Radiation Shielding

Radiation Therapy I

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Use NCRP (National Council on Radiation Protection) Report 151

- Supersedes NCRP Report No. 49 and No.51
- Dual energy machines (max energy in No. 49 was 10 MV)
- Deals with production of neutrons (replaces NCRP Report No. 79)
- Composite materials for barriers
- New treatment techniques (ex. IMRT and TBI)

Quantities and Units

- Dose equivalent (Sv)

$$H = QD$$

$$[Sv] = [Gy]$$

Q	LET (H_2O) (keV/μm)	Type of Radiation
1	≤3.5	photons and electrons
2-5	7-23	protons, neutrons
10	53	α particles

What's
WUT ?

Workload

- W = dose to iso (Gy m^2/week)

Low energy	High energy	
1000 Gy/wk		NCRP No. 49
	500 Gy/wk	NCRP # 51
< 350 Gy/week	< 250Gy/wk	Kleck and Elsalim (1994)
450 Gy/wk	400 Gy/wk	Meckalakos et al (2004)

$$WU]_{pri} = WU]_{wall\ scat} = W_{conv}U_{conv} + W_{TBI}U_{TBI} + W_{IMRT}U_{IMRT} + W_{QA}U_{QA} + \cdots$$

$$W]_{pat\ scat_{iso}} = W_{conv} + W_{IMRT} + W_{QA} + \cdots$$

$$\underline{W}_L = \underline{W}_{conv} + \underline{W}_{TBI} + \underline{C}_I\,\underline{W}_{IMRT} + \underline{C}_{QA}\,\underline{W}_{QA} + \cdots$$

IMRT Factor

- IMRT requires more MUs
- Leakage radiation increases
- IMRT factor is the ratio of average MU for IMRT (MU_{IMRT}) and the MUs for conventional treatment (MU_{conv})
- Take sample of IMRT cases, calculate average total MU to deliver prescribed dose per Fx for each case, sum all the cases to give MU_{IMRT}
- Calculate MU required to deliver same dose per Fx at 10 cm depth, 100 cm SAD using 10 x 10 field size to obtain MU_{conv}

$$\underline{MU}_{IMRT} = \Sigma_i \, \underline{MU}_i \, / \, (\underline{D}_{pre})_i$$

$$\underline{C}_I = \frac{\underline{MU}_{IMRT}}{\underline{MU}_{conv}}$$

$C_I \sim 2 - 10$

TBI Factor

- W_{TBI} (cGy/week at iso) significantly higher than conventional RT because of extended distance
- Leakage also higher
- W_{TBI} is product of the weekly total TBI dose to patient and square of treatment distance in meters

$$\underline{W}_{TBI} = \underline{D}_{TBI}\, \underline{d}_{TBI}^{\,2}$$

Weekly workload without TBI ~ 45,000 cGy m^2/wk

One TBI per/week ~1,200 cGy m^2/wk

W_{TBI}=1,200 cGy m^2/wk * $(3m)^2$ = 10,800 cGy/wk

U_{TBI}=10,800/45,000 = 0.24

Use Factor

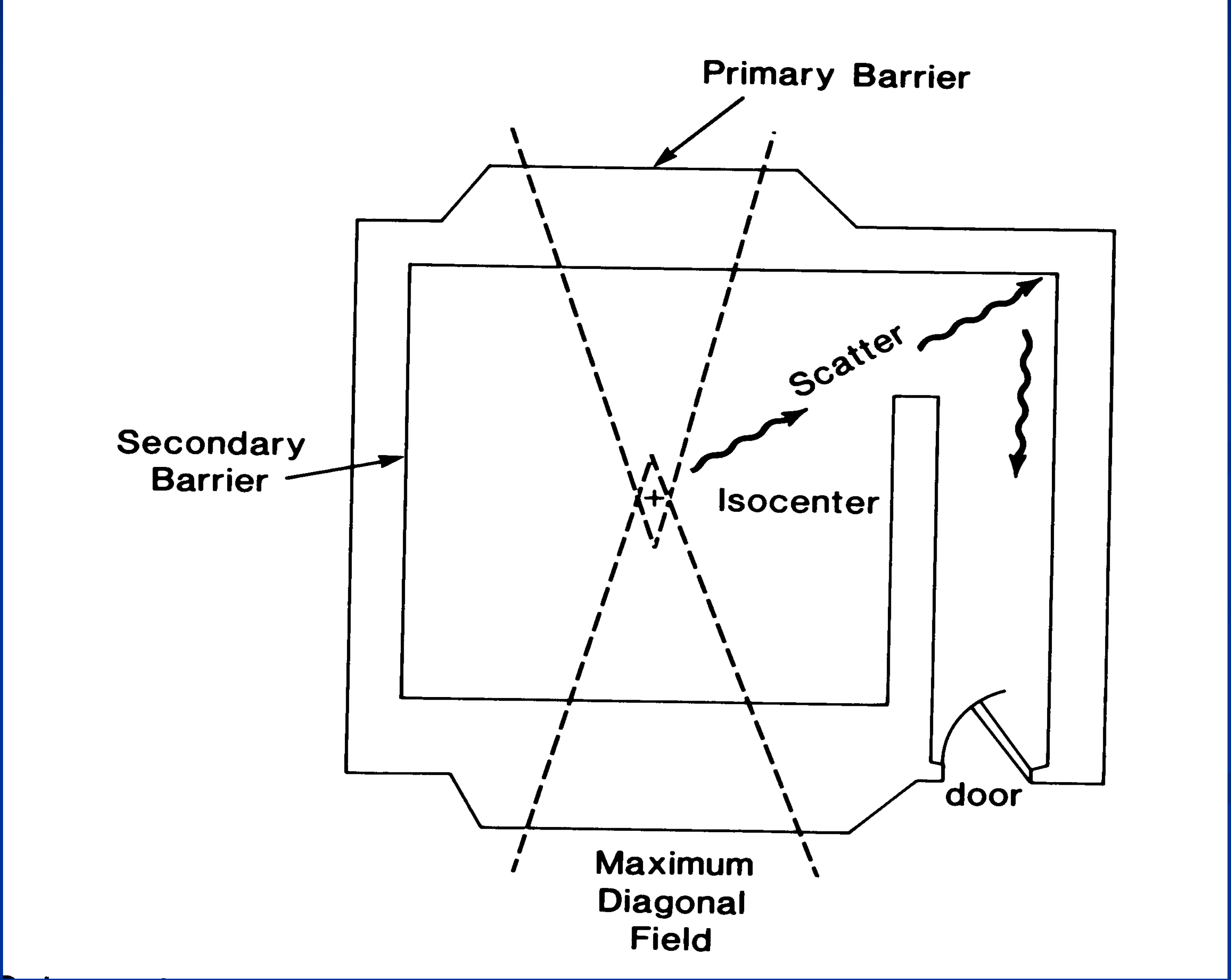
- U = fraction of primary beam workload directed toward barrier
- Breakdown important for specific facility depending on tx types (ex. tangent breast)

TABLE 3.1—*High-energy (dual x-ray mode) use-factor distribution at 90 and 45 degree gantry angle intervals.*[a]

Angle Interval Center	U (%)
90 degree interval	
0 degree (down)	31.0
90 and 270 degrees	21.3 (each)
180 degrees (up)	26.3
45 degree interval	
0 degree (down)	25.6
45 and 315 degrees	5.8 (each)
90 and 270 degrees	15.9 (each)
135 and 225 degrees	4.0 (each)
180 degrees (up)	23

[a]Rodgers, J.E. (2001). Personal communication (Georgetown University, Washington). Unpublished reanalysis of the survey data in Kleck and Elsalim (1994).

Basic Primary and Scatter Beam



Occupancy Factor

- T = avg fraction of time person is exposed

TABLE B.1—*Suggested occupancy factors*[a] *(for use as a guide in planning shielding when other sources of occupancy data are not available).*

Location	Occupancy Factor (T)
Full occupancy areas (areas occupied full-time by an individual), *e.g.*, administrative or clerical offices; 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 vault	1/2
Corridors, employee lounges, staff rest rooms	1/5
Treatment vault doors[b]	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

[a]When using a low occupancy factor for a room immediately adjacent to a therapy treatment vault, care *shall* be taken to also consider the areas further removed from the treatment room. The adjacent room may have a significantly higher occupancy factor and may therefore be more important in shielding design despite the larger distances involved.

[b]The occupancy factor for the area just outside a treatment vault door can often be assumed to be lower than the occupancy factor for the work space from which it opens.

Distance (d)

- Primary (d): Distance from Source to Barrier.
- Secondary (d_1, d_2, etc,): Distance from Source of Scatter to Barrier.
- Leakage (d): Distance from Source to Barrier.

- Inverse Square Law Assumed in all Cases.

Shielding Design Goals

- Controlled Areas
  - Limited access area where occupational dose of employees is controlled (ex. operator station)
  - Report recommends max dose level for controlled areas to:
    - 5 mSv/yr or 0.1 mSv/week

Shielding Design Goals

- Uncontrolled Areas
  - Areas occupied by pts, visitors, non-radiation workers
  - Report recommends max dose level for uncontrolled areas to:
    - 1 mSv/yr or 0.02 mSv/week
  - Limit based on NCRP recommendation for annual limit of effective dose to public

Regulatory Mandates

- Following the mandates of the NRC 10CFR20, the maximum permissible exposure levels are as follows:
- (a) The maximum annual occupational exposure, according to ALARA principles will be 500 mrem, or 0.1 mSv per week.
- (b) The maximum annual non-occupational exposure will be 100 mrem, or 0.02 mSv per week.
- (c) The dose to any unrestricted area will be no more than 2 mrem in any one hour.

Permissible Dose (P) and Transmission Factor (B)

- P = Maximum Permissible Dose Allowed to the Area to be Protected.
  - P = 100 mr/wk for Controlled Area
  - P = 2 mr/wk for Non-Controlled Area

- B = Required Transmission Factor to Reduce Dose to Barrier Area.

NCRP 91 Recommendations

A. Occupational exposures (annual)		
1. Effective dose equivalent limit (stochastic effects)	50 mSv	(5 rem)
2. Dose equivalent limits for tissues and organs (nonstochastic effects)		
a. Lens of eye	150 mSv	(15 rem)
b. All others (e.g., red bone marrow, breast, lung, gonads, skin and extremities)	500 mSv	(50 rem)
3. Guidance: cumulative exposure	10 mSv × age	(1 rem × age in years)
B. Planned special occupational exposure, effective dose equivalent limit	see Section 15*	
C. Guidance for emergency occupational exposure	See Section 16*	
D. Public exposures (annual)		
1. Effective dose equivalent limit, continuous or frequent exposure	1 mSv	(0.1 rem)
2. Effective dose equivalent limit, infrequent exposure	5 mSv	(0.5 rem)
3. Remedial action recommended when:		
a. Effective dose equivalent	>5 mSv	(>0.5 rem)
b. Exposure to radon and its decay products	>0.007 Jhm^{-3}	(>2 WLM)
4. Dose equivalent limits for lens of eye, skin and extremities	50 mSv	(5 rem)
E. Education and training exposures (annual)		
1. Effective dose equivalent	1 mSv	(0.1 rem)
2. Dose equivalent limit for lens of eye, skin and extremities	50 mSv	(5 rem)
F. Embryo-fetus exposures		
1. Total dose equivalent limit	5 mSv	(0.5 rem)
2. Dose equivalent limit in a month	0.5 mSv	(0.05 rem)
G. Negligible Individual Risk Level (annual) Effective dose equivalent per source or practice	0.01 mSv	(0.001 rem)

