Shielding Calculation Report
Varian iX
Methodist Hospital ~ Willowbrook
August 22, 2007

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MP 10019

1. Introduction

This report reviews the radiation shielding for the therapy rooms in a new facility being built in Willowbrook, Texas, by the Methodist Hospital System.

The center will begin with one linear accelerator and a vault for a second possible accelerator. The vault that is being built out is the south vault and all calculation points will be relative to this vault.

The calculations are based on the plans supplied by Carl Butler of Harrell Architects on 7/24/07. Any changes from the plans may invalidate the calculations.

2. Linear Accelerator

The accelerator is a Varian iX with On-Board-Imaging manufactured by Varian. The unit will be capable of producing 6 MV and 18 MV photons and electrons ranging from 6 MeV to 20 MeV. The accelerator is also capable of doing Intensity Modulated Radiation Therapy which will be discussed later. Electrons do not contribute to shielding requirements in the case of a linear accelerator that also produces photons.

The facility is attached to an office building, but there are no offices or useable space above the vaults. Currently no buildings are near the vaults themselves other than the one shown in the elevation plan. Addition of new buildings near the vaults may invalidate calculations. Floor and elevation plans used are found in Appendix 1.

3. Shielding Design Goal

The shielding design goals (P) are 0.02 mSv/week (1mSv/yr) for uncontrolled areas and 0.1 mSv/week (5mSv/yr) for controlled areas.

The maximum dose equivalent in any one hour (TADR) is 0.02 mSv (20µSv).

4. Assumptions

- The concrete density is 147 lbs./cu ft.
- Distances to calculation points are the distance from the target or isocenter to the wall + 1 foot. Ceiling distances are + 3 feet. Isocenter to target distance is 1 m.
- Primary and Leakage Tenth Value Layers (TVL) and Half Value Layers (HVL) are found below and are from NCRP Report #151 Tables B.2 and B.7.

Energy (MV)	Radiation Source	TVL$_1$ (first Tenth Value Layer)		TVL$_e$ (last Tenth Value Layer)		HVL	
		Cm	Inches	Cm	Inches	Cm	Inches
18	Primary	45	17.7	43	16.9	13.5	5.3
6	Primary	37	14.6	33	13	11.1	4.37
18	Leakage	36	14.2	34	13.4	10.8	4.25
6	Leakage	34	13.4	29	11.4	10.2	4.02

- Workload is the dose (Gy) per week at Isocenter and it is assumed that the conventional workloads, W_{conv} are W(6 MV) = 300 and W(18 MV) = 450 Gy/week.

  IMRT considerations:

  $$W_L = W_{conv} + C * W_{IMRT}$$

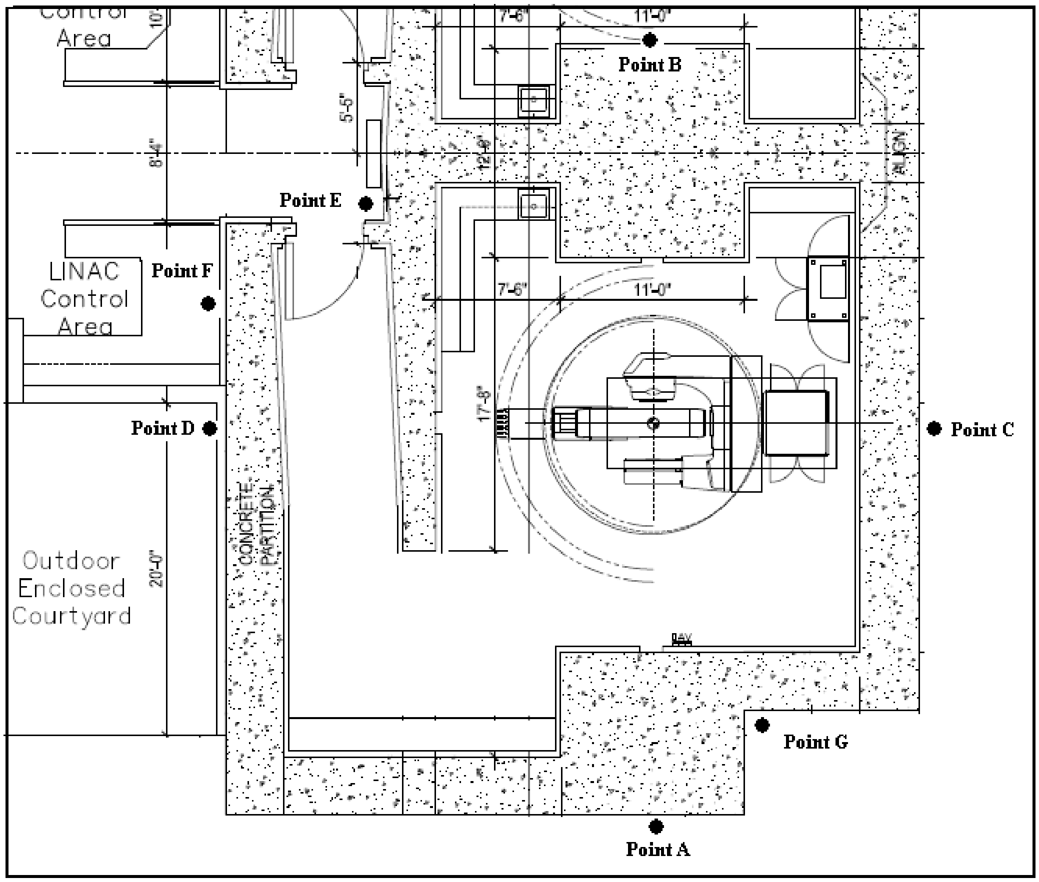
  Assume 80% of 6 MV patients are IMRT, and 40% of 18 MV patients are IMRT. C is the monitor unit efficiency and is assumed to be 3. Therefore the workloads with IMRT are 780 Gy/ week and 810 Gy/week respectively. Typically, conventional workloads will be used for primary barriers, and IMRT workloads will be used for scatter, leakage, and TADR calculations.

- Occupancy factors are given by table B1 of NCRP #151

5. Summary (full calculations are given in Appendix 2)

Point	P	inches needed	inches present	ok?
A	Uncontrolled	61.9 concrete	116	Y
B	Controlled	67.2 concrete	151	Y
C	Uncontrolled	25.9 concrete	42	Y
D	Uncontrolled	20.67 concrete	39	Y
E	Controlled	44.5 concrete	44.5	Y
F	Controlled	32.5 concrete	63.8	Y
G	Uncontrolled	27.4 concrete	48	Y
H	Uncontrolled	67.5 concrete	80	Y
I	Uncontrolled	28.2 concrete	44	Y
DOOR	Controlled	3.1´´ BPE & 0.86´´ Pb	0	N

Locations of points are given below.

