Overview, Basis & Revision of NCRP Report 151

Structural Shielding Design and Evaluation for Megavoltage x- and Gamma-ray Radiotherapy Facilities

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Outline

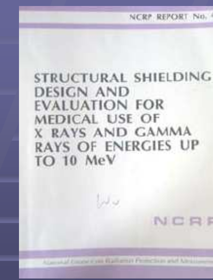
1. Revision of NCRP 151

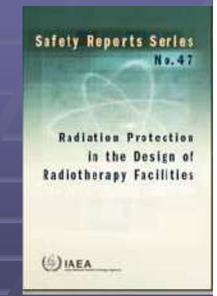
2. What's old?
   B_{pri}, B_L, B_{ps}
   W= workload
   U= use factor
   T= occupancy factor

3. What's new?
   C_I= IMRT factor
   IDR= instantaneous dose rate
   TADR= time average equivalent dose rate
   R_w= Weekly TADR
   R_h= Hourly TADR

4. Examples of how the shielding is done
   A. Primary barrier
   B. Secondary barrier (Leakage and scatter)
   C. Gamma and neutron capture
   D. Laminated (Pb & PBE)
   E. Leakage and scatter at maze door

Address new issues since NCRP #49





- New types of equipment (Trilogy, Elekta, Tomotherapy, Cyberknife etc)
- Many new uses for radiotherapy equipment
- Energy >10 MV, Dual energy machines
- Room designs without mazes
- Varied shielding composites
- Instantaneous Dose Rate (IDR) interpretation problems
- Address the structural shielding design and evaluation for medical use of megavoltage x and gamma rays for radiotherapy
- Supersedes NCRP Report No. 49- up to 10 MeV (Dough Simpkin,1976)
- Shielding for Brachytherapy and simulators are not included (Dr. Glen's talk, available at http://www.aapm.org/meetings/07SS/documents/Glasgow1and2.pdf)
- IAEA Safety Report Series No. 47 available at http://www-pub.iaea.org/MTCD/publications/pdf/pub1223_web.pdf

NCRP Report No. 151

TABLE 2. SUMMARY OF RECOMMENDED/LEGAL EFFECTIVE DOSE LIMITS AND DESIGN EFFECTIVE DOSE LIMITS

Dose limit	IAEA [1]	USA	United Kingdom
Occupational exposure dose limit	20 mSv per year averaged over 5 consecutive years and 50 mSv in any single year	Implied annual limit of 10 mSv, cumulative dose of age × 10 mSv, and 50 mSv in any single year [9]	20 mSv in a year or 100 mSv in 5 consecutive years and 50 mSv in any single year [7]
Design limit for occupational exposure		Fraction of 10 mSv annually [9]	6 mSv in a year [7] IDR is 7.5 $\mu Sv \cdot h^{-1}$ [6]
Public dose limit	1 mSv in a year	Infrequently, 5 mSv annually, and continually, 1 mSv annually [9]	1 mSv in a year [7]
Design limit for public area		1 mSv annually [10] 20 µSv in any hour [8]	0.3 mSv in a year [7] IDR is <7.5 $\mu Sv \cdot h^{-1}$ [6] TADR is <0.5 $\mu Sv \cdot h^{-1}$ [6] TADR2000 <0.15 $\mu Sv \cdot h^{-1}$

Continuous exposure

Permissible Dose/Design Goal (P)

- Controlled Areas:

  Shielding design goal (*P*) (in dose equivalent): 0.1 mSv week^{-1} (5 mSv/yr)

- Uncontrolled Areas:

  Shielding design goal (*P*) (in dose equivalent): 0.02 mSv week^{-1} (1 mSv/yr)