Primary Radiation Barrier

- P = Un-Absorbed Dose to Barrier
- B = Transmission required to reduce dose to Allowed Values

$$P = \frac{WUT}{d^2} \bullet B, \quad \therefore$$

$$\mathrm{B} = \frac{\mathrm{P} \bullet \mathrm{d}^2}{WUT}$$

Calculation Methods

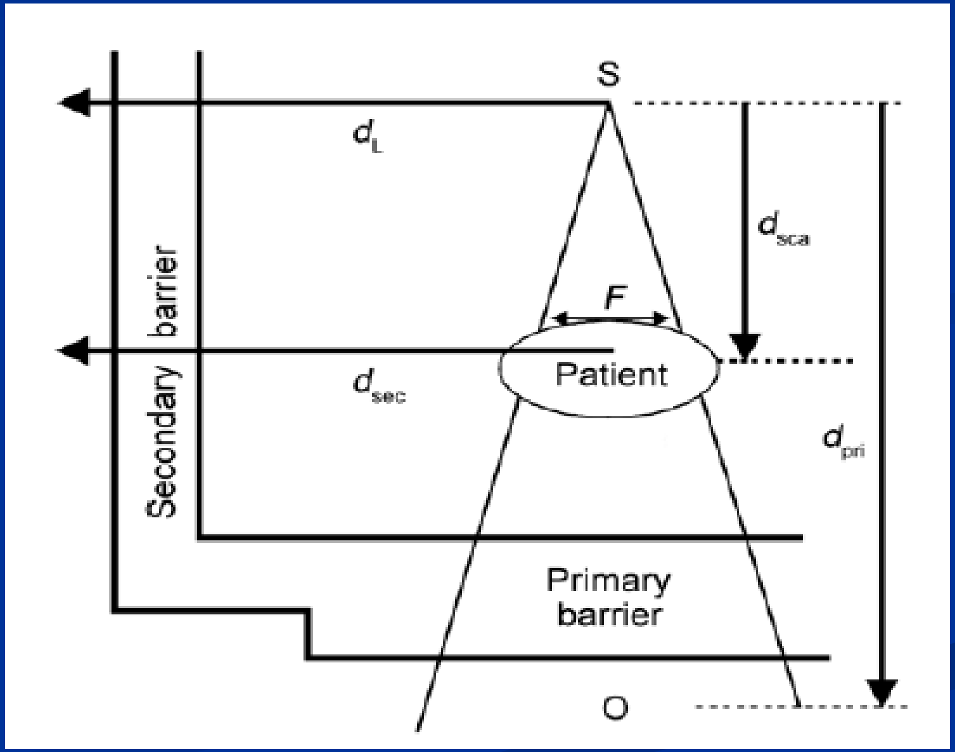
- Primary Barriers

$$n = -\log\left(B_{pri}\right)$$

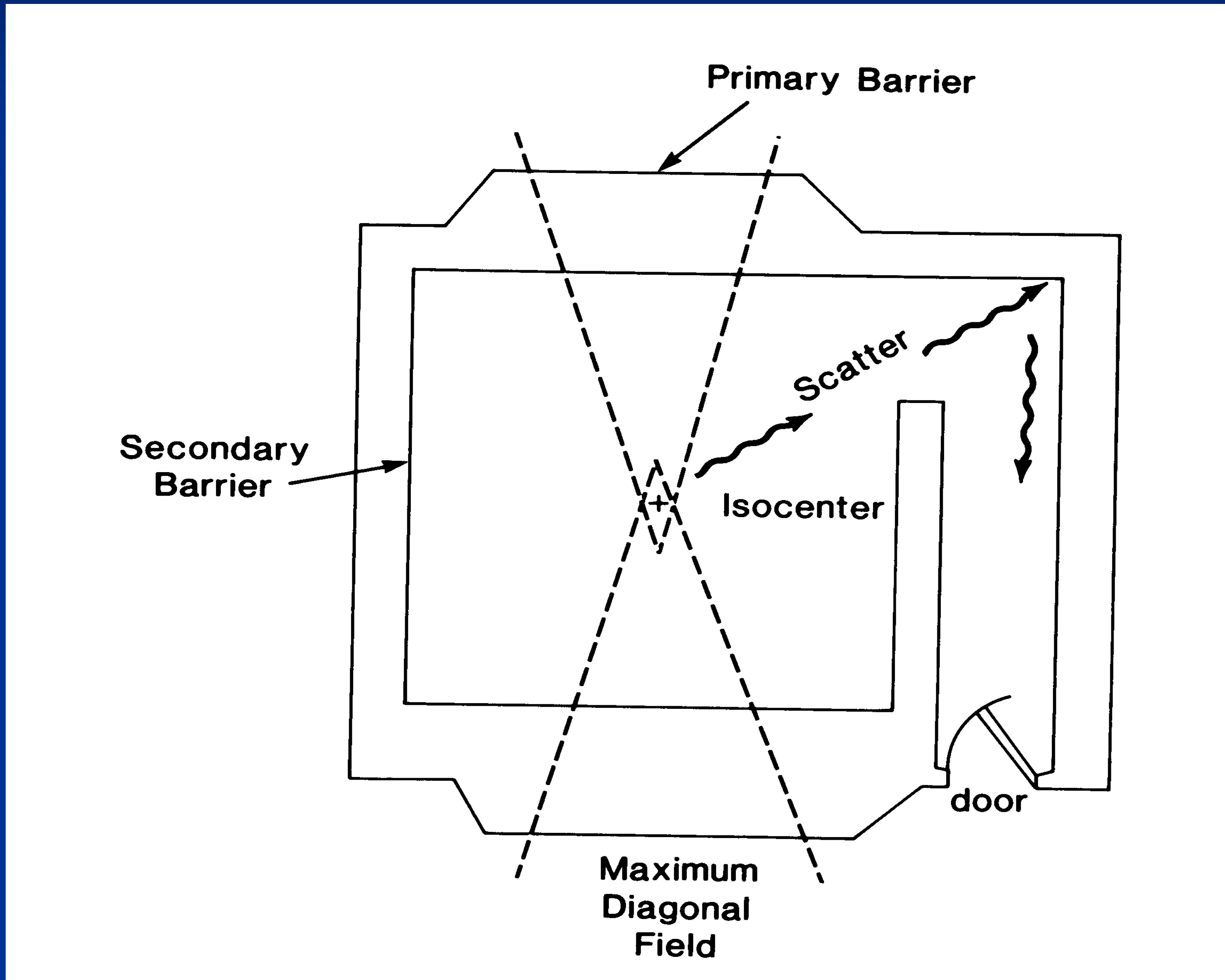
$$t_{\text{barrier}} = \text{TVL}_1 + \left(n-1\right)\text{TVL}_e$$

TVL_1 = first TVL

TVL_e = equilbrium TVL layer



Basic Primary and Scatter Beam



Calculation Methods

- Secondary Barriers (scatter and leakage)

$$B_{ps} = \frac{P}{aW_{ps}T} d_{sca}^2 d_{sec}^2 \frac{400cm^2}{F}$$

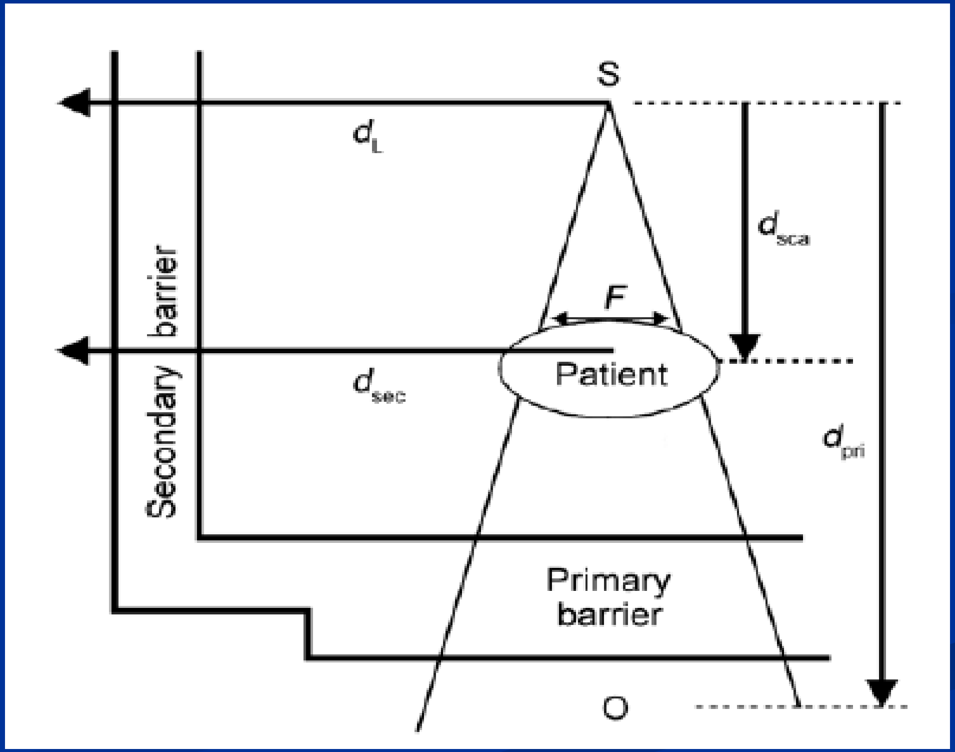
$$B_L = \frac{1,000Pd_L^2}{W_L T}$$

d_{sca} = distance from the x-ray target to the patient or scattering surface (meters)
d_{sec} = distance from the scattering object to the point protected (meters)
a = scatter fraction or fraction of the primary-beam absorbed dose that scatters from the patient at a particular angle (see Table B.4 in Appendix B)
F = field area at mid-depth of the patient at 1 m (cm^2)

$$n = -\log(B)$$

$$t_{sca} = n\mathrm{TVL}_{1_{sca}}$$

$$t_L = TVL_{1_L} + (n-1)TVL_{e_L}$$



α: Ratio of scatter to incident

TABLE B-2 – *Ratio, a, of scattered to incident exposure*[a]

Source	Scattering Angle (from Central Ray)					
	30	45	60	90	120	135
X Rays						
50 kV[b]	0.0005	0.0002	0.00025	0.00035	0.0008	0.0010
70 kV[b]	0.00065	0.00035	0.00035	0.0005	0.0010	0.0013
100 kV[b]	0.0015	0.0012	0.0012	0.0013	0.0020	0.0022
125 kV[b]	0.0018	0.0015	0.0015	0.0015	0.0023	0.0025
150 kV[b]	0.0020	0.0016	0.0016	0.0016	0.0024	0.0026
200 kV[b]	0.0024	0.0020	0.0019	0.0019	0.0027	0.0028
250 kV[b]	0.0025	0.0021	0.0019	0.0019	0.0027	0.0028
300 kV[b]	0.0026	0.0022	0.0020	0.0019	0.0026	0.0028
4 MV[c]	–	0.0027	–	–	–	–
6 MV[d]	0.007	0.0018	0.0011	0.0006	–	0.0004
Gamma Rays						
^{137}Cs[e]	0.0065	0.0050	0.0041	0.0028	–	0.0019
^{60}Co[f]	0.0060	0.0036	0.0023	0.0009	–	0.0006