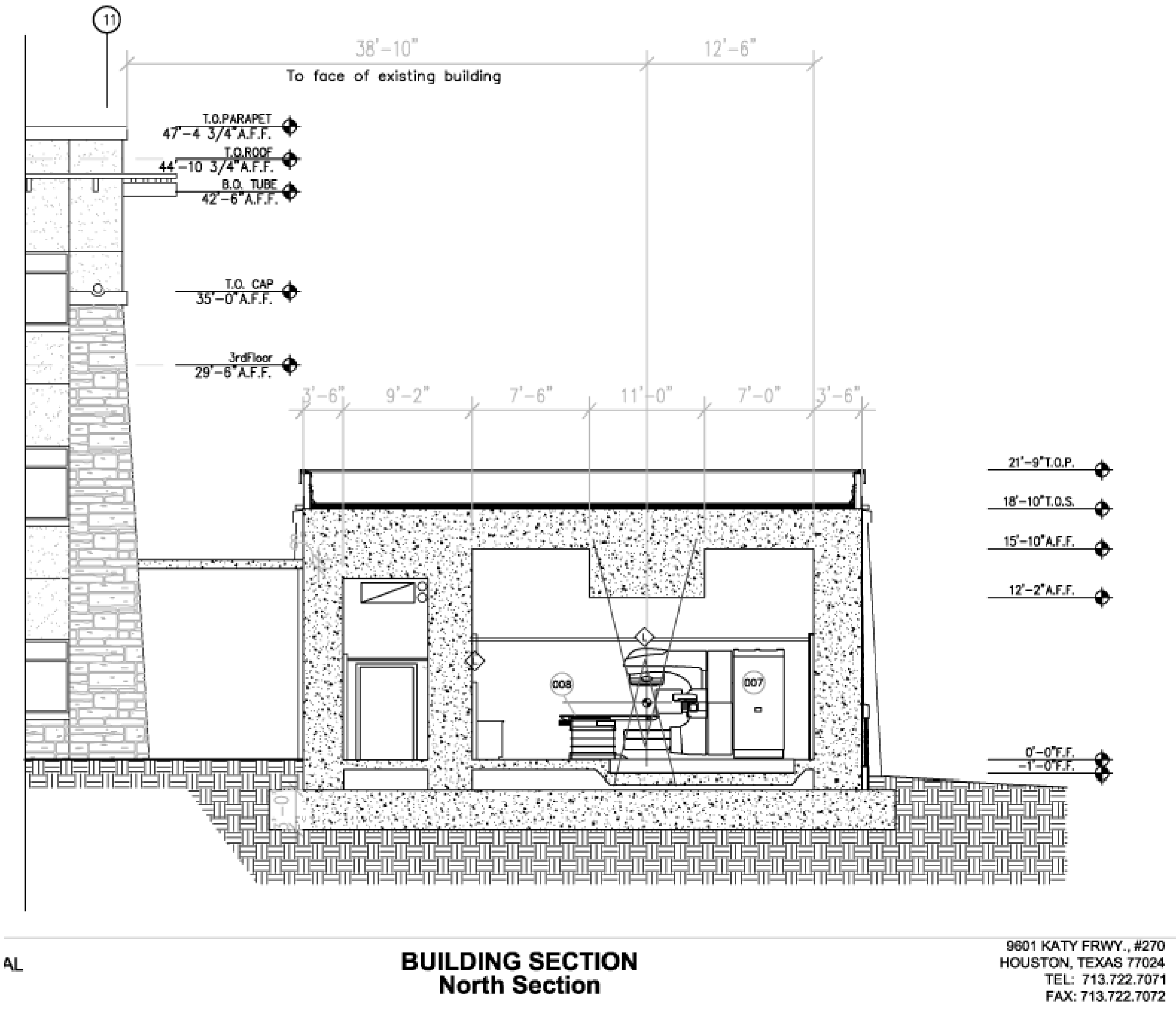


6. References

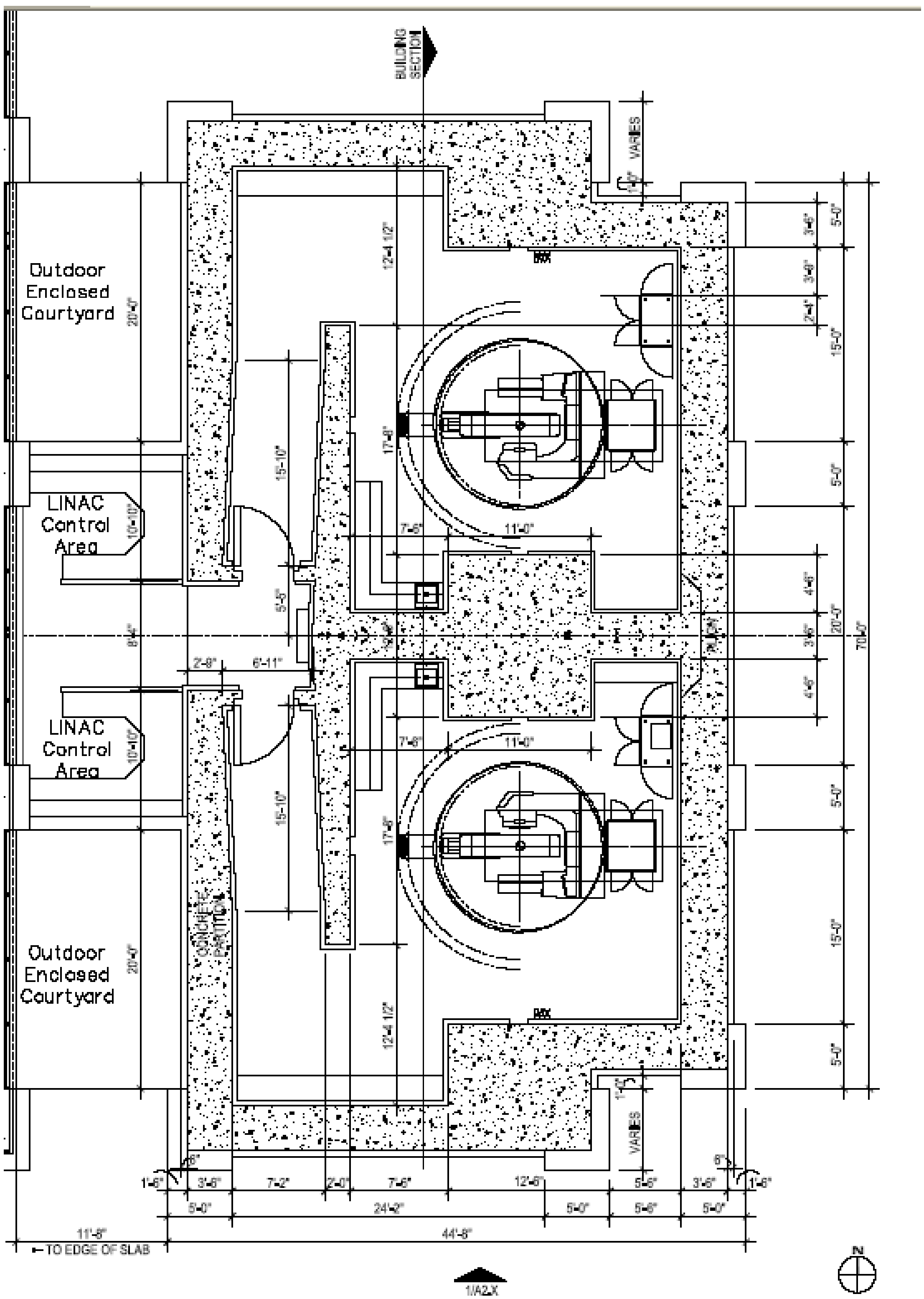
- National Council of Radiation Protection and Measurements. Structural Shielding Design and Evaluation for Megavoltage X- and Gamma-Ray Radiotherapy Facilities, Washington DC: NCRP, NCRP Report No. 151. 2006.
- McGinley, PH. Shielding Techniques in Radiation Oncology Facilities, 2nd Edition. Medical Physics Publishing. Madison, WI. 2002.
- CLINAC 1800, 2100C(/D) & 2300C/D, 21EX, 23EX RADIATION LEAKAGE DATA (http://www.varian.com/onc/shared/pdf/12000.pdf)
- National Council of Radiation Protection and Measurements. Structural shielding design and evaluation for medical use of x-ray and gamma rays of energies up to 10 MeV. Washington DC: NCRP, NCRP Report No. 49; 1976.
- National Council of Radiation Protection and Measurements. Radiation protection design guidelines for 0.1-100 MeV particle accelerator facilities. Washington DC: NCRP, NCRP Report No. 51; 1977.
- 25 Texas Administrative Code §289.229. Radiation Safety Requirements for Accelerators, Therapeutic Radiation Machines, and Simulators. October, 2000.

Appendix 1

Building North Section:



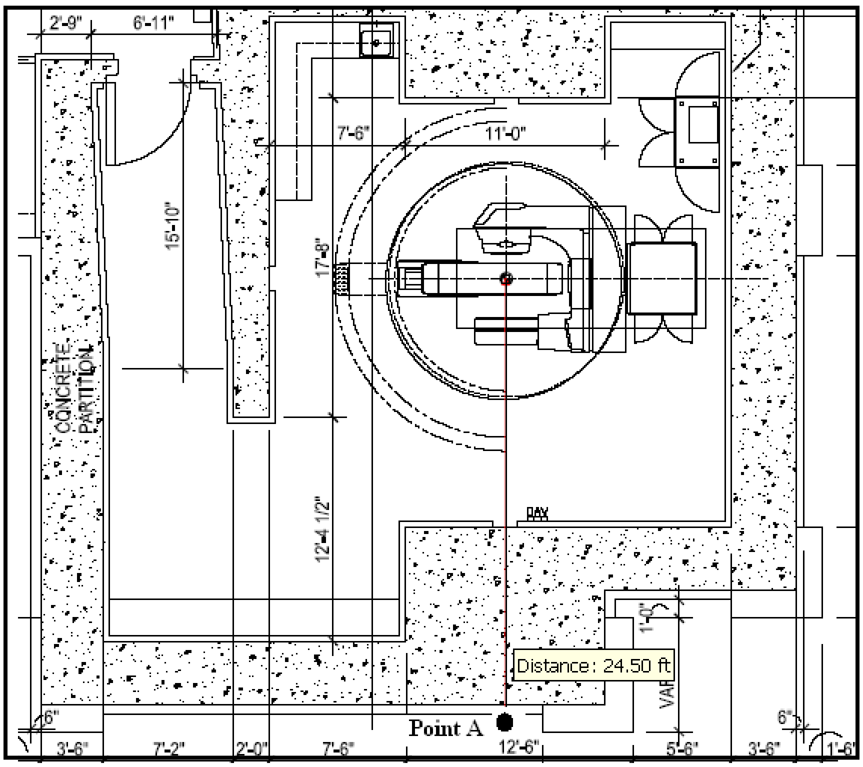
Floor Plan: Portrait



Appendix II

- **Point A**

Description: Primary barrier along south wall
Occupancy factor (T): Parking lot = 1/40 = 0.025
Distance from Isocenter to point, d= 23.5´+ 1´ = 24.5´= 7.46m
Dose per week outside barrier (P)= uncontrolled = $20*10^{-6}$ Sv
Use Factor (U) = .25



- *Primary Barrier Calculation*

Transmission factor of the primary barrier (Bx):

$$B_x(18MV) = \frac{Pd_{pri}^2}{WUT} = \frac{20*10^{-6}*(7.46+1)^2}{450*.025*.25} = 5.09*10^{-4}$$

Number of tenth value layers required (n):

$$n = -\log(B_x) = \log\left(\frac{1}{B_x}\right) = \log\left(\frac{1}{5.09*10^{-4}}\right) = 3.29$$

Barrier thickness (t) is given by:

$$t = TVL_1 + (n-1)TVL_e = 45 + (3.29-1)*43 = 143.6cm = 56.5''$$

When a barrier is thickness t is greater than the first TVL, the total transmission factor, B, is given by:

$$B_x = 10^{-\left\{1+\left(\frac{t-TVL_1}{TVL_e}\right)\right\}}$$

To determine if this is adequate for the additional workload from 6 MV, the following are used:

$$H(6MV) = B_x \frac{WUT}{d^2} = \frac{10^{-\left\{1+\left(\frac{143.6-37}{33}\right)\right\}} *300*.25*.025}{(7.46+1)^2} = 1.54*10^{-6}\frac{Sv}{week} = 1.54\frac{\mu Sv}{week}$$

The 6 MV dose equivalent is only 8% of the shielding design goal and will not effect the primary beam shielding.

- *TADR Calculation*

The maximum dose equivalent in any one hour is determined from the maximum absorbed dose rate at isocenter. This is $\dot{D}_o$ = 12 Gy/min or 720 Gy/hr. The instantaneous dose rate at location A with transmission factor B_x is:

$$IDR(18MV) = \frac{\dot{D}_0 * B_x}{d^2} = \frac{720*5.09x10^{-4}}{(7.46+1)^2} = 5.12*10^{-3}\frac{Sv}{hr}$$

And

$$IDR(6MV) = \frac{720*10^{-\left\{1+\left(\frac{143.6-37}{33}\right)\right\}}}{(7.46+1)^2} = 5.91*10^{-4}\frac{Sv}{hr}$$

The weekly time averaged dose equivalent rate, Rw, is the time averaged dose rate at the location averaged over a 40 hour work week. It is as follows:

$$R_w(18MV) = \frac{IDR*WU}{\dot{D}_0} = \frac{5.12*10^{-3}*450*.25}{720} = 8.00*10^{-4}\frac{Sv}{week} = 800\frac{\mu Sv}{week}$$

And

$$R_w(6MV) = \frac{5.91*10^{-4}*300*.25}{720} = 6.16*10^{-5}\frac{Sv}{week} = 62\frac{\mu Sv}{week}$$

The maximum number of patients per hour is 6. The average number of patients per hour is 5. M = 6/5=1.2. The dose equivalent in any one hour from both 6MV and 18MV patients is:

$$R_h = \left(\frac{M}{40}\right)R_{x(total)} = \left(\frac{1.2}{40}\right)*(800+62) = 26\frac{\mu Sv}{hour}$$

This does not satisfy the 20μSv in any one hour requirement. 1 HVL (18MV) must be added to meet the requirement.

$$t = 143.6cm + 13.5cm = 157.1cm = 61.9''$$

- *Scatter Dose Calculation*

For this patient scatter calculation, a position of 10º off the beam central axis is assumed. This is the worst case scenario because when the beam is pointing at point A the scatter fraction (α) is highest and the energy of the small angle scattered radiation is also the highest. We will just consider 18 MV scatter due to the higher energy and penetration of the scatter beam.

