E-7	1.0E-5	0.4

Table 25: Door Materials, Thicknesses, and surrounding shielding

Door Layer	**Material**	**Thickness**[cm]
Layer 1	Lead	11.252
Layer 2	Borated Polyethylene	6.946
Layer 3	Lead	1.900
Full Door	-	20.098
Additional Lead Shielding on Jambs	Lead	8.165
Additional BPE shielding on Jambs	BPE	6.946

References

[1] Deye, J. A., et al. *NCRP REPORT No. 151 - Structural Shielding Design and Evaluation for Megavoltage X- and Gamma-Ray Radiotherapy Facilities*, National Council on Radiation Protection and Measurements (2005).

A Schematic

The following images are blueprints of the room with our suggested dimensions for shielding considerations.

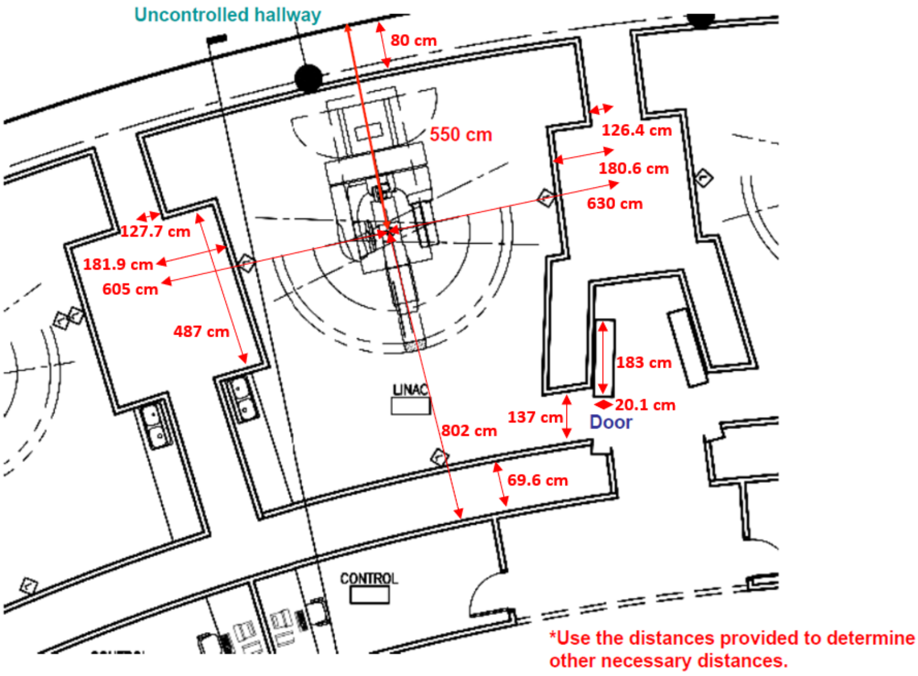

Figure 5: Recommended dimensions for shielding, as viewed from above

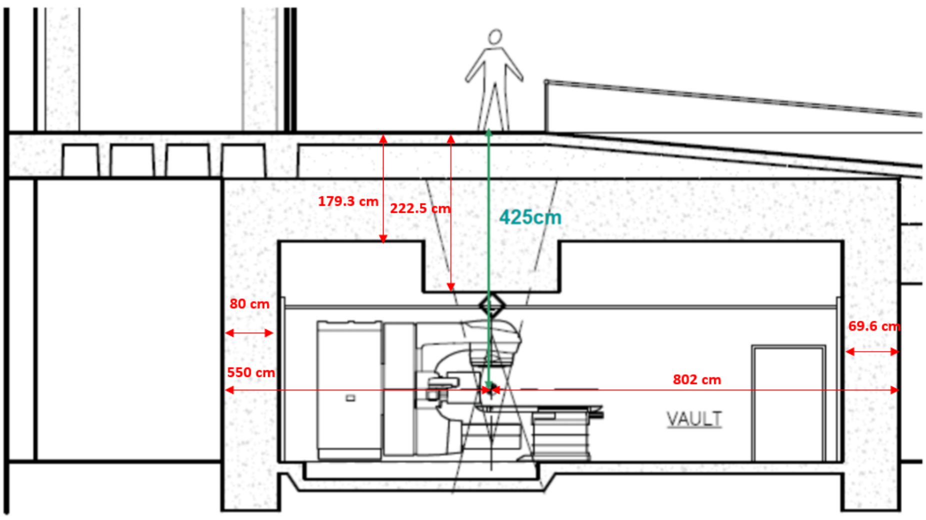

Figure 6: Recommended dimensions for shielding, as viewed from the side

B Reference Tables

The following tables are reproduced from NCRP-151 for ease of reference [1].

Table 26: Occupancy Factors (T) as provided by Table B.1 in NCRP-151.

Location	Occupancy Factor (T)
Full occupancy areas, treatment planning areas, treatment control rooms, nurse stations, receptionist areas, attended waiting rooms, occupied space in nearby building	1
Adjacent treatment room, patient examination room adjacent to shielded treatment wall	1/2
Corridors, employee lounges, staff rest rooms	1/5
Treatment vault doors	1/8
Public toilets, unattended vending rooms, storage areas, outdoor areas with seating, unattended waiting rooms, patient holding areas, attics, janitors' closets	1/20
Outdoor areas with only transient pedestrian or vehicular traffic, unattended parking lots, vehicular drop off areas (unattended), stairways, unattended elevators	1/40

Table 27: Primary-barrier TVLs for concrete as provided by Table B.2 in NCRP-151.

Energy (MV)	TVL_1 (cm)	TVL_e (cm)
4	35	30
6	37	33
10	41	37
15	44	41
18	45	43

Table 28: Scatter fractions (a) as provided by Table B.4 in NCRP-151.

Angle (Degrees)	6 MV	10 MV	18 MV	24MV
10	1.04×10^{-2}	$1.66 \times 10^{\cdot 2}$	1.42×10^{-2}	1.78×10^{-2}
20	6.73×10^{-3}	5.79×10^{-3}	5.39×10^{-3}	6.32×10^{-3}
30	2.77×10^{-3}	3.18×10^{-3}	2.53×10^{-3}	2.70×10^{-3}
45	1.39×10^{-3}	1.35×10^{-3}	8.64×10^{-4}	8.30×10^{-4}
60	8.24×10^{-4}	7.46×10^{-4}	4.24×10^{-4}	3.86×10^{-4}
90	4.26×10^{-4}	3.81×10^{-4}	1.89×10^{-4}	1.74×10^{-4}
135	3.00×10^{-4}	3.02×10^{-4}	1.24×10^{-4}	1.20×10^{-4}
150	2.87×10^{-4}	2.74×10^{-4}	1.20×10^{-4}	1.13×10^{-4}

Table 29: Scatter TVLs in concrete based on Table B.5a of NCRP-151. All values other than the scatter angle have units of [cm]

Scatter Angle (Degrees)	4 MV	6 MV	10 MV	15 MV	18 MV	20 MV	24MV
15	30	34	39	42	44	46	49
30	25	26	28	31	32	33	36
45	22	23	25	26	27	27	29
60	21	21	22	23	23	24	24
90	17	17	18	18	19	19	19
135	14	15	15	15	15	15	16

Table 30: Leakage TVLs for concrete as provided by Table B.7 in NCRP-151.

Energy (MV)	TVL_1 (cm)	TVL_e (cm)
4	33	28
6	34	29
10	35	31
15	36	33
18	36	34