Barrier Cross-Considerations

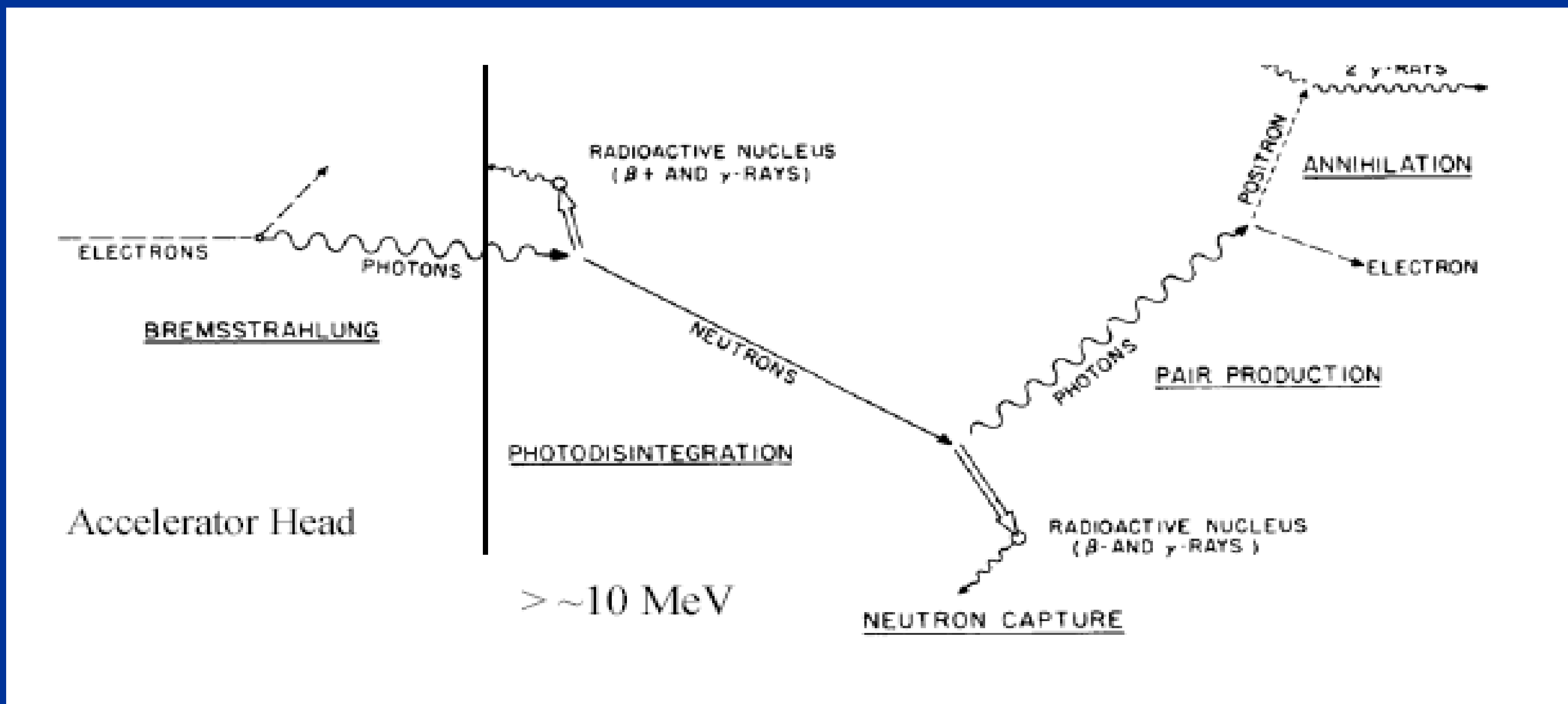
- Primary Barrier is adequate for Secondary Radiation.
- Leakage Barriers Usually Exceed Scatter Barriers. (higher energy)
- If the Barriers differ > 3 HVL, Thicker Shield is adequate.
- If they differ by < 3 HVL, 1 HVL is Added.

Shielding for Neutrons

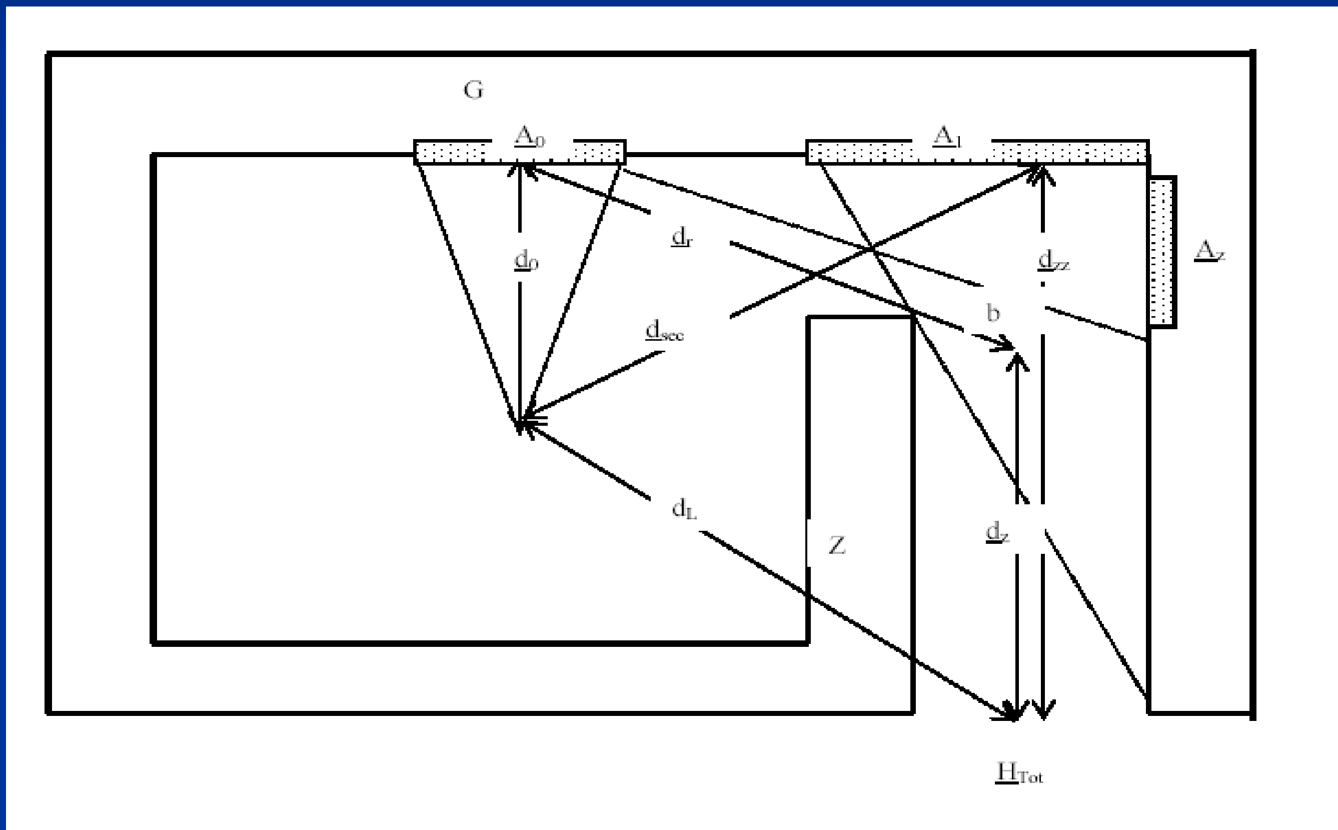
- Energies > 10 MV introduce neutrons due to hv, e- interaction with target, flat. Filter, collimators, etc. (Mainly copper activation)
- This is a small component of the total beam, 0.5% in-field, 1.0% out.
- Concrete within the walls is hydrogenous enough to absorb neutrons.

Doors and Mazes

- Low-Energy Accelerators (≤ 10 MV)
- High-Energy Accelerators (>10 MV)



Doors and Mazes (≤ 10 MV)



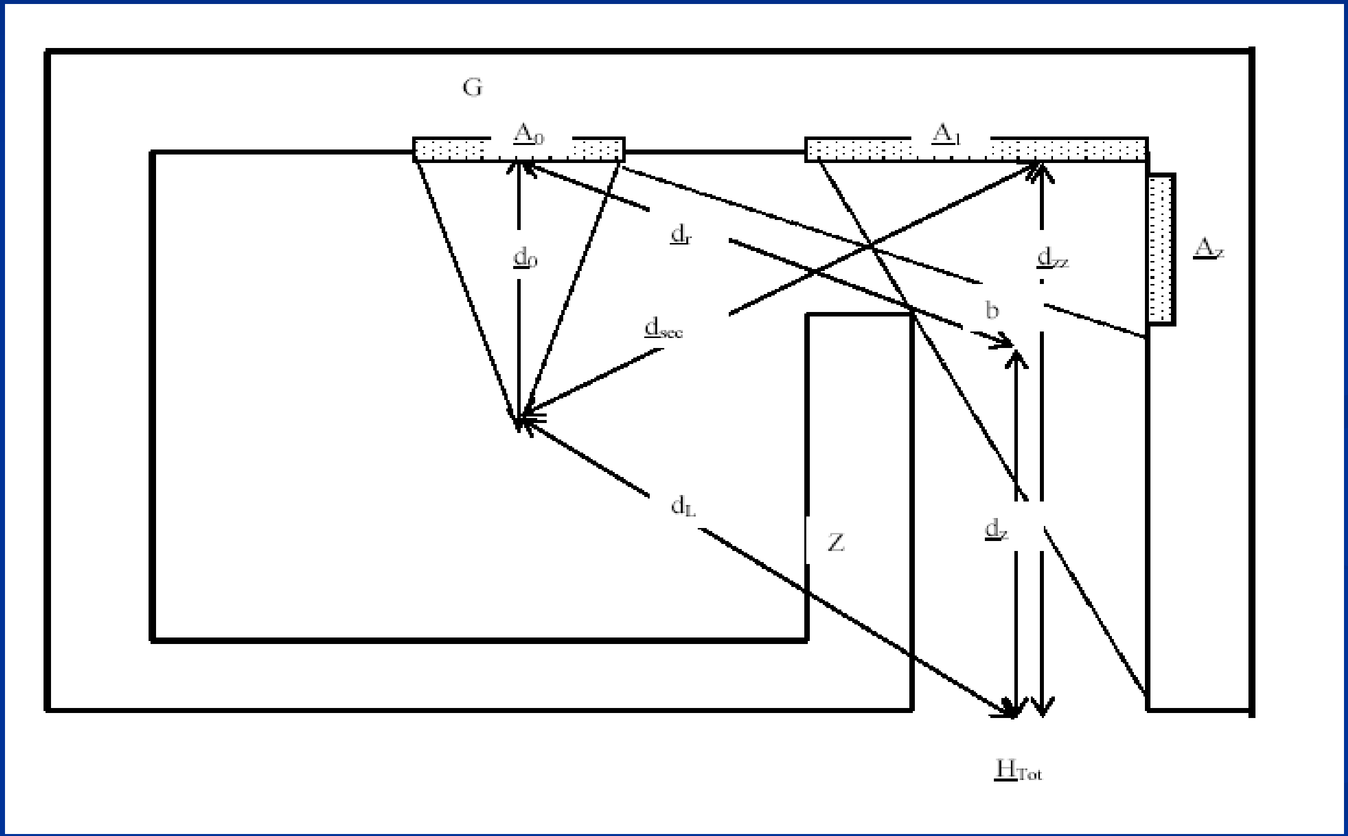
H_s = scatter dose

H_L = head-leakage dose

H_{ps}=patient scatter

H_{LT}=leakage transmitted

Doors and Mazes (≤ 10 MV)