Calculated slant thickness of barrier = 157.1 cm
Distance from target to patient, d_{sca} = 1m
Distance from isocenter to point A = d_{sec}= 7.46m
F = field area at mid depth of patient at 1m = 40x40 cm^2
α = Scatter fraction for 10º= $1.42x10^{-2}$ from table B.4 of NCRP 151
TVL (18MV, scattered at 10º) = 45 cm concrete from table B.5a of NCRP 151

The maximum transmitted patient scattered dose equivalent at location A from 18 MV is:

$$B_{sca} = 10^{-\left(\frac{t}{TVL}\right)} = 10^{-\left(\frac{157.1}{45}\right)} = 3.23*10^{-4}$$

Then

$$H_{sca} = B_{sca}\alpha\frac{F}{400}\frac{WUT}{d_{sca}^2 d_{\sec}^2} = (3.23*10^{-4})(1.42*10^{-2})\left(\frac{40*40}{400}\right)\left(\frac{450*.25*.025}{1^2*7.46^2}\right) = 9.27*10^{-7}\,Sv/week$$

The dose of 0.927 μSv/week is well below the 20μSv/week limit and is therefore negligible. The primary barrier is sufficient for patient scattered radiation.

- *Leakage Radiation Calculation*

W = IMRT workloads given in part 4 - Assumptions

Use TVLs are the same as tabulated in part 4 – Assumptions

The transmitted 6 MV leakage dose equivalent is:

$$H_L = \frac{B_L * WT * 10^{-3}}{d_L^2} = \frac{10^{-\left\{1+\left(\frac{157.1-34}{29}\right)\right\}} 10^{-3}(780)(.025)}{7.46^2} = 1.1*10^{-3}\,\mu Sv/week$$

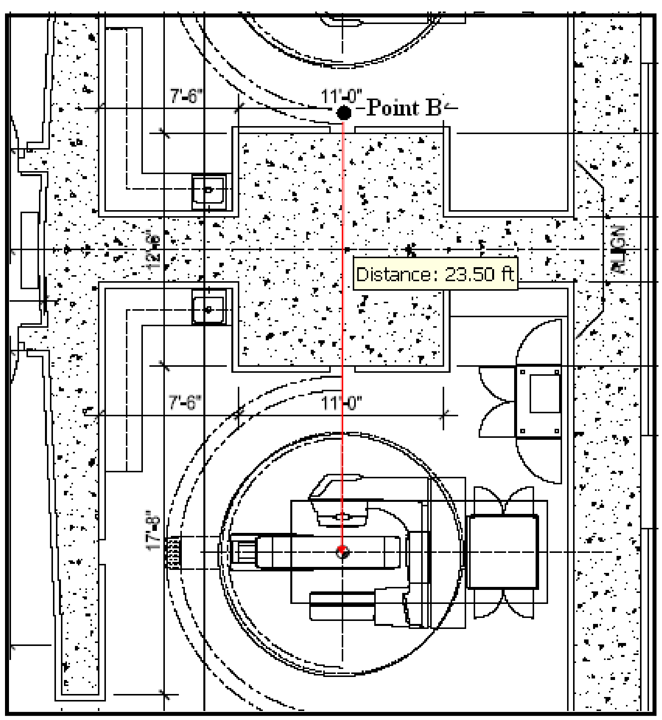
And for 18MV:

$$H_L = \frac{B_L * WT * 10^{-3}}{d_L^2} = \frac{10^{-\left\{1+\left(\frac{157.1-36}{34}\right)\right\}} 10^{-3}(810)(.025)}{7.46^2} = 5.76*10^{-3}\,\mu Sv/week$$

Both these values are well below the limit. Because the treatment head is generally shielded to better than 0.1%, the primary barrier is adequate for shielding from additional leakage radiation, even with additional workload from IMRT.

- Point B

Description: Primary barrier between vaults
Occupancy factor (T): Adjacent Treatment Room = 0.5
Distance from Isocenter to point, d = 22.5´+ 1´= 23.5´ = 7.16m
Dose per week outside barrier (P) = controlled area = $0.1*10^{-3}$ Sv
Use Factor (U) = .25



Transmission factor of the primary barrier (Bx):

$$B_x(18MV) = \frac{Pd_{pri}^2}{WUT} = \frac{0.1*10^{-3}*(7.16+1)^2}{450*.5*.25} = 1.18*10^{-4}$$

Number of tenth value layers required (n):

$$n = \log\left(\frac{1}{B_x}\right) = \log\left(\frac{1}{1.18*10^{-4}}\right) = 3.9$$

Barrier thickness (t) is given by:

$$t = TVL_1 + (n-1)TVL_e = 45 + (3.9-1)*43 = 170.8cm = 67.2''$$

To determine if this is adequate for the additional workload from 6 MV, the following are used:

$$H(6MV) = B_x \frac{WUT}{d^2} = \frac{10^{-\left\{1+\left(\frac{170.8-37}{33}\right)\right\}}*300*.25*.5}{(7.16+1)^2} = 4.95*10^{-6}\frac{Sv}{week} = 4.95\frac{\mu Sv}{week}$$

The 6 MV dose equivalent is only 5% of the shielding design goal and will not effect the primary beam shielding.

The instantaneous dose rate at point B with transmission factor B_x is:

$$IDR(18MV) = \frac{\dot{D}_0 * B_x}{d^2} = \frac{720*1.18x10^{-4}}{(7.16+1)^2} = 1.28*10^{-3}\frac{Sv}{hr}$$

$$IDR(6MV) = \frac{720*10^{-\left\{1+\left(\frac{170.8-37}{33}\right)\right\}}}{(7.16+1)^2} = 9.51*10^{-5}\frac{Sv}{hr}$$

R_w is as follows:

$$R_w(18MV) = \frac{IDR*WU}{\dot{D}_0} = \frac{1.28*10^{-3}*450*.25}{720} = 2.00*10^{-4}\frac{Sv}{week} = 200\frac{\mu Sv}{week}$$

$$R_w(6MV) = \frac{9.51*10^{-5}*300*.25}{720} = 9.9*10^{-6}\frac{Sv}{week} = 9.9\frac{\mu Sv}{week}$$

The dose equivalent in any one hour from both 6MV and 18MV patients is:

$$R_h = \left(\frac{M}{40}\right) R_{x(total)} = \left(\frac{1.2}{40}\right) * (200 + 9.9) = 6.3 \frac{\mu Sv}{hour}$$

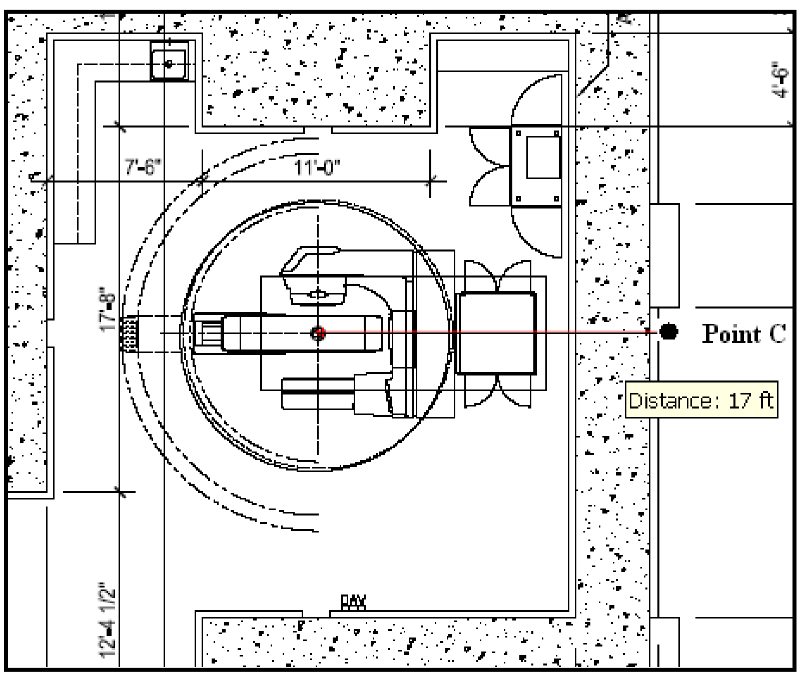
This satisfies the 20µSv in any one hour requirement.

- *Patient Scatter and Leakage Calculation*

As we have seen from point A, patient scatter and leakage doses are negligible when the point in question is behind a primary barrier. Therefore, the patient scatter and leakage calculations will not be duplicated for point B.

- Point C

Description: Secondary barrier along East wall directly behind Linac
Occupancy Factor: Parking Lot = 1/40 =.025
Use Factor = 1 for scatter barriers
W = IMRT workloads given in part 4 - Assumptions
Distance from target to patient, d_{sca} = 1m
Distance from isocenter to point C = d_{sec}= d_L=16´+1´=17´=5.18m
Dose per week outside barrier (P)= uncontrolled = $20 * 10^{-6}$ Sv



- *Patient Scatter Calculation*

α (18 MV)= Scatter fraction for 90º= 1.89×10^{-4} from table B.4 of NCRP 151
α (6 MV)= Scatter fraction for 90º= 4.26×10^{-4} from table B.4 of NCRP 151
TVL (6 MV, scattered at 90º) = 17 cm concrete from table B.5a of NCRP 151

TVL (18 MV, scattered at 90º) = 19 cm concrete from table B.5a of NCRP 151
F = field area at mid depth of patient at 1m = 40x40 cm^2

For 6 MV the barrier thickness required is:

$$B_{ps}(6MV) = \frac{Pd_{\sec}^2 d_{sca}^2}{\alpha WUT}\frac{400}{F} = \frac{20*10^{-6}(1^2)(5.18^2)}{4.26*10^{-4}(780)(1)(.025)}\left(\frac{400}{40*40}\right) = 1.62*10^{-2}$$

Then the number of TVLs is:

$$n = \log\left(\frac{1}{B_x}\right) = \log\left(\frac{1}{1.62*10^{-2}}\right) = 1.79$$

Barrier thickness (t) is given by:

$$t = n*TVL = 1.79*17 = 30.4cm$$

For 18 MV x-rays we get:

$$B_{ps}(18MV) = \frac{Pd_{\sec}^2 d_{sca}^2}{\alpha WUT}\frac{400}{F} = \frac{20*10^{-6}(1^2)(5.18^2)}{1.89*10^{-4}(810)(1)(.025)}\left(\frac{400}{40*40}\right) = 3.51*10^{-2}$$