Linac Primary Barrier

$$B_L = \frac{P\, d_L^2}{10^{-3}\, W\, T}$$

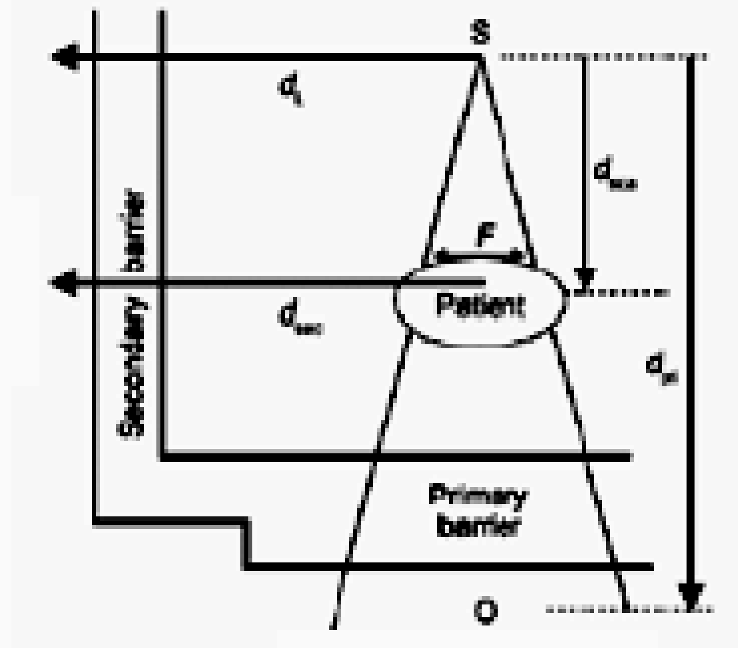
$$B_{ps} = \frac{P}{a W T}\, d_{sca}^{\,2}\, d_{sec}^{\,2}\, \frac{400}{F}$$

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 (cm²)



$$B_{pri} = \frac{P\, d_{pri}^2}{W U T}$$

U = use factor or fraction of the workload that the primary beam is directed at the barrier in question

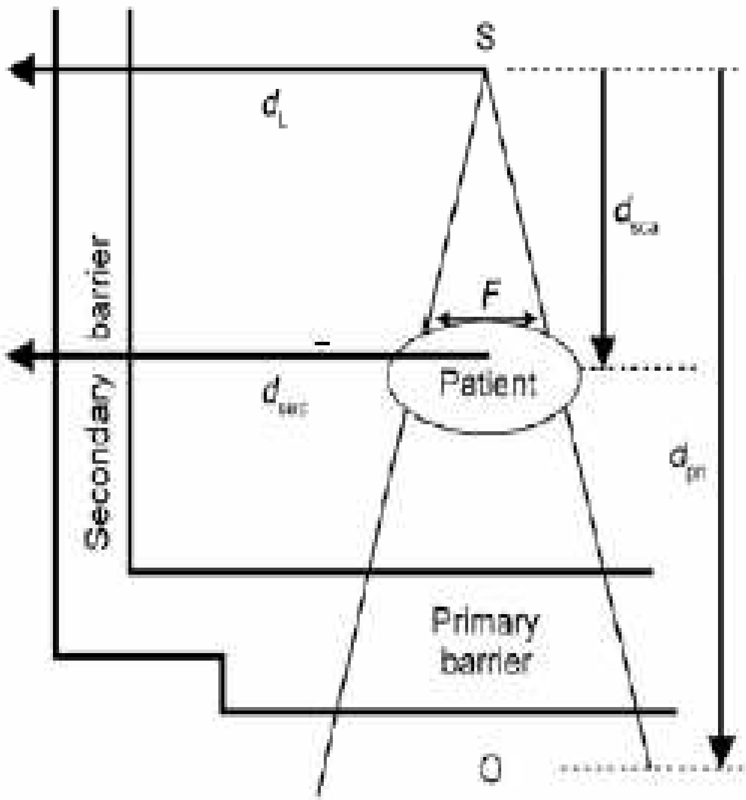
T = occupancy factor for the protected location or fraction of the workweek that a person is present beyond the barrier. This location is usually assumed to be 0.3 m beyond the barrier in question (see Table B.1 in Appendix B for recommended occupancy values)

P = shielding design goal (expressed as dose equivalent) beyond the barrier and is usually given for a weekly time frame (Sv week^{-1})

d_{pri} = distance from the x-ray target to the point protected (meters)

W = workload or photon absorbed dose delivered at 1 m from the x-ray target per week (Gy week^{-1})[6]