$$H_s = \frac{W U_G \alpha_0 A_0 \alpha_z A_z}{(d_0 d_r d_z)^2}$$

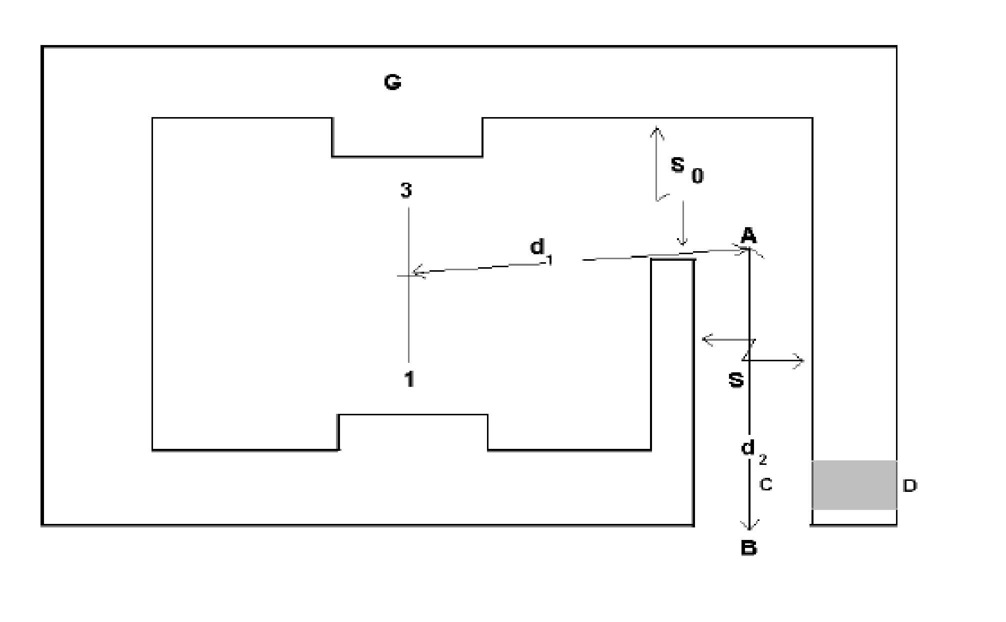
$$H_{LS} = \frac{L_f W_L U_G \alpha_1 A_1}{(d_{sec} d_{zz})^2}$$

$$H_{PS} = \frac{a(\theta) W U_G (F/400) \alpha_1 A_1}{(d_{sca} d_{sec} d_{zz})^2}$$

$$H_{LT} = \frac{L_f W_L U_G B}{(d_L)^2}$$

Doors and Mazes (>10 MV)

Weekly dose equivalent at the door due to neutron capture gamma rays:



$$H_{cg} = W_L \left\{ K\, \varphi_A\, 10^{-\left(\frac{d_2}{TVD}\right)} \right\}$$

K = ratio of the neutron capture gamma-ray dose equivalent (sievert) to the total neutron fluence at Location A in Figure 2.8 (an average value of 6.9×10^{-16} Sv m^2 per unit neutron fluence was found for K based on measurements carried out at 22 accelerator facilities)[10]

φ_A = total neutron fluence (m^{-2}) at Location A per unit absorbed dose (gray) of x rays at the isocenter

d_2 = distance from Location A to the door (meters)

TVD = tenth-value distance[11] having a value of ~5.4 m for x-ray beams in the range of 18 to 25 MV, and a value of ~3.9 m for 15 MV x-ray beams

Shielding for Neutrons

- The door poses a challenge: The maze helps considerably.
- A few inches (2-3) of borated polyethylene will effectively absorb neutrons, but δ rays are produced.
- Therefore, for scattered photons and generated δ rays, lead distal to the poly-ethylene is needed.

Shielding Materials

Shielding Material	Density g/cm^3	Atomic Number	H conc. x 10^{22} (atoms/cm^3)	Relative cost
Ordinary concrete	2.35	11	0.8-2.4	$$
Heavy-density concrete	3.7-4.8	26	0.8-2.4	$$$$
Lead	11.35	82	0	$$$
Steel	7.8	26	0	$$
Borated Polyethylene			8	$$$
Earth	1.5	?		

HVL and TVL Values

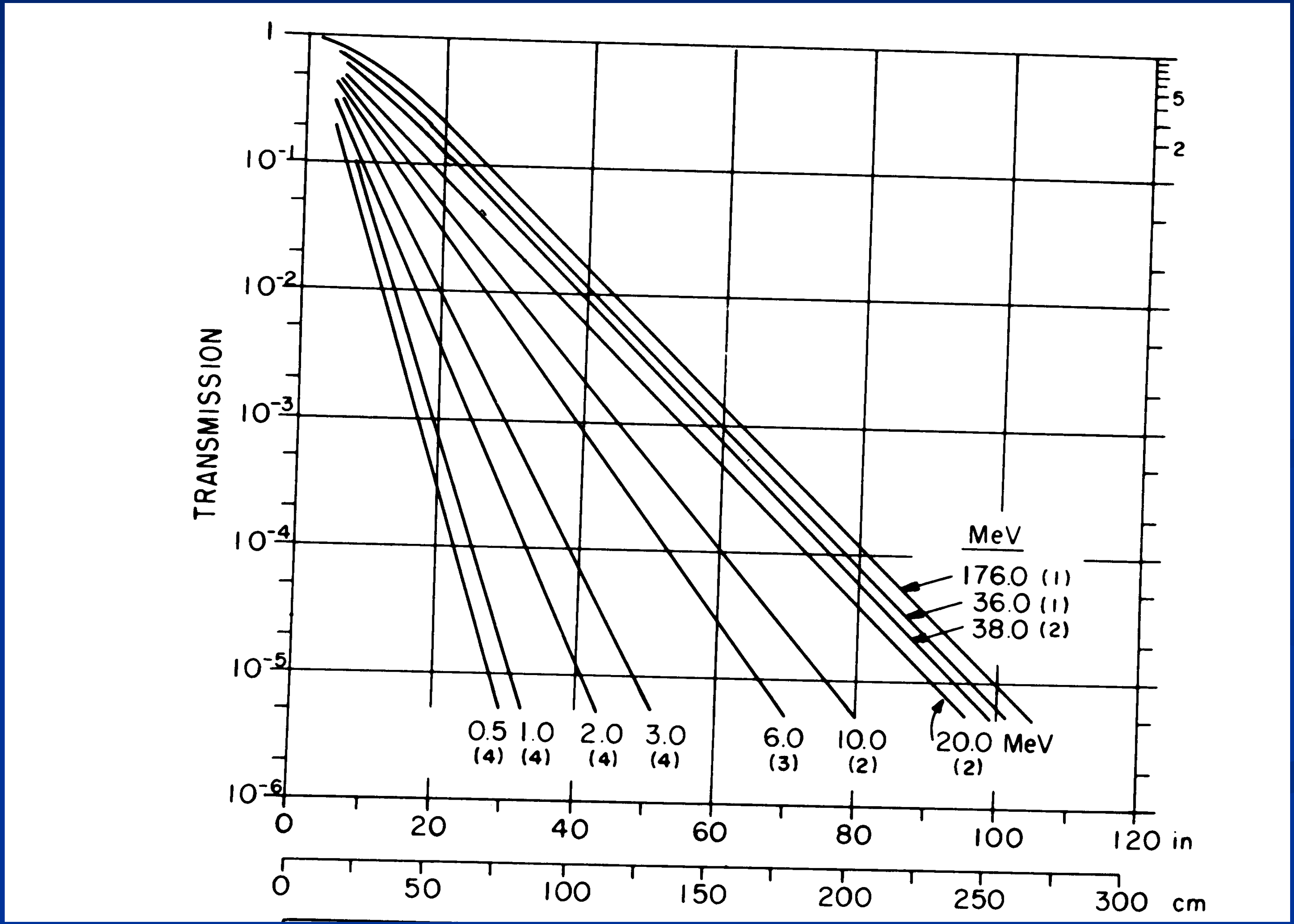
Peak Voltage (kV)	Lead (mm)		Concrete (cm)		Iron (cm)	
	HVL	*TVL*	*HVL*	*TVL*	*HVL*	*TVL*
50	0.06	0.17	0.43	1.5		
70	0.17	0.52	0.84	2.8		
100	0.27	0.88	1.6	5.3		
125	0.28	0.93	2.0	6.6		
150	0.30	0.99	2.24	7.4		
200	0.52	1.7	2.5	8.4		
250	0.88	2.9	2.8	9.4		
300	1.47	4.8	3.1	10.4		
400	2.5	8.3	3.3	10.9		
500	3.6	11.9	3.6	11.7		
1,000	7.9	26	4.4	14.7		
2,000	12.5	42	6.4	21		
3,000	14.5	48.5	7.4	24.5		
4,000	16	53	8.8	29.2	2.7	9.1
6,000	16.9	56	10.4	34.5	3.0	9.9
8,000	16.9	56	11.4	37.8	3.1	10.3
10,000	16.6	55	11.9	39.6	3.2	10.5
Cesium-137	6.5	21.6	4.8	15.7	1.6	5.3
Cobalt-60	12	40	6.2	20.6	2.1	6.9
Radium	16.6	55	6.9	23.4	2.2	7.4

Primary Barrier TVL's (cm)

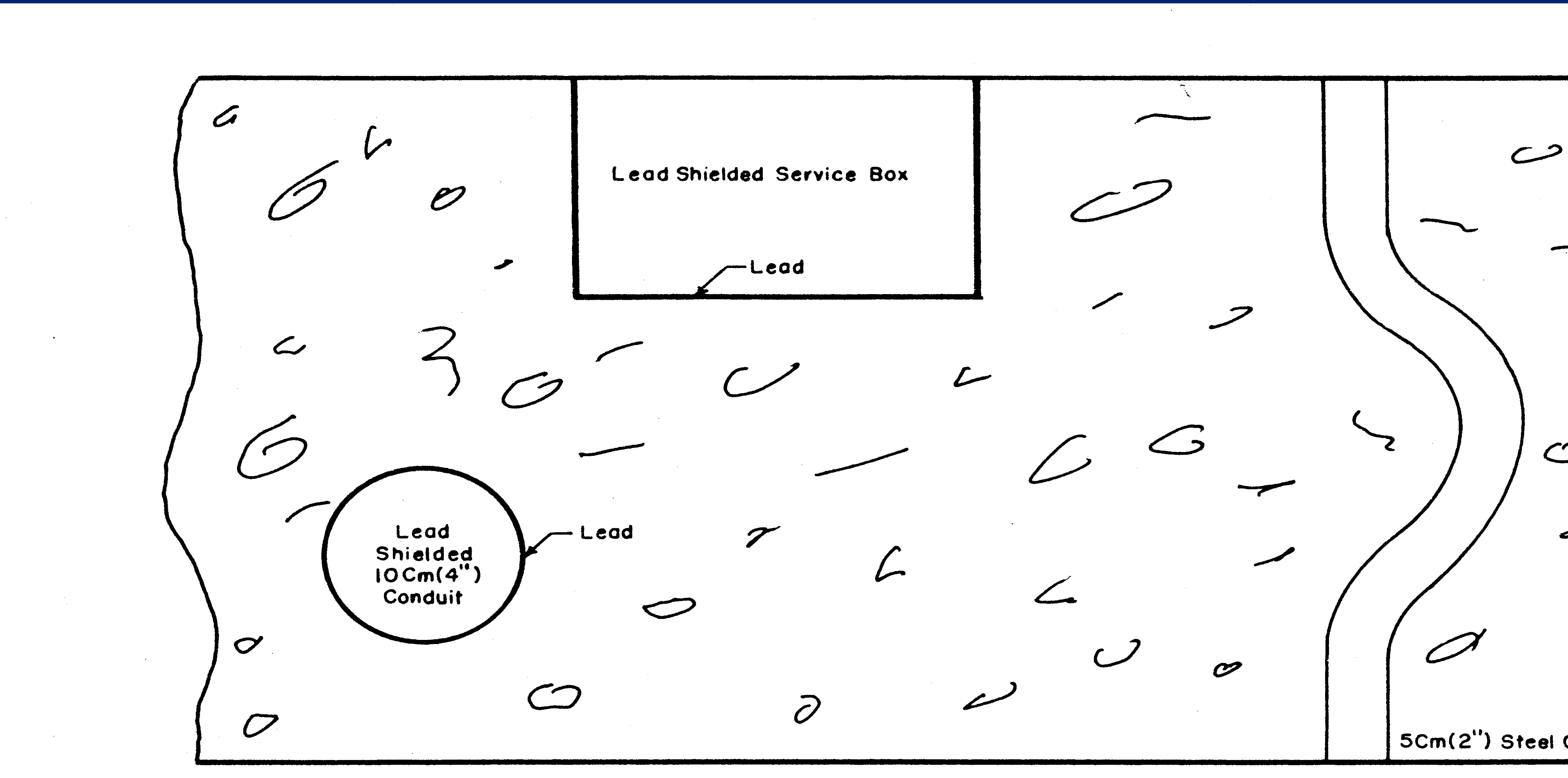
	Co-60	6 MV	10 MV	18 MV
Concrete	21/18	37/33	41/37	45/43
Steel	6/5	10/10	11/11	11/11
Lead	4/6	5.7/5.7	5.7/5.7	5.7/5.7
Earth	34	50	72	74