Then the number of TVLs is:

$$n = \log\left(\frac{1}{B_x}\right) = \log\left(\frac{1}{3.51*10^{-2}}\right) = 1.46$$

Barrier thickness (t) is given by:

$$t = n*TVL = 1.46*19 = 27.7cm$$

Since the scatter thicknesses required for 6 MV and 18MV are within 1 TVL of each other, one HVL needs to be added according to the two source rule. Therefore, the total shielding to cover patient scattered dose is:

$$t' = t + 0.301(TVL) = 30.4 + (.301)(19) = 36.1cm$$

- *Leakage Calculation*

$$B_L(6MV) = \frac{P*d_L^2}{10^{-3}*WT} = \frac{20*10^{-6}(5.18^2)}{10^{-3}*780*.025} = 2.75*10^{-2}$$

Then the number of TVLs is:

$$n = \log\left(\frac{1}{B_x}\right) = \log\left(\frac{1}{2.75*10^{-2}}\right) = 1.56$$

Barrier thickness (t) is given by:

$$t = 34 + (1.56 - 1)*29 = 50.3cm$$

And for 18MV:

$$B_L(18MV) = \frac{P*d_L^2}{10^{-3}*WT} = \frac{20*10^{-6}\left(5.18^2\right)}{10^{-3}*810*.025} = 2.65*10^{-2}$$

Then the number of TVLs is:

$$n = \log\left(\frac{1}{B_x}\right) = \log\left(\frac{1}{2.65*10^{-2}}\right) = 1.58$$

Barrier thickness (t) is given by:

$$t = 36 + (1.58 - 1)*34 = 55.6cm$$

Since the leakage thicknesses required for 6 MV and 18MV are within one TVL of each other, one HVL needs to be added according to the two source rule. Therefore, the total shielding to cover leakage dose is:

$$t' = t + 0.301(TVL) = 55.6 + (.301)(34) = 65.8cm = 25.9''$$

The scattered radiation contributions are negligible and this wall can be shielded for IMRT leakage alone.

- *TADR Calculation*

The instantaneous dose equivalent rates for patient scatter are:

$$IDR_{PS}(6MV) = \frac{\dot{D}_0\,\alpha F}{400*d_{sca}^2}10^{-\left(\frac{t}{TVL}\right)} = \frac{720*4.26*10^{-4}*40*40}{400*5.18^2}*10^{-\left(\frac{65.8}{17}\right)} = 6.12*10^{-6}\,\frac{Sv}{hr}$$

and

$$IDR_{PS}(18MV) = \frac{\dot{D}_0\,\alpha F}{400*d_{sca}^2}10^{-\left(\frac{t}{TVL}\right)} = \frac{720*1.89*10^{-4}*40*40}{400*5.18^2}*10^{-\left(\frac{65.8}{19}\right)} = 6.95*10^{-6}\,\frac{Sv}{hr}$$

The instantaneous dose equivalent rates for leakage we have:

$$IDR_{Leak}(6MV) = \frac{720*10^{-3}*10^{-\left\{1+\left(\frac{65.8-34}{29}\right)\right\}}}{5.18^2} = 2.14*10^{-4}\frac{Sv}{hr}$$

and

$$IDR_{\ Leak}(18MV) = \frac{720*10^{-3}*10^{-\left\{1+\left(\frac{65.8-36}{34}\right)\right\}}}{5.18^2} = 3.56*10^{-4}\frac{Sv}{hr}$$

We find the scattered radiation contributions are insignificant at point C, so only leakage radiation contributions will be computed. The results are:

$$R_w(6MV) = \frac{IDR_{Leak}*W}{\dot{D}_0} = \frac{2.14*10^{-4}*780}{720} = 2.32*10^{-4}\frac{Sv}{week} = 232\frac{\mu Sv}{week}$$

And

$$R_w(18MV) = \frac{IDR_{Leak}*W}{\dot{D}_0} = \frac{3.56*10^{-4}*810}{720} = 4.00*10^{-4}\frac{Sv}{week} = 400\frac{\mu Sv}{week}$$

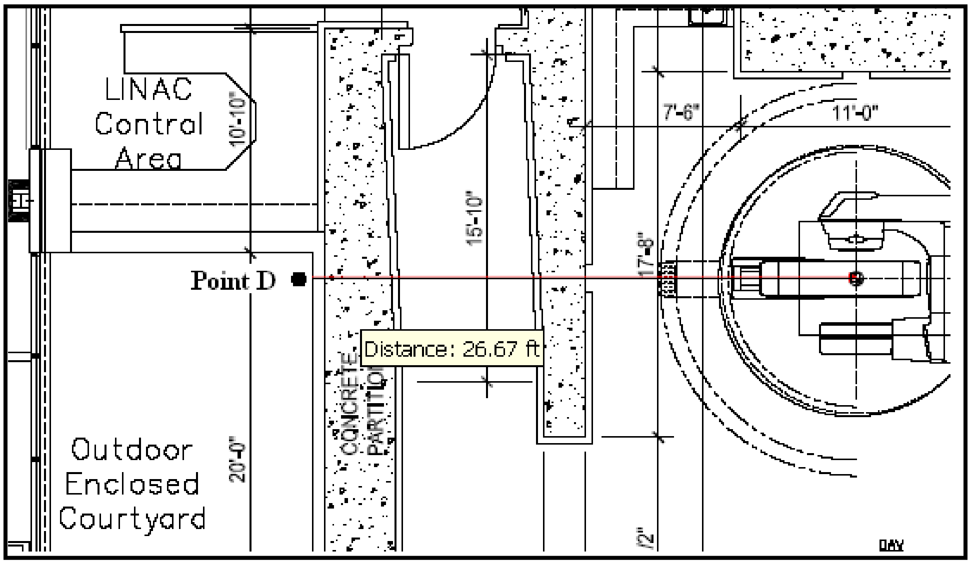
And therefore:

$$R_h = \left(\frac{M}{40}\right)R_{x(total)} = \left(\frac{1.2}{40}\right)*\left(400+232\right) = 19\frac{\mu Sv}{hour}$$

This is below the 20µSv/hour limit.

- Point D

Description: Outdoor courtyard secondary barrier along west wall
Occupancy Factor: Outside, no seating = 1/40 =.025
Use Factor = 1 for scatter barriers
W = IMRT workloads given in part 4 - Assumptions
Distance from target to patient, d_{sca} = 1m
Distance from isocenter to point D = d_{sec}= d_L=25.67´+1´=26.67´=8.13m
Dose per week outside barrier (P)= uncontrolled = $20*10^{-6}$ Sv



As seen for point C, patient scatter will be negligible at this point. We will only consider leakage dose:

- *Leakage Calculation*

$$B_L(6MV) = \frac{P * d_L^2}{10^{-3} * WT} = \frac{20 * 10^{-6}\left(8.13^2\right)}{10^{-3} * 780 * .025} = 6.78 * 10^{-2}$$

Then the number of TVLs is:

$$n = \log\left(\frac{1}{B_x}\right) = \log\left(\frac{1}{6.78 * 10^{-2}}\right) = 1.17$$

Barrier thickness (t) is given by:

$$t = 34 + (1.17 - 1) * 29 = 38.9cm$$

And for 18MV:

$$B_L(18MV) = \frac{P * d_L^2}{10^{-3} * WT} = \frac{20 * 10^{-6}\left(8.13^2\right)}{10^{-3} * 810 * .025} = 6.53 * 10^{-2}$$

Then the number of TVLs is:

$$n = \log\left(\frac{1}{B_x}\right) = \log\left(\frac{1}{6.53 * 10^{-2}}\right) = 1.18$$

Barrier thickness (t) is given by:

$$t = 36 + (1.18 - 1) * 34 = 42.3cm$$

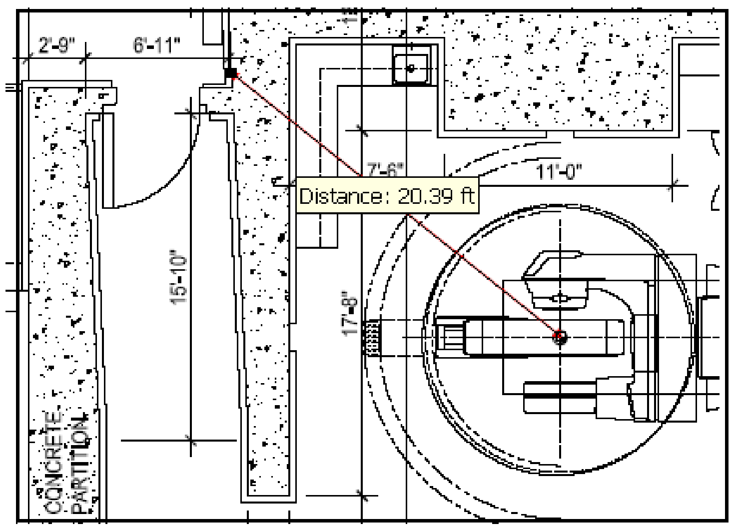
Since the leakage thicknesses required for 6 MV and 18MV are within one TVL of each other, one HVL needs to be added according to the two source rule. Therefore, the total shielding to cover leakage dose is:

$$t' = t + 0.301(TVL) = 42.3 + (.301)(34) = 52.5cm = 20.7''$$

Similar to point C, the instantaneous dose rate is below the limit.