Equivalent Dose (H_{pri})



re-arranging any of the barrier transmission equations, one gets the dose equivalent beyond the barrier

$$B_{pri} = \frac{P\,d_{pri}^2}{WUT}$$

$$H_{pri} = \frac{WUTB_{pri}}{d^2}$$

TVLs

- The required number (n) of TVLs is given by:

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

- And the barrier thickness ($t_{barrier}$) is given by:

$$t_{barrier} = TVL_1 + (n-1)\, TVL_e$$

NCRP Report No. 151

workload (W): The average absorbed dose of radiation produced by a source over a specified time (most often one week) at a specific location.

Gy wk^{-1}

	Low energy	High energy		
< 10 MV	1000			NCRP #49
		500		NCRP # 51
> 10 MV	< 350	< 250		Kleck and Elsalim (1994)
6 MV	450	400 *		Mechalakos et al (2004) * dual energy machine

$$WU]_{pri} = WU]_{wall\ scat}$$

6, 15 MV

$$= (W_{conv}\, U_{conv} + W_{TBI}\, U_{TBI} + W_{IMRT}\, U_{IMRT} + W_{QA}\, U_{QA} + \ldots)$$

$$W_L = W_{conv} + W_{TBI} + C_I\, W_{IMRT} + C_{QA}\, W_{QA} + \ldots$$

NCRP Report No. 151

U factor

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).

T factor

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

The IMRT factor (C_I)

- Address IMRT cases as well as SRS and SRT
- The ratio of MU per unit prescribed absorbed dose (D_{pre}) needed for IMRT (MU_{IMRT}) and MU per unit absorbed dose for conventional treatment (MU_{conv})
- No change in W_{pri}, higher by a factor in $W_{leakage}$
- C_I: 2 – 10 (Followill et al.)
- C_I (CyberKnife) = 15, W= 12.5 Gy/case
- C_I (Tomotherapy) is significantly large, 1TVL and 2 TVLs thicker for primary and secondary barrier for leakage

$$MU_{IMRT} = \sum_i \frac{MU_i}{(D_{pre})_i}$$

$$C_I = \frac{MU_{IMRT}}{MU_{conv}}$$

Instantaneous Dose Rate (IDR)

- Measured value depending on the absorbed-dose output rate of machine
- Specified at 30 cm beyond the barrier
- Designed for Co^{60} and pulsed beam
- For Linac, it is averaged over 20-60 s depending on the instrument activation response time and the pulse cycle of the accelerator
- Used to calculate R_h

- $IDR = DR_m 60 B_e / d^2$ in Sv/hr

DR_m= maximum dose rate output @1m (Gy/hr)

B_e= expected transmission factor

d= distance from the x ray target to the point protected (m)

Time Averaged Dose-Equivalent Rates (TADR)

- The **use of *IDR* does not properly represent the true operating conditions and radiation environment** of the facility.
- It is more useful if the W and U are considered together with the *IDR* when evaluating the adequacy of a barrier.
- Therefore, TADR is used along with the measured or calculated *IDR*.
- The TADR is the barrier attenuated dose-equivalent rate averaged over a specified time or period of operation.
- TADR is α to *IDR*, and depends on *W* and *U*.
- Hourly TADR (R_h) and weekly TADR (R_w)

R_w & R_h

- If $R_w \times T$ is $< P$, the barrier is adequate
- NRC specifies that the dose equivalent in any unrestricted area from external sources < 0.02 mSv (20 μSv) in-any-one-hour (NRC, 2005a).
- R_h derives from the maximum number of patient treatments that could possibly be performed in-any-one-hour when the time for setup of the procedure is taken into account.
- N_{max} = maximum number of patient treatments in-any one-hour
- H_{pt} = average dose equivalent per patient treatment at 30 cm beyond the penetrated barrier