$TVL_1/TVL_{effective}$

B (Transmission) vs. Absorber Thickness



Conduit and Void Shielding

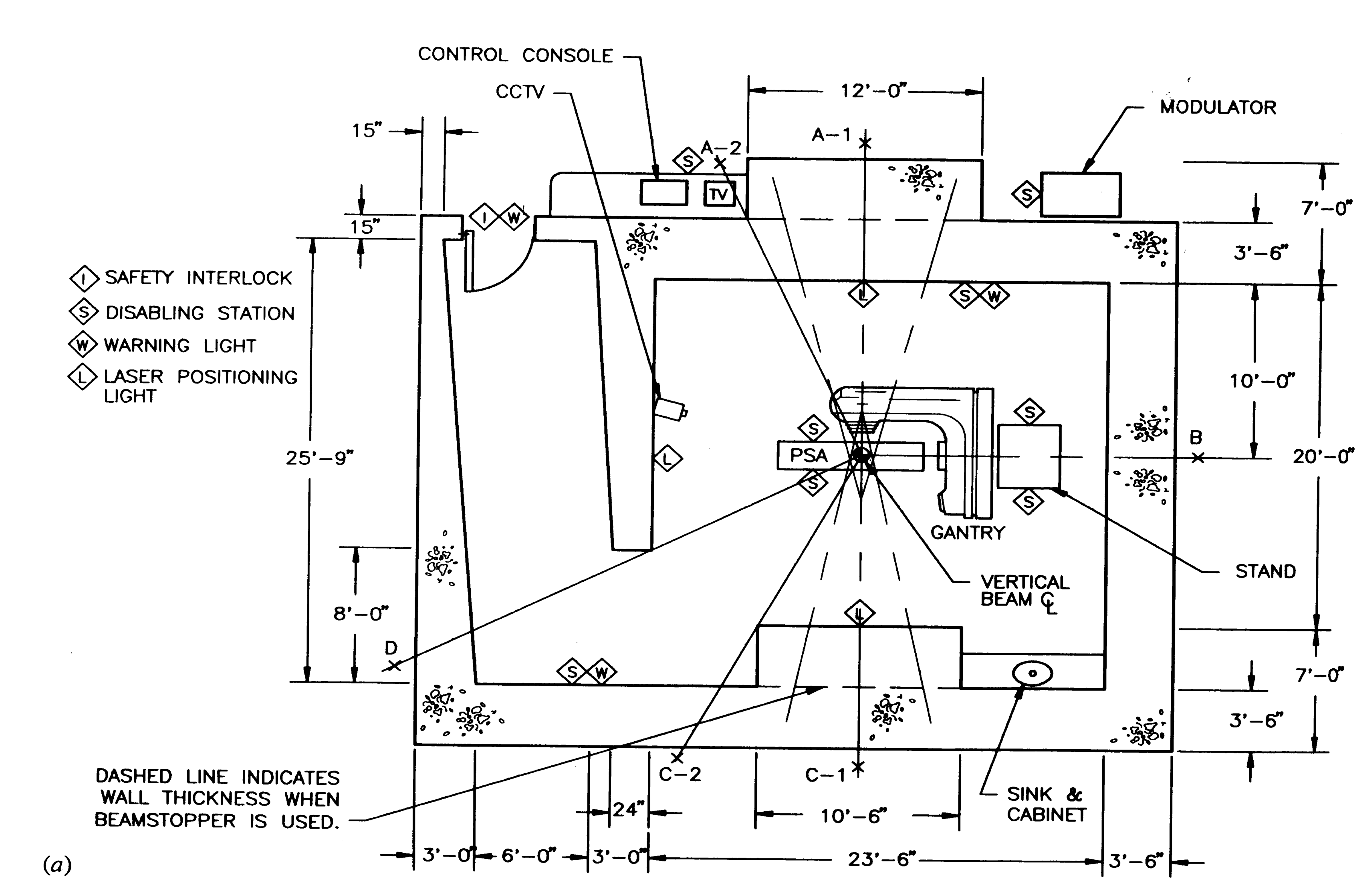


Shielding Design Assumptions

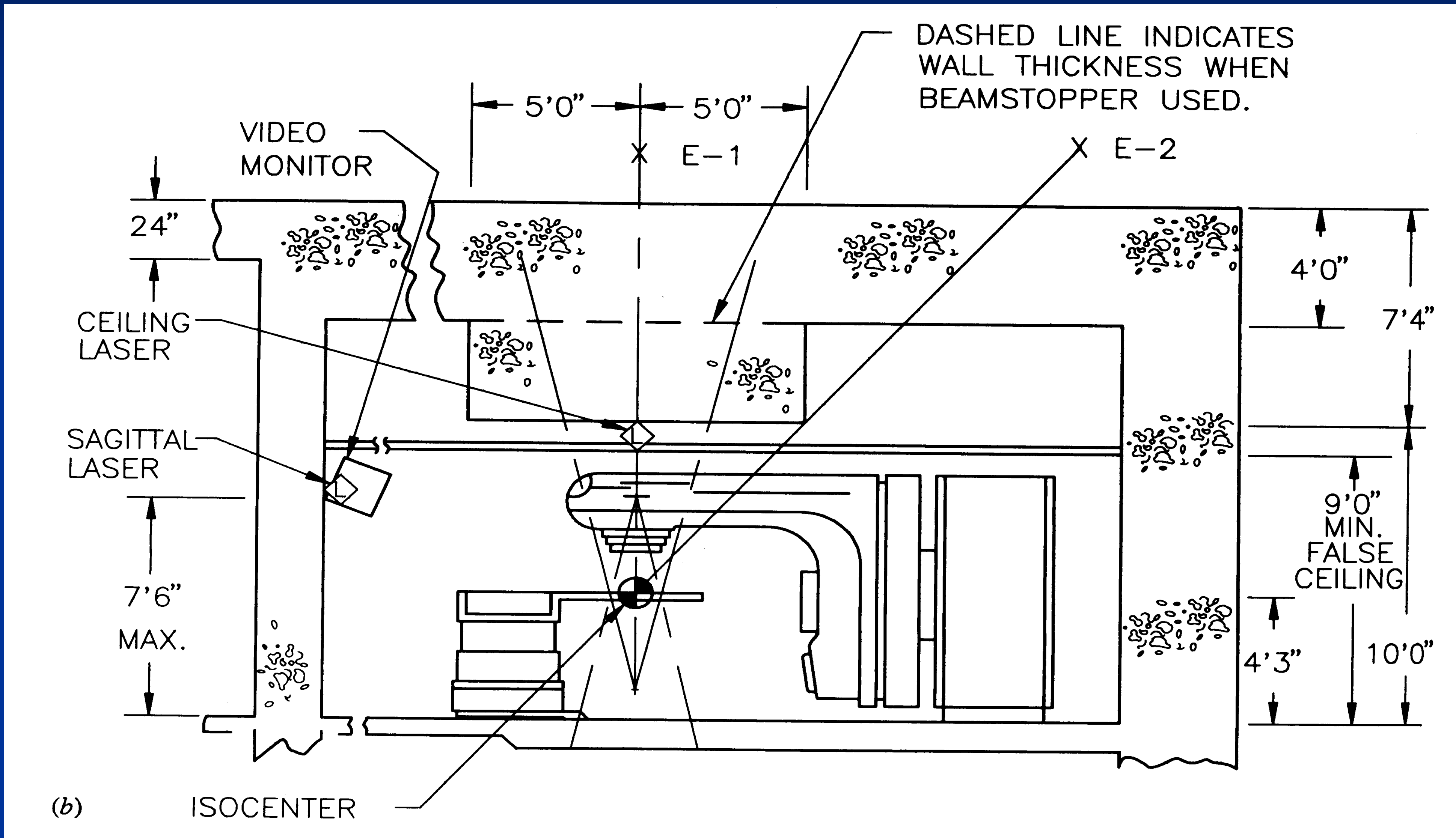
Conservative Assumptions

- Attenuation of primary beam by pt is neglected. Pt attenuates primary beam by 30% or more.
- Calculations of barrier thickness assume perpendicular incidence of radiation
- Leakage radiation from radiotherapy equipment is assumed to be at the maximum value recommended
- Recommended occupancy factors for uncontrolled areas are conservatively high
- The minimum distance to the occupied area from a shielded wall is assumed to be 0.3 m.

Typical Room Design



Typical Room Design



Typical Room Design

Unit	: Clinac 1800	Date	: 15 Oct. 90
Hospital	: 18 MV x rays	Fig No	: 14-2
Primary TVL	: 17.5 in. concrete	Leakage	: 0.001
Leakage TVL	: 13.0 in. concrete	Workload	: 10^8 cGy/wk
1-in. Steel =	4.0 in. concrete	Beamstopper	
1-in. Lead =	8.0 in. concrete	Yes ______	No ✓

Wall	U	Dist {ft}	P/L[b]	TVL[a] required	concrete[a] required	concrete[a] used	mR week
A-1	1/4	21.5	P	4.8	84	84	10
A-2	1	18	L	2.5	33	42	2
B	1	18	L	2.5	33	42	2
C-1	1/4	21.5	P	4.8	84	84	10
C-2	1	20	L	2.43	31.6	42	2
D	1	27	L	2.2	28.5	33	5
E-1	1/4	17.5	P	4.9	87	88	10
E-2	1/4	18	L	2.5	33	48	1

[a]TVL and inches of concrete required for 10 mR/week for occupancy factor T = 1.0.
[b]P-primary beam, L-leakage beam

Example

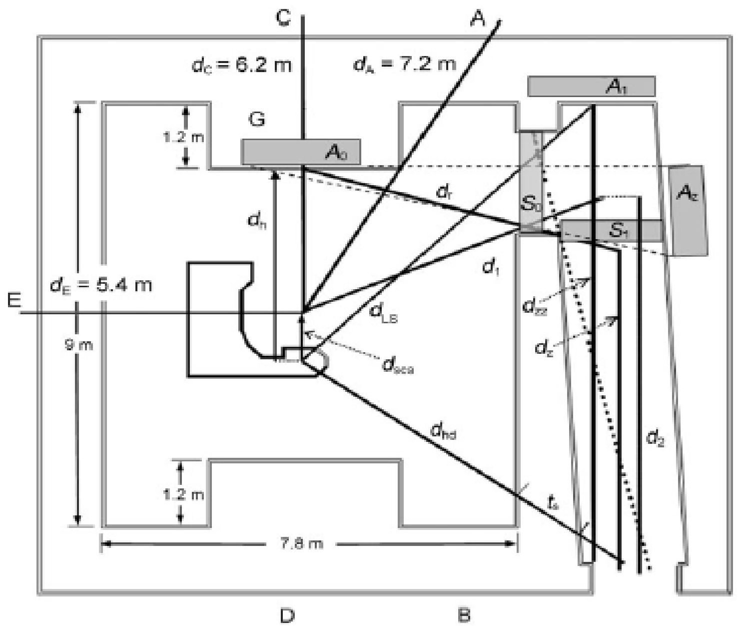


Fig. 7.1. Example for a dual-energy linear accelerator room with maze barrier.