- Point E

Description: Directly outside treatment room door
Occupancy Factor: control room door = 1/8=.125
Distance from isocenter to point F=d_L=20.39´+1´=21.39´=6.2m
Dose per week outside barrier (P)= controlled = $0.1*10^{-3}$ Sv



- *Leakage Calculation*

As seen for previous points, patient scatter will be negligible at this point. We will only consider leakage dose. Point E is complicated by the fact that dose through the door is also at this point and contributes to the 0.1mSv dose limit. Instead of calculating required barrier thickness, we will calculate the actual expected dose through the planned barrier. The existing barrier slant thickness, t, is 113.1 cm (44.5´´).

$$H(6MV) = \frac{10^{-3} BWT}{d^2} = \frac{10^{-3} 10^{-\left\{1+\left(\frac{t-TVL_1}{TVL_e}\right)\right\}} WT}{d^2} = \frac{10^{-3} * 10^{-\left\{1+\left(\frac{113.1-34}{29}\right)\right\}} * 780 * .125}{6.2^2} = 0.47 \frac{\mu Sv}{week}$$

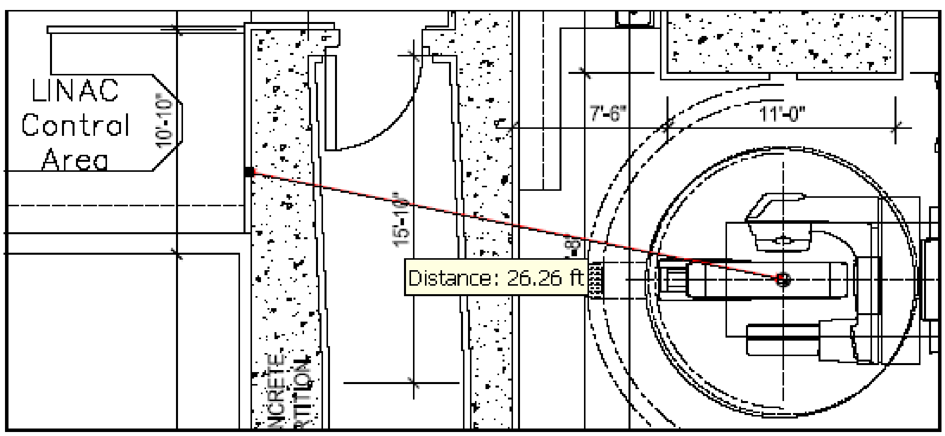
And

$$H(18MV)=\frac{10^{-3}BWT}{d^2}=\frac{10^{-3}10^{-\left\{1+\left(\frac{t-TVL_1}{TVL_e}\right)\right\}}WT}{d^2}=\frac{10^{-3}*10^{-\left\{1+\left(\frac{113.1-36}{34}\right)\right\}}*810*.125}{6.2^2}=1.42\frac{\mu Sv}{week}$$

Adding together, we get 1.85μSv/week. We will find in the dose calculation for the door that compensating for the additional shielding by the steel encasing of the door will net us an extra 16 μSv/week that can be allotted for this dose requirement.

- Point F

Description: Linac control room
Occupancy Factor: control room = 1
Distance from isocenter to point F=d_L=26.26´+1´=27.26´=8.31m
Dose per week outside barrier (P)= controlled = $0.1*10^{-3}$ Sv
As seen for previous points, patient scatter will be negligible at this point. We will only consider leakage dose:



- *Leakage Calculation*

$$B_L(6MV)=\frac{P*d_L^2}{10^{-3}*WT}=\frac{.1*10^{-3}\left(8.31^2\right)}{10^{-3}*780*1}=8.85*10^{-3}$$

Then the number of TVLs is:

$$n=\log\left(\frac{1}{B_x}\right)=\log\left(\frac{1}{8.85*10^{-2}}\right)=2.05$$

Barrier thickness (t) is given by:

$$t=34+(2.05-1)*29=64.5cm$$

And for 18MV:

$$B_L(18MV) = \frac{P*d_L^2}{10^{-3}*WT} = \frac{.1*10^{-3}(8.31^2)}{10^{-3}*810*1} = 8.53*10^{-3}$$

Then the number of TVLs is:

$$n = \log\left(\frac{1}{B_x}\right) = \log\left(\frac{1}{8.53*10^{-2}}\right) = 2.07$$

Barrier thickness (t) is given by:

$$t = 36 + (2.07 - 1)*34 = 72.4cm$$

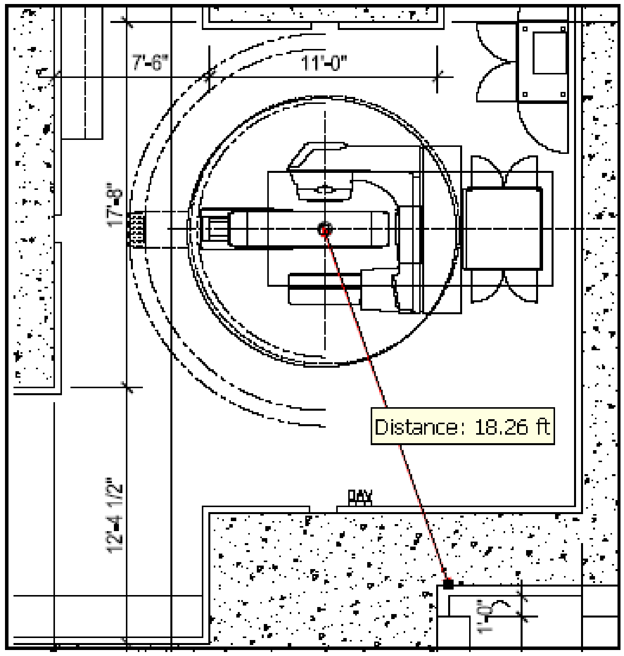
Since the leakage thicknesses required for 6 MV and 18MV are within one TVL of each other, one HVL needs to be added according to the two source rule. Therefore, the total shielding to cover leakage dose is:

$$t' = t + 0.301(TVL) = 72.4 + (.301)(34) = 82.6cm = 32.5''$$

Similar to point C, the instantaneous dose rate is below the limit.

- Point G

Description: Off primary wall at 30º away from primary beam
Occupancy Factor: Parking Lot = 0.025
Use Factor = ¼ = .25
Distance from isocenter to point G = d_{sec} = d_L = 18.26´+1´=19.26´=5.87m
Distance from target to isocenter = d_{sca} = 1m
Dose per week outside barrier (P)= uncontrolled = $20*10^{-6}$ Sv
α (18 MV)= Scatter fraction for 30º= $2.53x10^{-3}$ from table B.4 of NCRP 151
α (6 MV)= Scatter fraction for 30º= $2.77 x10^{-3}$ from table B.4 of NCRP 151
TVL (6 MV, scattered at 30º) = 26 cm concrete from table B.5a of NCRP 151
TVL (18 MV, scattered at 30º) = 32 cm concrete from table B.5a of NCRP 151
F = field area at mid depth of patient at 1m = 40x40 cm^2



- *Patient Scatter Calculation*

For 6 MV the barrier thickness required is:

$$B_{ps}(6MV) = \frac{Pd_{\sec}^2 d_{sca}^2}{\alpha WUT}\frac{400}{F} = \frac{20*10^{-6}(1^2)(5.87^2)}{2.77*10^{-3}(780)(.25)(.025)}\left(\frac{400}{40*40}\right) = 1.28*10^{-2}$$

Then the number of TVLs is:

$$n = \log\left(\frac{1}{B_x}\right) = \log\left(\frac{1}{1.28*10^{-2}}\right) = 1.89$$

Barrier thickness (t) is given by:

$$t = n*TVL = 1.89*26 = 49.1cm$$

For 18 MV x-rays we get:

$$B_{ps}(18MV) = \frac{Pd_{\sec}^2 d_{sca}^2}{\alpha WUT}\frac{400}{F} = \frac{20*10^{-6}(1^2)(5.87^2)}{2.53*10^{-3}(810)(.25)(.025)}\left(\frac{400}{40*40}\right) = 1.35*10^{-2}$$

Then the number of TVLs is:

$$n = \log\left(\frac{1}{B_x}\right) = \log\left(\frac{1}{1.35*10^{-2}}\right) = 1.87$$

Barrier thickness (t) is given by:

$$t = n * TVL = 1.87 * 32 = 59.8cm$$

Since the scatter thicknesses required for 6 MV and 18MV are within 1 TVL of each other, one HVL needs to be added according to the two source rule. Therefore, the total shielding to cover patient scattered dose is:

$$t' = t + 0.301(TVL) = 59.8 + (.301)(32) = 69.5cm = 27.4''$$

- *Leakage Calculation*

$$B_L(6MV) = \frac{P * d_L^2}{10^{-3} * WT} = \frac{20*10^{-6}\left(5.87^2\right)}{10^{-3}*780*.025} = 3.53*10^{-2}$$

Then the number of TVLs is:

$$n = \log\left(\frac{1}{B_x}\right) = \log\left(\frac{1}{3.53*10^{-2}}\right) = 1.45$$

Barrier thickness (t) is given by:

$$t = 34 + (1.45 - 1) * 29 = 47.1cm$$

And for 18MV:

$$B_L(18MV) = \frac{P * d_L^2}{10^{-3} * WT} = \frac{20*10^{-6}\left(5.87^2\right)}{10^{-3}*810*.025} = 3.40*10^{-2}$$

Then the number of TVLs is:

$$n = \log\left(\frac{1}{B_x}\right) = \log\left(\frac{1}{3.40*10^{-2}}\right) = 1.47$$

Barrier thickness (t) is given by:

$$t = 36 + (1.47 - 1) * 34 = 51.9cm$$

Since the leakage thicknesses required for 6 MV and 18MV are within one TVL of each other, one HVL needs to be added according to the two source rule. Therefore, the total shielding to cover leakage dose is:

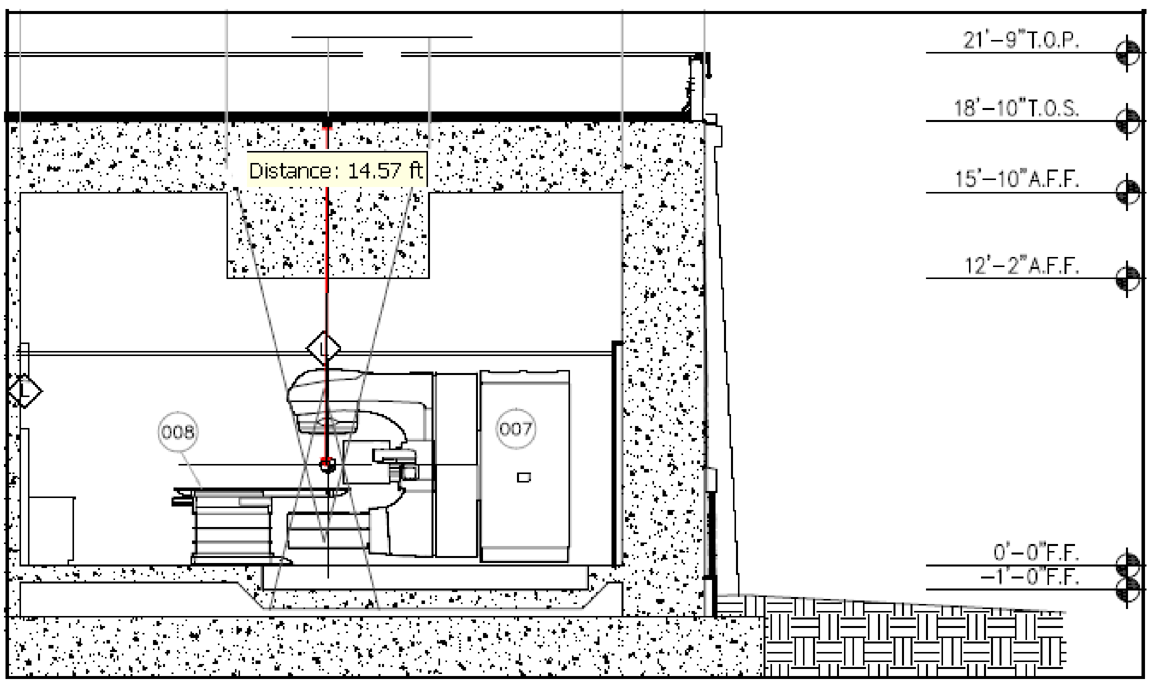
$$t' = t + 0.301(TVL) = 51.9 + (.301)(34) = 62.2cm$$

Similar to point C, the instantaneous dose rate is below the limit.