$$B_{pri} = \frac{Pd_{pri}^2}{[WU]_{pri}T}$$

$$n = -\log\left(B_{pri}\right)$$

$$t_{\text{barrier}} = \text{TVL}_1 + (n-1)\text{TVL}_e$$

- Primary Barrier at D (tx control area)
- P=5 mSv/yr (0.1 mSv/wk)
- d_D=6.2m (iso to 0.3m beyond barrier), d_{prim}=7.2m
- W(18MV)=450 Gy m^2/wk
- W(6MV)=225 Gy m^2/wk
- U=0.25
- T=1
- B_{pri}(18 MV)=4.61×10^{-5}
- n=4.34
- $t_{barrier}$=47 cm + (4.34-1)43 cm=191 cm

Example

- Check barrier thickness is adequate for 6 MV primary
- P=0.1 mSv/wk
- $t_{barrier}$=47 cm + (4.34-1)43 cm=191 cm

$$H = \frac{B_{pri}\left[WU\right]_{pri} T}{d^2_{pri}}$$

$$B_{pri} = 10^{-n} = 10^{-\left(1+\left(\frac{t_{barrier} - TVL_1}{TVL_e}\right)\right)}$$

$$H = \frac{10^{-\left(1+\left(\frac{191cm - 37cm}{33cm}\right)\right)} 225 \frac{Gy \cdot m^2}{wk}(0.25)(1)}{(6.2m + 1m)^2} = 2.3x10^{-3}\frac{mSv}{wk}$$

Example

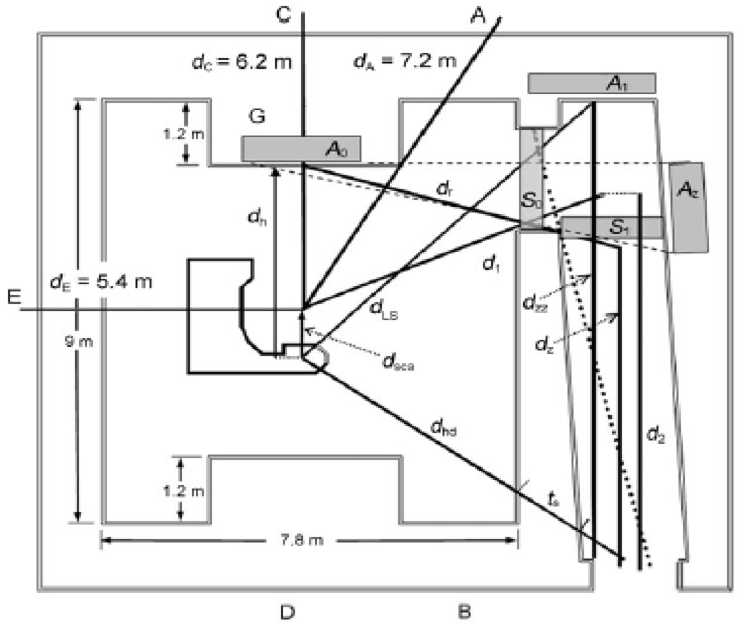


Fig. 7.1. Example for a dual-energy linear accelerator room with maze barrier.

$$B_{ps} = \frac{P}{aW_{ps}T} d_{sca}^2 d_{sec}^2 \frac{400cm^2}{F}$$

$$n = -\log(B)$$

$$t_{sca} = n\mathrm{TVL}_1$$

- Secondary Barrier at B (tx control area)
- Patient Scatter
- P=5 mSv/yr (0.1 mSv/wk)
- d_{sca}=1m
- d_{sec}-=7.2 m
- W(18MV)=450 Gy m^2/wk
- W(6MV)=225 Gy m^2/wk
- U=0.25
- T=1
- α(18MV)=2.53x10^{-3} m^2 (18 MV 30☜ 2.5 cm depth)
- F=40x40cm^2
- B_{ps}(18 MV)=4.55x10^{-3}
- n=2.34
- TVL_{sca}(18 MV)=32 cm concrete (30☜ sca)
- TVL_{sca}(6 MV)=26 cm concrete (30☜ sca)
- t_{sca}(18 MV)=2.34 (32 cm)=75 cm
- t_{sca}(6 MV)=2.08 (26 cm)=54 cm
- t_{sca}=75 cm +log2 (32cm)=85 cm (2 source rule)

Example

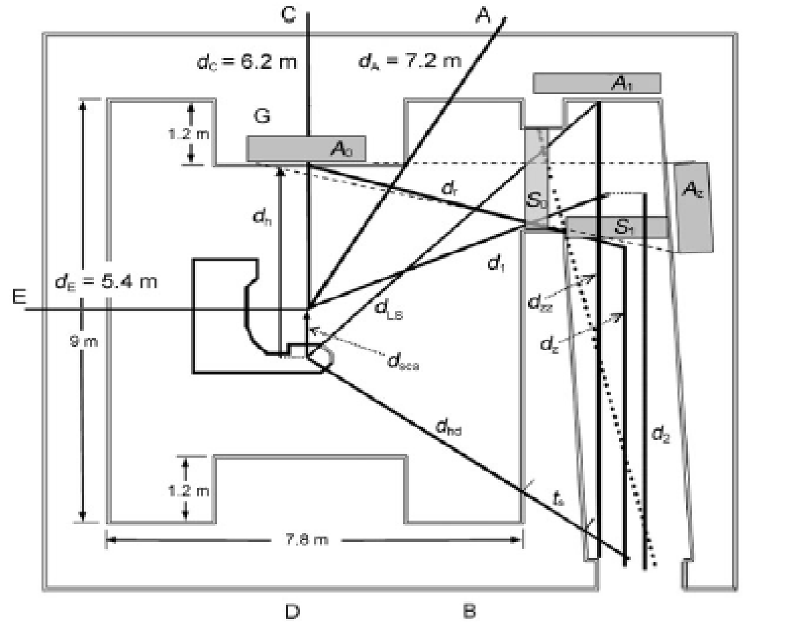


Fig. 7.1. Example for a dual-energy linear accelerator room with maze barrier.

$$B_L = \frac{1,000 P d_L^2}{W_L T}$$

$$n = -\log(B)$$

$$t_L = TVL_1 + (n-1) TVL_e$$

- Secondary Barrier at B (tx control area)
- Leakage
- P=5 mSv/yr (0.1 mSv/wk)
- d_L=7.2 m
- W(18MV)=450 Gy m^2/wk
- W(6MV)=225 Gy m^2/wk
- U=0.25
- T=1
- B_L(18 MV)=1.15×10^{-2}
- n=1.94
- TVL_L(18 MV)=36/34 cm
- TVL_L(6 MV)=34/29 cm
- t_L(18 MV)=36cm+(1-1.94) (34 cm)=68 cm
- t_L(6 MV)=34cm+(1-1.64) (29 cm)=53 cm
- t_L=68 cm +log2 (34 cm)=78 cm (2 source rule)

Example

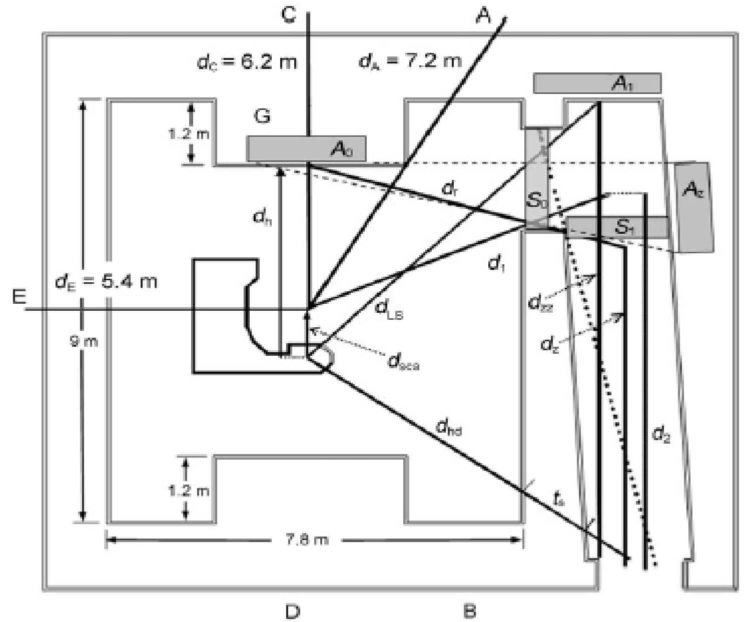


Fig. 7.1. Example for a dual-energy linear accelerator room with maze barrier.

- Secondary Barrier at B (tx control area)
- Patient Scatter + Leakage
- Apply 2 source rule once more
- t_{sca}=85cm
- t_L=78 cm
- t_{Tot}=85+log2 (34 cm)=95 cm

Example

- Check all secondary barrier thicknesses
- P=0.1 mSv/wk
- t_{Tot}=85+log2 (34 cm)=95 cm

Example

- For 18 MV scatter at B

Note: use factor is used in patient scatter

$$H_{ps} = \frac{B_{ps} a W_{ps} U T}{d_{\text{sca}}^2 d_{\text{sec}}^2} \frac{F}{400 cm^2}$$

$$B_{ps} = 10^{-\frac{t_{barrier}}{TVL_{sca}}}$$

$$H_{ps} = \frac{10^{-\left(\frac{95 cm}{32 cm}\right)} \left(2.5x10^{-3} m^2\right)\left(450 \frac{Gy \cdot m^2}{wk}\right)(0.25)(1)}{(1m)^2 (7.2m)^2} \left(\frac{40x40 cm^2}{400 cm^2}\right) = 0.023 \frac{mSv}{wk}$$

Example

- For 18 MV leakage at B

$$H_L = \frac{B_L W_L T}{1{,}000 d_L^2}$$

$$B_L = 10^{-n} = 10^{-\left(1+\left(\frac{t_{barrier} - TVL_{1_L}}{TVL_{e_L}}\right)\right)}$$

$$H_L = \frac{10^{-\left(1+\left(\frac{95cm - 36cm}{34cm}\right)\right)} 450 \frac{Gy \cdot m^2}{wk}(1)}{1{,}000\left(6.2m + 1m\right)^2} = 0.016 \frac{mSv}{wk}$$

Example

- Repeat calc for 6 MV leakage and scatter at B
- 18 MV scatter + leakage = (0.023 +0.016) mSv/wk
- 6 MV scatter + leakage = (0.0027 + 0.0035) mSv/wk
- Total sum=0.045 mSv/wk at B
- Design goal 0.1 mSv/wk

Example

- IMRT modifications
- Leakage-radiation workloads increase with C_I
  - 18 MV 1,170 Gy/wk (factor of 2.6)
  - 6 MV 945 Gy/wk (factor of 4.2)

$$B_L(18MV) = \frac{1{,}000 P d_L^2}{W_L T} = \frac{1{,}000\left(0.1x10^{-3}\frac{Sv}{wk}\right)(7.2m)^2}{\left(1{,}170\frac{Gy \cdot m^2}{wk}\right)(1)} = 4.43x10^{-3}$$

$$n_L(18MV) = \log\left(\frac{1}{4.43x10^{-3}}\right) = 2.35$$

$$t_L(18MV) = 36cm + (1 + 2.35)34cm = 82cm$$

$$B_L(6MV) = 5.49x10^{-3}$$

$$n_L(6MV) = 2.26$$

$$t_L(6MV) = 34cm + (1 + 2.26)29cm = 70.5cm$$

Example

- IMRT modifications
- Leakage-radiation workloads increase with C_I
  - 18 MV 1,170 Gy/wk (factor of 2.6)
  - 6 MV 945 Gy/wk (factor of 4.2)

$$t_L\left(18MV\right) = 36cm + \left(1 + 2.35\right)34cm = 82cm$$
$$t_L\left(6MV\right) = 34cm + \left(1 + 2.26\right)29cm = 70.5cm$$

apply 2 source rule

$$t_L\left(18MV\right) = 82cm + \log 2\left(34cm\right) = 92.2cm$$

recall

$$t_{sca} = 84.5cm$$

apply 2 source rule once more

$$t_{Tot} = 92.2cm + \log 2\left(34cm\right) = 102.4cm$$

Secondary barriers increase from 95 cm to 102.4 cm

Barnes-Jewish West County Hospital (BJWCH): Background

- 40 patients a day in the single linac room
- The treatment room resides on the first floor of the new building, and only one of the walls of the room is attached to the building.
- Below the vault is earth, so no shielding will be required on the floor.
- Nothing is planned to reside above the vault, so a low occupancy on the ceiling is assumed.
- To the south and east of the vault will be parking spaces.