- Point H

Description: Primary ceiling barrier
Occupancy factor (T): roof = 1/40 = 0.025
Distance from Isocenter to point, d = 14.57´ + 1´ = 15.57´= 4.75m
Dose per week outside barrier (P) = uncontrolled = $20*10^{-6}$ Sv
Use Factor (U) = .25

The roof is unoccupied open space and the primary beam currently does not point towards another building. The roof area is accessible by ladder only. It will occasionally have maintenance personnel working on the roof. If the amount of time spent on the roof is more than approximately 2 hrs/month during operational hours, the radiation oncology physicist should be notified. Furthermore, the barrier must be 11´ wide and run the full length of the roof in the direction of the primary beam swath.



- *Primary Barrier Calculation*

Transmission factor of the primary barrier (Bx):

$$B_x(18MV) = \frac{Pd_{pri}^2}{WUT} = \frac{20*10^{-6}*(4.75+1)^2}{450*.025*.25} = 2.35*10^{-4}$$

Number of tenth value layers required (n):

$$n = -\log(B_x) = \log\left(\frac{1}{B_x}\right) = \log\left(\frac{1}{2.35*10^{-4}}\right) = 3.63$$

Barrier thickness (t) is given by:

$$t = TVL_1 + (n-1)TVL_e = 45 + (3.63-1)*43 = 158cm = 62.2''$$

When a barrier is thickness t is greater than the first TVL, the total transmission factor, B, is given by:

$$B_x = 10^{-\left\{1+\left(\frac{t-TVL_1}{TVL_e}\right)\right\}}$$

To determine if this is adequate for the additional workload from 6 MV, the following are used:

$$H(6MV) = B_x \frac{WUT}{d^2} = \frac{10^{-\left\{1+\left(\frac{158-37}{33}\right)\right\}} *300*.25*.025}{(4.75+1)^2} = 1.21*10^{-6}\frac{Sv}{week} = 1.21\frac{\mu Sv}{week}$$

The 6 MV dose equivalent is only 6% of the shielding design goal and will not effect the primary beam shielding.

- *TADR Calculation*

The maximum dose equivalent in any one hour is determined from the maximum absorbed dose rate at isocenter. This is $\dot{D}_o$ = 12 Gy/min or 720 Gy/hr. The instantaneous dose rate at location A with transmission factor B_x is:

$$IDR(18MV) = \frac{\dot{D}_0 * B_x}{d^2} = \frac{720*2.35*10^{-4}}{(4.75+1)^2} = 5.12*10^{-3}\frac{Sv}{hr}$$

And

$$IDR(6MV) = \frac{720*10^{-\left\{1+\left(\frac{158-37}{33}\right)\right\}}}{(4.75+1)^2} = 4.68*10^{-4}\frac{Sv}{hr}$$

The weekly time averaged dose equivalent rate, Rw, is the time averaged dose rate at the location averaged over a 40 hour work week. It is as follows:

$$R_w(18MV) = \frac{IDR * WU}{\dot{D}_0} = \frac{5.12*10^{-3}*450*.25}{720} = 8.00*10^{-4}\frac{Sv}{week} = 800\frac{\mu Sv}{week}$$

$$R_w(6MV) = \frac{4.68*10^{-4}*300*.25}{720} = 4.88*10^{-5}\frac{Sv}{week} = 49\frac{\mu Sv}{week}$$

The maximum number of patients per hour is 6. The average number of patients per hour is 5. M = 6/5=1.2. The dose equivalent in any one hour from both 6MV and 18MV patients is:

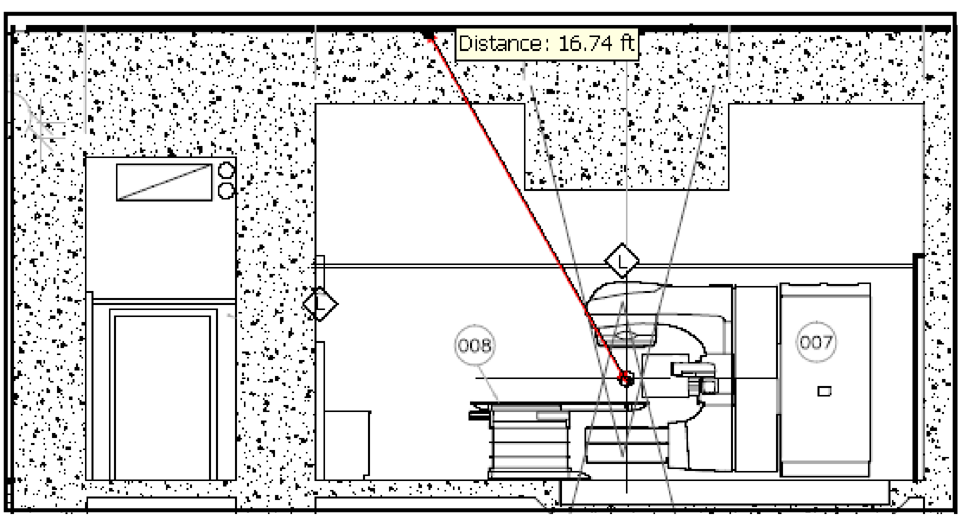
$$R_h = \left(\frac{M}{40}\right)R_{x(total)} = \left(\frac{1.2}{40}\right)*(800+49) = 25.5\frac{\mu Sv}{hour}$$

This does not satisfy the 20µSv in any one hour requirement. 1 HVL must be added to meet the requirement.

$$t = 158cm + 13.5cm = 171.5cm = 67.5''$$

- Point I

Description: Secondary ceiling barrier
Occupancy factor (T): roof = 1/40 = 0.025
Distance from Isocenter to point (d_{sec}): 16.74´ + 1´ = 17.74´ = 5.4m
Dose per week outside barrier (P)= uncontrolled = $20*10^{-6}$ Sv
Use Factor (U) = .25
α (18 MV)= Scatter fraction for 30º= 2.53x10^{-3} from table B.4 of NCRP 151
α (6 MV)= Scatter fraction for 30º= 2.77 x10^{-3} from table B.4 of NCRP 151
TVL (6 MV, scattered at 30º) = 26 cm concrete from table B.5a of NCRP 151
TVL (18 MV, scattered at 30º) = 32 cm concrete from table B.5a of NCRP 151
F = field area at mid depth of patient at 1m = 40x40 cm^2
IMRT workloads are used.



- *Patient Scatter Calculation*

For 6 MV the barrier thickness required is:

$$B_{ps}(6MV)=\frac{Pd_{\sec}^2 d_{sca}^2}{\alpha WUT}\frac{400}{F}=\frac{20*10^{-6}(1^2)(5.4^2)}{2.77*10^{-3}(780)(.25)(.025)}\left(\frac{400}{40*40}\right)=1.08*10^{-2}$$

Then the number of TVLs is:

$$n=\log\left(\frac{1}{B_x}\right)=\log\left(\frac{1}{1.08*10^{-2}}\right)=1.97$$

Barrier thickness (t) is given by:

$$t=n*TVL=1.97*26=51.2cm$$

For 18 MV x-rays we get:

$$B_{ps}(18MV)=\frac{Pd_{\sec}^2 d_{sca}^2}{\alpha WUT}\frac{400}{F}=\frac{20*10^{-6}(1^2)(5.4^2)}{2.53*10^{-3}(810)(.25)(.025)}\left(\frac{400}{40*40}\right)=1.14*10^{-2}$$

Then the number of TVLs is:

$$n=\log\left(\frac{1}{B_x}\right)=\log\left(\frac{1}{1.14*10^{-2}}\right)=1.94$$

Barrier thickness (t) is given by:

$$t=n*TVL=1.94*32=62.08cm$$

Since the scatter thicknesses required for 6 MV and 18MV are within 1 TVL of each other, one HVL needs to be added according to the two source rule. Therefore, the total shielding to cover patient scattered dose is:

$$t'=t+0.301(TVL)=62.08+(.301)(32)=71.7cm=28.2''$$

- *Leakage Calculation*

$$B_L(6MV)=\frac{P*d_L^2}{10^{-3}*WT}=\frac{20*10^{-6}(5.4^2)}{10^{-3}*780*.025}=2.99*10^{-2}$$

Then the number of TVLs is:

$$n = \log\left(\frac{1}{B_x}\right) = \log\left(\frac{1}{2.99*10^{-2}}\right) = 1.52$$

Barrier thickness (t) is given by:

$$t = 34 + (1.52 - 1)*29 = 49.2cm$$

And for 18MV:

$$B_L(18MV) = \frac{P*d_L^2}{10^{-3}*WT} = \frac{20*10^{-6}\left(5.4^2\right)}{10^{-3}*810*.025} = 2.88*10^{-2}$$

Then the number of TVLs is:

$$n = \log\left(\frac{1}{B_x}\right) = \log\left(\frac{1}{2.88*10^{-2}}\right) = 1.54$$

Barrier thickness (t) is given by:

$$t = 36 + (1.54 - 1)*34 = 54.4cm$$

Since the leakage thicknesses required for 6 MV and 18MV are within one TVL of each other, one HVL needs to be added according to the two source rule. Therefore, the total shielding to cover leakage dose is:

$$t' = t + 0.301(TVL) = 54.4 + (.301)(34) = 64.6cm$$

Similar to point C, the instantaneous dose rate is below the limit.