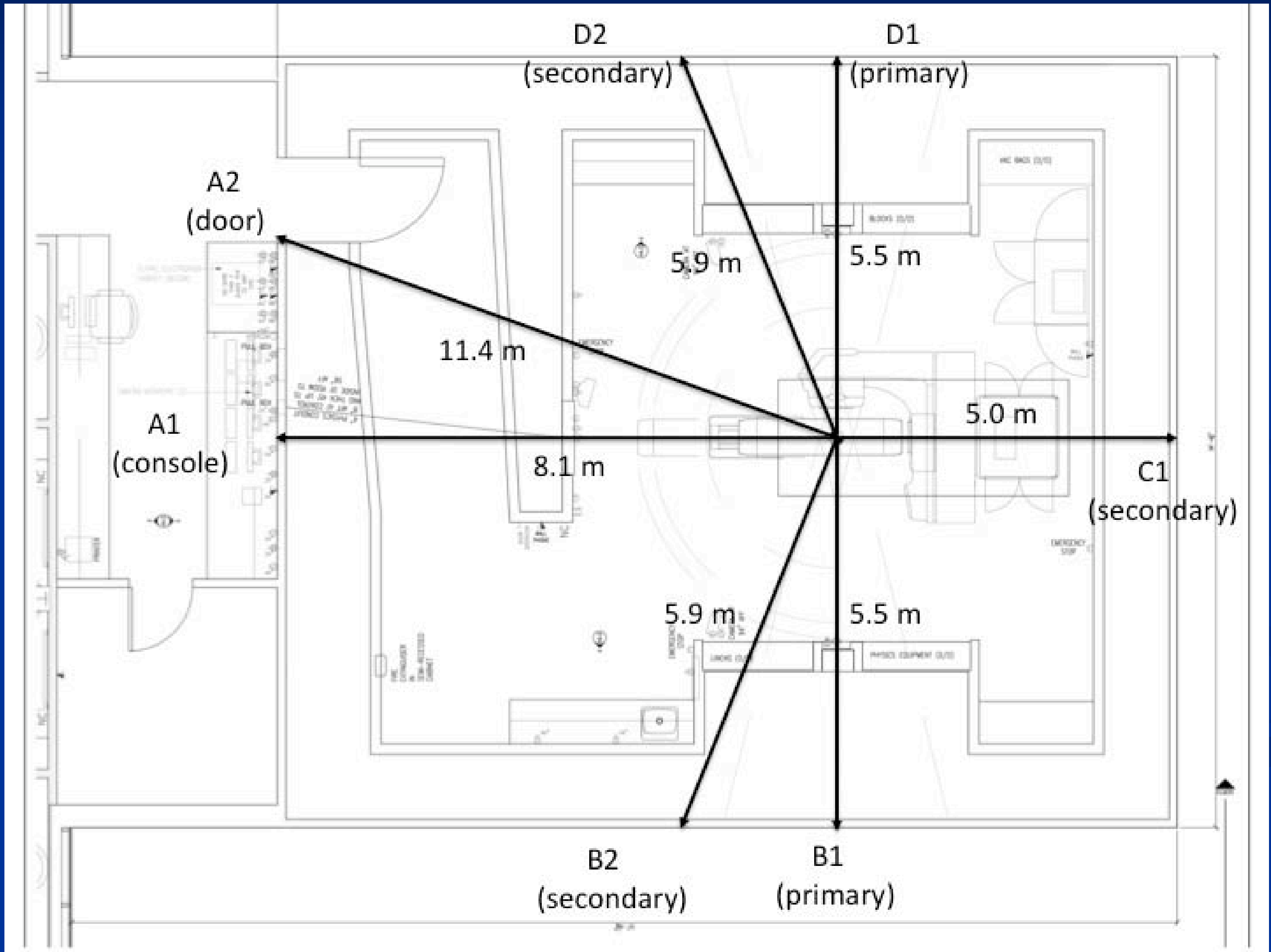
BJWCH: Room Dimensions and Geometry

- The console where the therapists will control the linear accelerator is on the west wall, with the swinging entry door in the northwest corner.

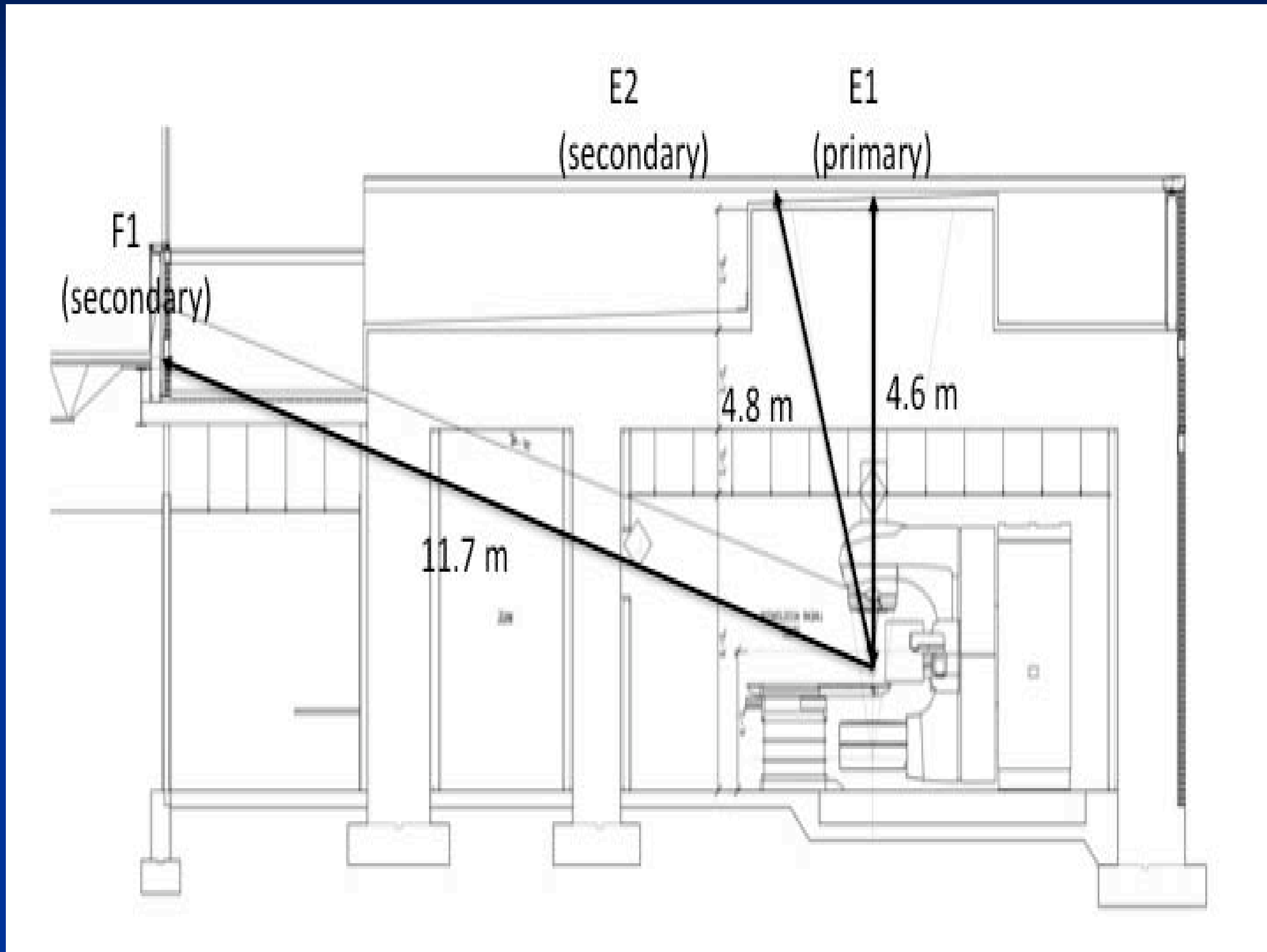
BJWCH: Room Dimensions and Geometry

Barriers	Description	Category	Controlled Area?	Minimum distance (m)
A1	West wall (Console)	secondary	Y	8.10
A2	West entrance (Door)	secondary	Y	7.65
B1	**South wall**	**primary**	**N**	**6.50**
B2	South wall	secondary	N	5.90
C1	East wall	secondary	N	5.00
D1	**North wall**	**primary**	**N**	**6.50**
D2	North wall	secondary	N	5.90
E1	**Ceiling**	**primary**	**N**	**5.60**
E2	Ceiling	secondary	N	4.81
F1	2nd floor diagonal	secondary	N	11.65

BJWCH: Room Dimensions and Geometry



BJWCH: Room Dimensions and Geometry



Workload and Usage Assumptions

- \- A number of factors went into the consideration of the workload of the BJCWC linac facility.
- The clinic is assumed to treat approximately 40 patients per day at capacity, with the average prescription dose being approximately 200 cGy.
- The QA load on the machine (plus a buffer on the average dose per treatment) gives a conservative estimate of **50,000 cGy delivered per week** by the linear accelerator.