- Maze Door

The dose at the treatment vault door is due to a contribution of photons and neutron doses. The dose equivalent at the door, H_d is given by:

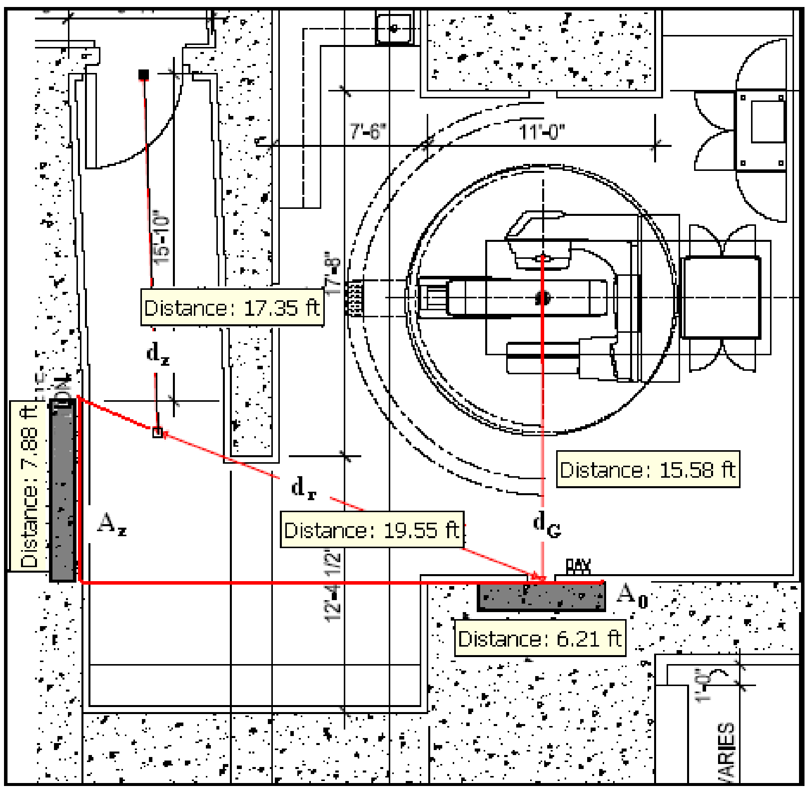
$$H_d = fH_s + H_{LS} + H_{PS} + H_{LT}$$

Each contribution will be calculated separately and then summed together.

- *Wall Scattered Radiation Component, H_S.*

The ceiling is 15´10´´ = 4.83m
Normal use workloads will be used for this calculation.
U = 0.25
d_G = perpendicular distance from the target to the first reflection surface = 15.58´ = 4.75 m

d_r = distance from the beam center at the first reflection surface, past the edge of the inner maze wall, to the midline of the maze =19.55´=5.96m
d_z = centerline distance along the maze to the door =17.35´=5.29m
A_0 = maximum field size projected onto scatter wall = 40x40 projected a distance of 4.75 m = 1.9 x 1.9 m^2 = 3.8 m^2.
A_z = cross sectional area of the maze inner entry projected from A_0 = 7.88´x 15´10´´ = 2.4m x 4.83m =11.6 m^2.
α_G(18MV)= $1.6x10^{-3}$ from Table B.8a of NCRP 151, normal incidence, 75º angle of reflection.
α_G(6MV)= $2.7x10^{-3}$ from Table B.8a of NCRP 151, normal incidence, 75º angle of reflection.
α_z= $8x10^{-3}$ from Table B.8a of NCRP 151, normal incidence, 75º angle of reflection of 0.5 MeV.



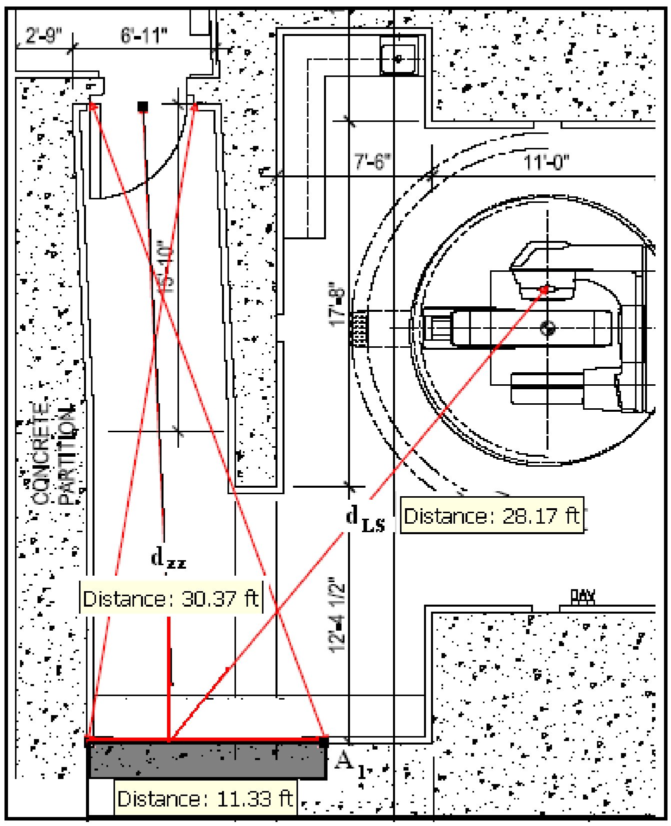
Then H_S is:

$$H_S = \frac{WU\alpha_0\alpha_Z A_0 A_Z}{(d_G d_r d_z)^2} = \frac{[(450*1.6*10^{-3})+(300*2.7*10^{-3})]*.25*3.8*8*10^{-3}*11.6}{(4.75*5.96*5.29)^2} = \frac{6.01\mu Sv}{week}$$

- *Single Scattered Head Leakage Component, H_{LS}.*

Head leakage can scatter once against the wall and reach the maze door. IMRT workloads will be used for this calculation.

U=.25
L_f = head leakage radiation ratio = 0.1% per IEC 2002 requirement
A_1 = area of wall seen from maze door = 11.33´ x 15.83´ = 16.63 m^2
d_{zz} = centerline distance along maze = 9.26m
d_{LS} = distance from target to wall along maze centerline = 8.59 m
α_1 (6MV) = reflection coefficient for scatter of leakage radiation from wall (from Table B.8b from NCRP 151) for 45º incidence and 0 º reflection = 6.4×10^{-3}.
α_1 (18MV) = reflection coefficient for scatter of leakage radiation from wall (from Table B.8b from NCRP 151) for 45º incidence and 0 º reflection = 4.5×10^{-3}.



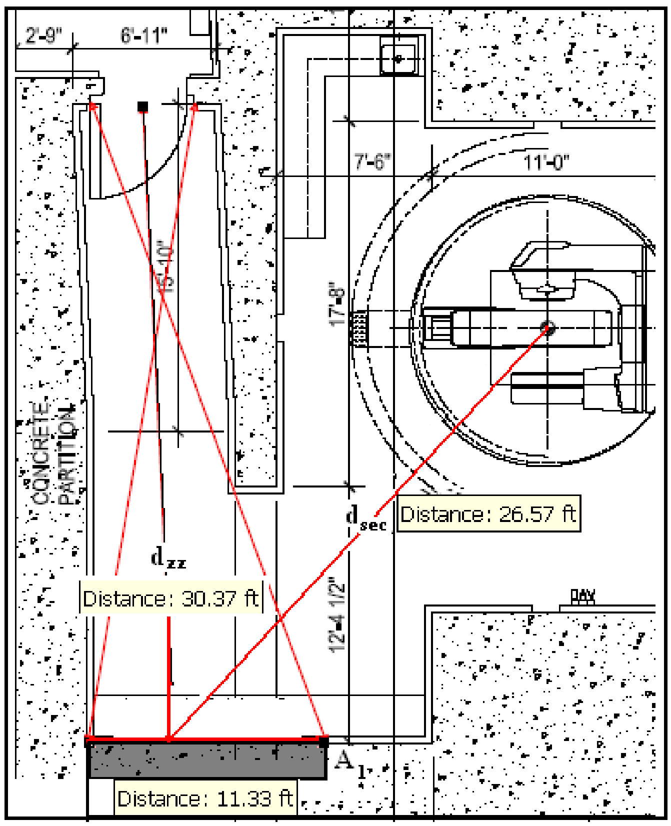
The dose equivalent at the maze door from head leakage is thus:

$$H_{LS} = \frac{L_f W U \alpha_1 A_1}{(d_{\sec} d_{zz})^2} = \frac{10^{-3} * \left[\left(780 * 6.4 * 10^{-3}\right) + \left(810 * 4.5 * 10^{-3}\right)\right] * .25 * 16.63}{(8.59 * 9.26)^2} = 5.67 \frac{\mu Sv}{week}$$

- *Patient Scattered Radiation Component, H_{PS}.*

Normal workloads will be used for this calculation.
U = .25

F = 40x40 cm^2
A_1 = area of wall seen from maze door = 11.33´ x 15.83´ = 16.63 m^2
d_{zz} = centerline distance along maze = 9.26m
d_{sca} = 1 m
d_{sec} = distance from isocenter to wall along maze centerline = 26.57´=8.1m
a_1(6MV) = The 6 MV scatter fraction at 45º scatter angle (from Table B.4 from NCRP 151) = 1.39x10^{-3}.
a_1(18MV) = The 18 MV scatter fraction at 45º scatter angle (from Table B.4 from NCRP 151) = 8.64x10^{-4}.
α_1 = the concrete wall reflection coefficient for incident angle 45º and reflection angle of 0º for 0.5 MeV monoenergetic photons (NCRP 151 table B.8b) = 2.22x10^{-2}



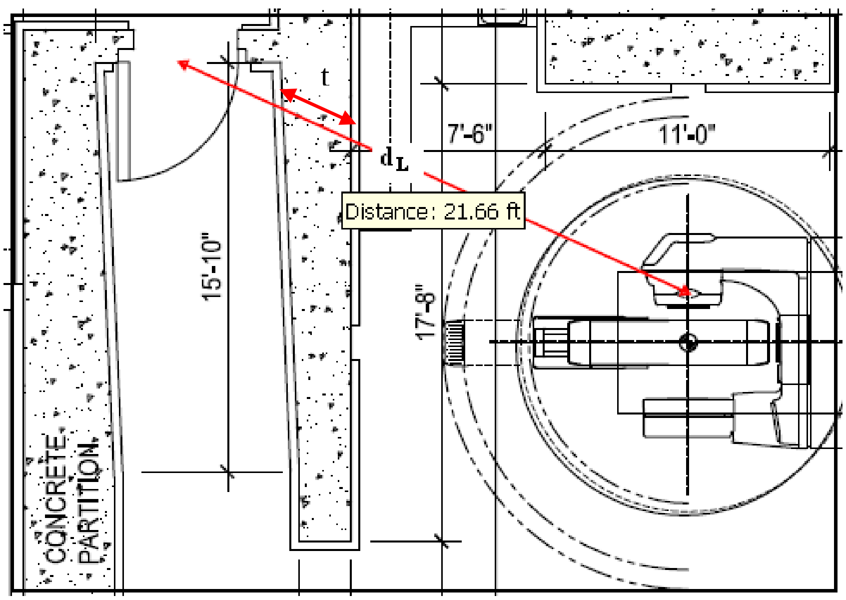
The 6 and 18 MV patient scatter contributions are:

$$H_{PS} = \frac{a(\theta)WU\frac{F}{400}\alpha_1 A_1}{(d_{sca}d_{sec}d_{zz})^2} = \frac{\left[\left(780*1.39*10^{-3}\right)+\left(810*8.64*10^{-4}\right)\right]*.25*\frac{40*40}{400}*2.22*10^{-2}*16.63}{(1*9.26*8.1)^2} =$$

$$H_{PS} = 116\frac{\mu Sv}{week}$$

- *Head Leakage Radiation Through the Maze Wall, H_{LT}.*

IMRT workloads will be used for this calculation.
U = .25
L_f = head leakage radiation ratio = 0.1% per IEC 2002 requirement
d_L = distance from target to center of maze door through the inner maze wall = 21.66´=6.6m
t = the oblique wall slant thickness = 2.89´= 88 cm
TVLs are as given in Assumptions.