Workload and Usage Assumptions

Workload Calc

Max txs,QA/week:	250	(200 pts + QA + buffer)
Avg dose to iso:	200	cGy
Dose to iso/week:	50000	cGy

Energies	% load	% IMRT	IMRT MU ratio	% conv	conventional MU ratio	Final MU ratio	MU totals
6x	50%	75%	3.5	25%	1	2.86	71406
10x	50%	75%	3.0	25%	1	2.52	62969

LEAKAGE	W_L:	**134,500**	MU/week
PRIMARY	W:	**500**	Gy m^2/wk

Workload and Usage Assumptions

Type of Tx	MU ratio	6x %	10x %
Head/neck	4	40%	10%
Prostate	2.5	20%	15%
GYN	6	10%	10%
GI	2.5	15%	50%
Thorax	3	10%	10%
Other	2	5%	5%
	MU ratio:	**3.5**	**3.0**

Use Factors

Angular distribution estimation:

Gantry angle	% use factor (U)	Facing
0	15%	Down
45	10%	Down
90	15%	North
135	10%	North-Up
180	15%	Up
225	10%	South-Up
270	15%	South
315	10%	Down

Occupancy Factors

Barriers	Description	T (occ.)
A1	West wall (Console)	1
A2	West entrance (Door)	1/4
B1	***South wall***	***1/40***
B2	South wall	1/40
C1	East wall	1/40
D1	***North wall***	***1/40***
D2	North wall	1/40
E1	***Ceiling***	***1/40***
E2	Ceiling	1/40
F1	2nd Floor diagonal (west)	1

Secondary Location

- *F1 (2nd floor diagonal)* :
- - Uncontrolled area
- - Secondary scattering dominant
- - T = 1
- - dmin = 11.65 meters
- - q = 14 degrees
- - Pmax = 0.02 mSv/week
- <u>Required shielding:</u>
- nF1 = 2.70*cos(14°) + 0.30 (HVL) = 2.92

Primary Location

- (b) *B1 (south wall primary)* :
- - Uncontrolled area
- - Primary beam dominant
- - U = 15% (right lateral fraction)
- - T = 1/40 (unattended parking lot)
- - dmin = 6.50 meters
- - Pmax = 0.02 mSv/week
- Required shielding:
- nB1 = 3.35 (min) + 0.30 (HVL) = 3.65
- For aesthetic reasons, this barrier should have the same thickness as the concrete secondary barrier
- tB2 = 65.6 cm. Therefore, lead and concrete should be utilized in the following proportions:
- **tB1 = 53.0 cm (concrete) + 12.6 cm (lead) = 65.6 cm (total)**

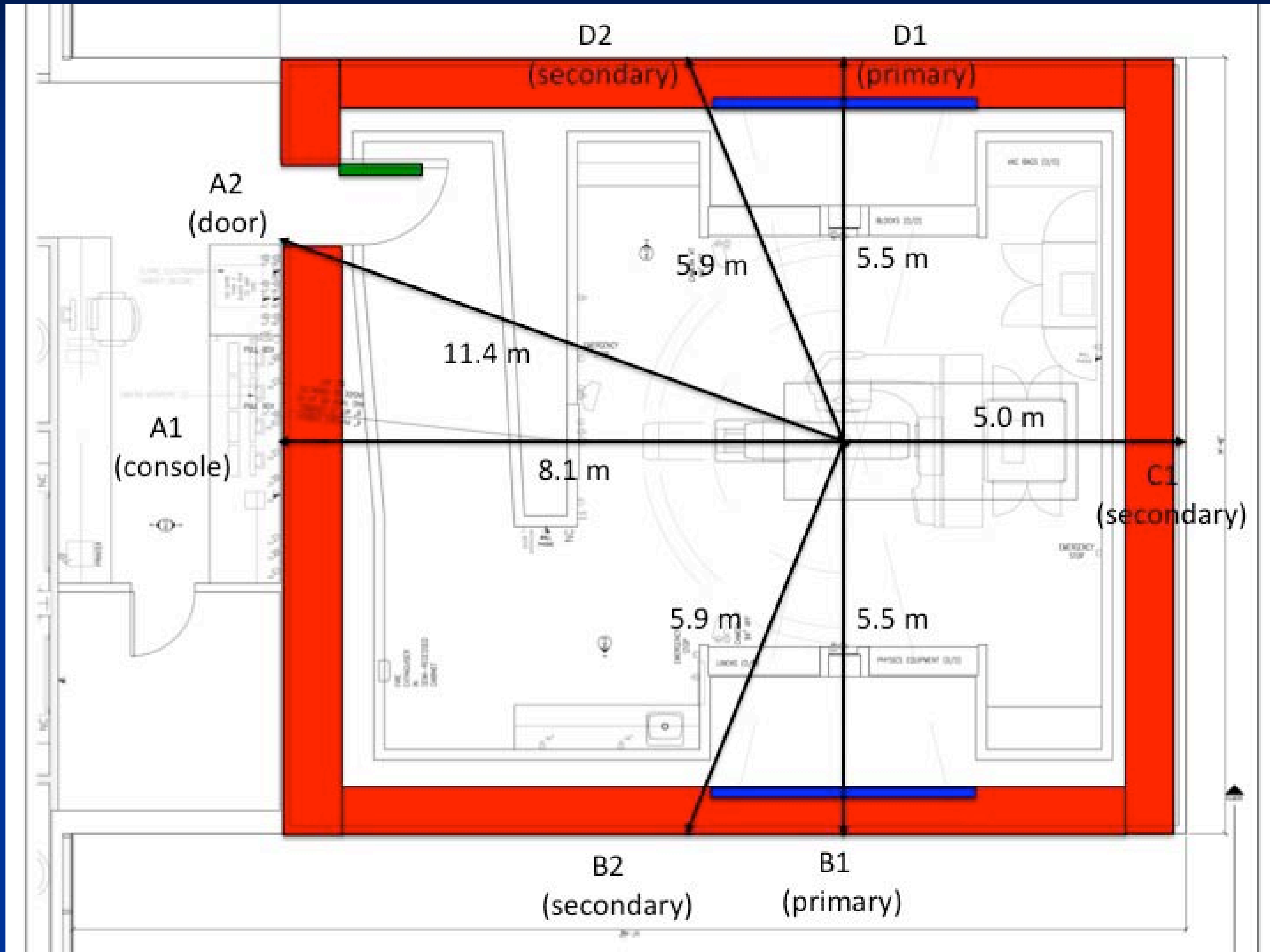
TVL Data

leakage	**TVL1 (10X):**	5.7*	35	11*
leakage	**TVLe (10X):**	5.7*	31	11*

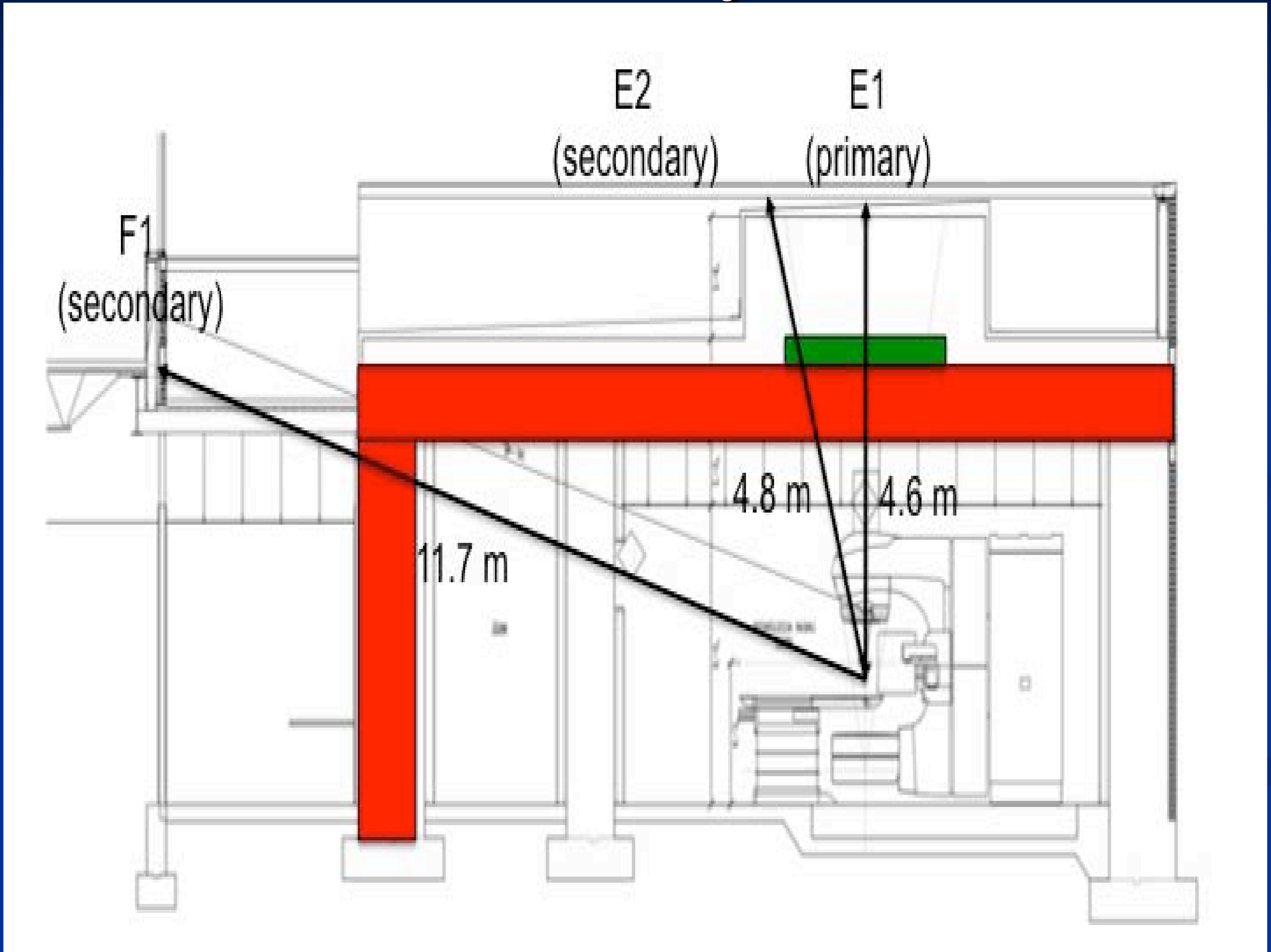
** no data provided for lead or concrete, therefore used TVL of primary*

Table 6 – First and equilibrium tenth value layers for the recommended construction materials. (From Tables B.2 and B.7, NCRP 151.)

Final Layout



Final Layout



Radiation Surveys

- Ionization Chambers
  - Large Volume (~600 ml)
  - Usually calibrated for Cs-137; there are slight corrections for energy and ranges used
- Geiger Muller Counters (G-M)
  - High voltage applied to gas. Initial ionization creates secondary irradiations that "avalanche" the charge.
  - Much more sensitive than ion. Chamber, but events can be missed.

Linac Survey

- Leakage
  - With jaws closed, film (XTL) is wrapped around housing to determine "hot spot". An ionization chamber is then placed @ 1m from source to quantify leakage (< 0.1%) of useful beam.
- Area Survey: Performed with survey meter, and scatterer (phantom)
  - Survey records instantaneous exposure rates. Workload, operating conditions, use and occupance factors, and field size effects; yield weekly rates.

Radiation Surveys

- Neutron Detectors
  - Activation Detector
    - Uses photoneutron production in moderating material. For example a gold foil in a polyethelyne cylinder. The activity generated in the gold is read by a Ge(Li) detector system.
  - Gas Proportional Counters
    - A moderated BF3 counter [$^{10}B(n,\alpha)^{7}Li$], where the α-particles are counted (or their ionization).
  - Superheated Drop (Bubble) Counters
    - Neutron interacts with drop which boils forming a visible gas bubble. The # of bubbles =~ neutron dose.

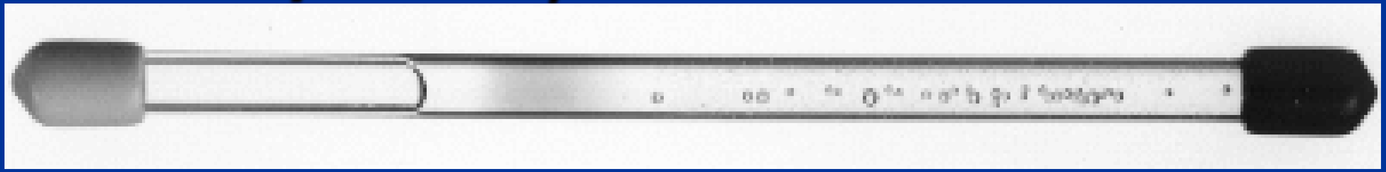
In-Room Photoneutron Doses

- Produced by high energy x-ray beams from linear accelerators
- May constitute 40% of dose to fetus in treatment of pregnant women (AAPM report No. 36)
- May increase due to use of high-Z materials in room shielding components and beam modifiers

Neutron Detectors

- **Neutrometer (Apfel, 1981) showing 32 bubbles after exposure to approximately 6 millirem (60 μSv).**

  5 bubbles/mrem, 50 bubbles max.



- **Neutron rem meter: BF_3 proportional counter in 9" cadmium-loaded polyethylene sphere, operates at 1600~2000 V, and detects neutrons from thermal to ~10MeV.**