Calculating 18MV first, we find the barrier transmission for slant thickness t is:

$$B_x(18MV) = 10^{-\left\{1+\left(\frac{t-TVL_1}{TVL_e}\right)\right\}} = 10^{-\left\{1+\frac{88-36}{34}\right\}} = 2.96*10^{-3}$$

Then the dose equivalent is

$$H_{LT}(18MV) = \frac{L_f WUB}{d_L^2} = \frac{10^{-3}*810*.25*2.96*10^{-3}}{6.6^2} = 13.7\frac{\mu Sv}{week}$$

Similarly for 6 MV:

$$B_x(6MV) = 10^{-\left\{1+\left(\frac{t-TVL_1}{TVL_e}\right)\right\}} = 10^{-\left\{1+\frac{88-34}{29}\right\}} = 1.37*10^{-3}$$

Then the dose equivalent is

$$H_{LT}(6MV) = \frac{L_f WUB}{d_L^2} = \frac{10^{-3}*780*.25*1.37*10^{-3}}{6.6^2} = 6.15\frac{\mu Sv}{week}$$

Total dose equivalent at the wall due to leakage through the inner maze wall is 13.7 + 6.15 = 20µSv/week.

The fraction of the primary radiation transmitted through the patient is represented by f and is assumed to be 0.34 for a high energy Linac. When use factors are employed for dose equivalent considerations, the total is not 4*H_{tot}. It is estimated as 2.64*H_{tot} (McGinley, 2002).The total dose equivalent due to scatter and leakage radiations, H_{tot} is then:

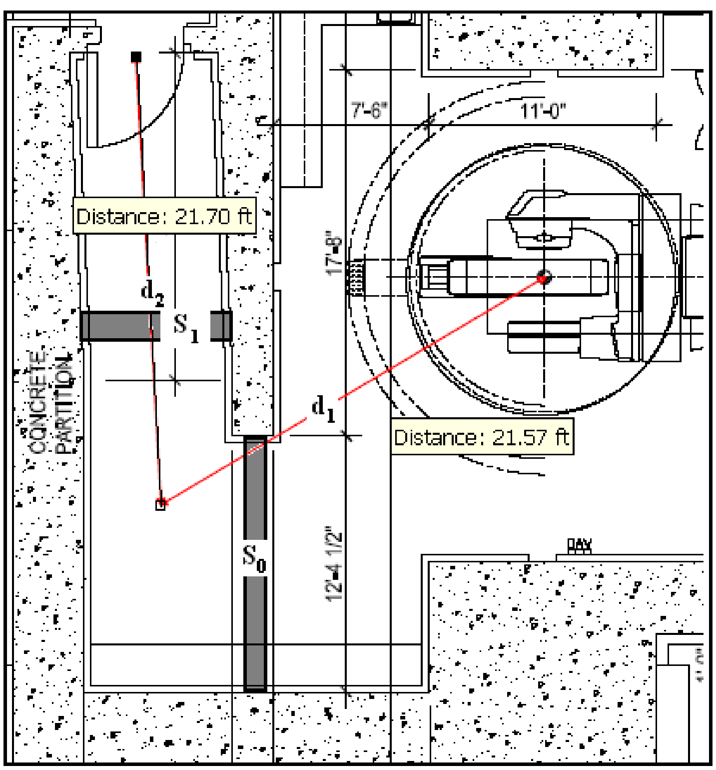
$$H_{tot} = 2.64 * H_d = 2.64\left(fH_s + H_{LS} + H_{PS} + H_{LT} \right) = 2.64 * \left(6.01 + 5.67 + 116 + 20\right) = 389 \frac{\mu Sv}{week}$$

- *Neutron Capture Gamma-Ray Dose Equivalent at Maze Door*

Photoneutron production and neutron capture is proportional to the leakage radiation workload of high-energy x-rays (18 MV).

First, the area of the room must be known.
Average ceiling height = 14´= 4.27m
Average room length = 23.8´= 7.25m
Average room width = 25.5´ = 7.77m

$$S_r = 2 * \{(4.27 * 7.25) + (4.27 * 7.77) + (7.77 * 7.25)\} = 241 m^2$$



- *Total neutron fluence per isocenter x-ray Gray at inner maze point, Φ_A:*

Qn = neutron source strength in neutrons emitted from the accelerator head per gray of x-ray absorbed dose at the isocenter = $1.0*10^{12}$ for a Varian iX model.
d_1 = distance from isocenter to center of maze = 6.57m
β = neutron transmission through linac head = 1 for Lead housing

$$\Phi_A = \frac{\beta Q_n}{4\pi d_1^2} + \frac{5.4\beta Q_n}{2\pi S_r} + \frac{1.3 Q_n}{2\pi S_r} = \frac{1.0*10^{12}}{4\pi * 6.57^2} + \frac{5.4*1.0*10^{12}}{2\pi * 241} + \frac{1.3*1.0*10^{12}}{2\pi * 241} = 6.27*10^9 \frac{neutrons}{m^2}$$

- *Photon Dose Equivalent Calculation at the Maze Door, h_φ:*

K = ration of neutron capture gamma-ray dose equivalent to the total neutron fluence = $6.9*10^{-16}$ Sv/m^2 (NCRP 151)
Φ_A= neutron fluence, found above
d_2=distance along maze = 21.7´= 6.61m
TVD = Tenth Value Distance for photons = 5.4 m for x-rays from 18-25 MV.

$$h_\phi = K\Phi_A 10^{-\left(\frac{d_2}{TVD}\right)} = 6.9*10^{-16} * 6.27*10^9 * 10^{-\left(\frac{6.61}{5.4}\right)} = 2.58*10^{-7} \frac{Sv}{Gy}$$

- *Weekly neutron capture gamma-ray dose equivalent at the door, H_{cg}:*

$$H_{cg} = Wh_\phi = 810 * 2.58*10^{-7} = 2.09*10^{-4} = 209 \frac{\mu Sv}{week}$$

- *Neutron dose equivalent at the door, $H_{n,D}$:*

S_0 = inner maze cross sectional area = 15´10´´ x 12.42´ = 18.31 m^2
S_1 = cross sectional area along maze = 15´10´´ x 7.17´ = 10.58 m^2

The Tenth Value Distance for the Maze will be determined by:

$$TVD = 2.06\sqrt{S_1} = 2.06\sqrt{10.58} = 6.7m$$

The neutron dose equivalent will be calculated by the method of Wu & McGinley (2003):

$$H_{n,D} = 2.4*10^{-15}\Phi_A \sqrt{\frac{S_0}{S_1}}\left[1.64*10^{-\frac{d_2}{1.9}} + 10^{-\frac{d_2}{TVD}}\right] = 2.4*10^{-15} * \left(6.27*10^9\right)\sqrt{\frac{18.31}{10.58}}\left[1.64*10^{-\frac{6.61}{1.9}} + 10^{-\frac{6.61}{6.7}}\right]$$

$$H_{n,D} = 2.05*10^{-6}\frac{Sv}{Gy} = 2.05\frac{\mu Sv}{Gy}$$

The weekly dose equivalent H_n at the door due to neutrons is W* H_n:

$$H_n = WH_{n,D} = 810*2.05 = 1660\frac{\mu Sv}{week}$$

- *Total Dose Equivalent at the Maze Door H_w:*

$$H_w = H_{TOT} + H_{cg} + H_n = 389 + 209 + 1660 = 2258\frac{\mu Sv}{week}$$

- *Shielding Barrier for Maze Door:*

The maze entrance is located in a controlled area and the shielding design goal is 0.1mSv/week. The TVL for scatter and leakage photons, H_{TOT}, varies between 3-6 mm of Pb depending on maze length. The TVL for neutron capture gamma rays, H_{cg}, can be as much as 61 mm of Pb (NCRP, 1984). We will assume the shielding for the neutron capture rays will suffice for the scattered and leakage radiation. We will set 30% of our allowable dose to be from neutrons, and 70% from the capture gammas. We will then have:

$$n(H_n) = \log\left(\frac{1660}{30}\right) = 1.73$$

And

$$n(H_{c,g}) = \log\left(\frac{209}{70}\right) = 0.475$$

The TVL for Borated Polyethylene is 45mm. We then get:

$$t(H_n) = 1.73*45 = 78.8mm = 3.1''BPE$$

The BPE is on the inside of the door, followed by the lead. 3´´ of BPE allows about 77% transmission of capture gamma rays of the equivalence of 7.1mm of Pb. We find we need:

$$t(H_{c,g}) = 0.475*61 = 28.98mmPb \Rightarrow 28.98 - 7.1 = 21.88mmPb = 0.86''Pb$$

This calculation neglects the steel casing on the door, which is ¼´´ on each side for a total of ½´´ of steel. The TVL of steel is 0.108m (McGinley) or 4.25´´. The amount of radiation that is attenuated by this is:

$$\%_{attenuated} = 1 - \left(10^{-\frac{.t}{TVL}}\right) = 1 - \left(10^{-\frac{.50}{4.25}}\right) = 23.7\%$$

Our allowed dose through the door was 0.1mSv, 70% of which are capture gammas that are also attenuated by the steel. Therefore, we have overshielded the door by:

$$H = 0.1mSv * 0.70 * .237 = .0166mSv = 16.6\mu Sv$$

This dose is the extra allowable dose that will added to point E.