$$R_W = \frac{IDR \; W_{pn} \; U_{pn}}{\dot{D}_0}$$

$$R_h = N_{max} \; \overline{H}_{pt}$$

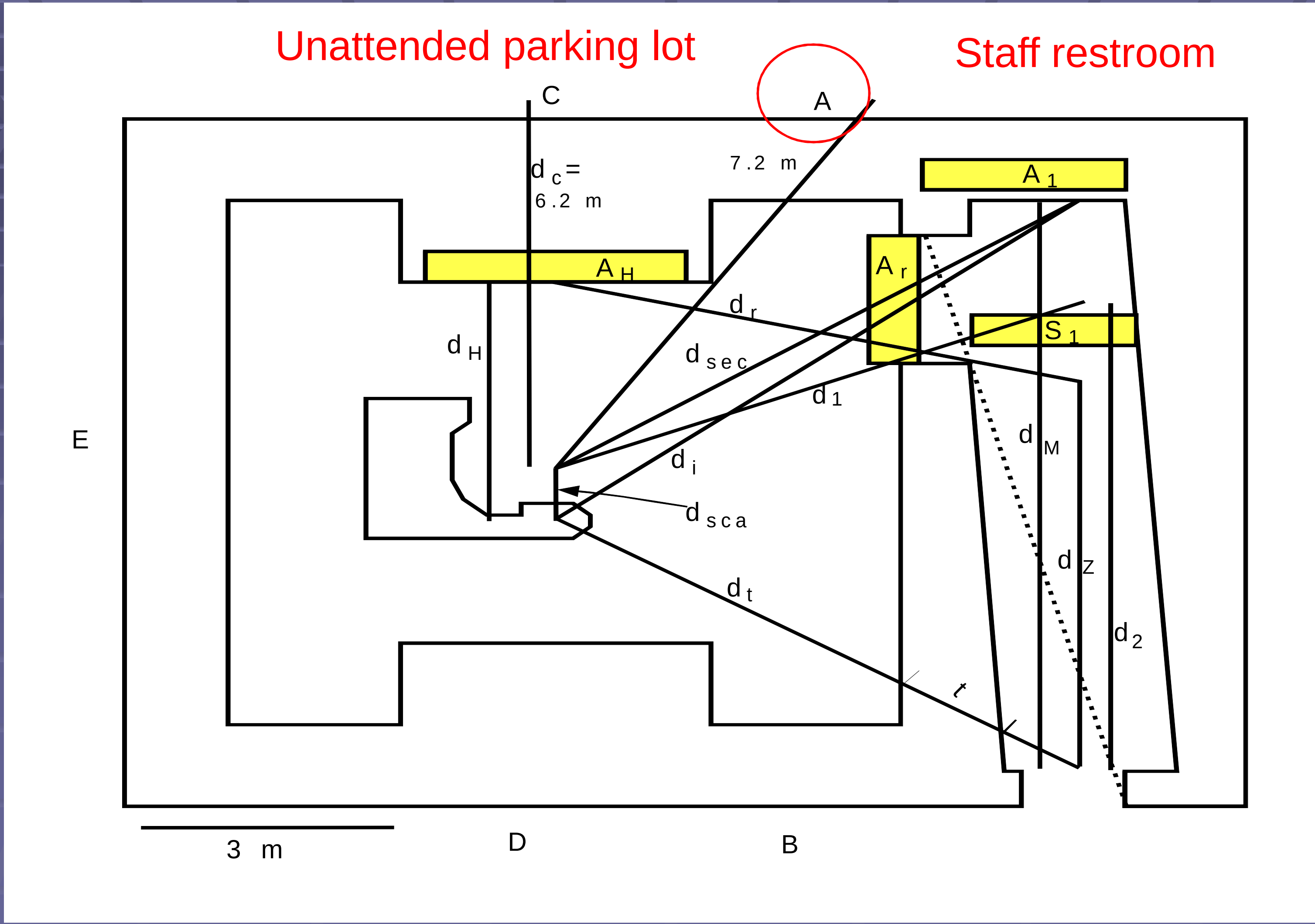
The in-any-hour R_h is related to R_w

$$R_h = \left(\frac{N_{max}}{\overline{N}_h} \right) \times \frac{R_W}{40}$$

N_{max} is the maximum number of patient treatments in any hour

$\overline{N}_h$ is the average number of patient treatments in an hour

Linac Primary Barrier



Linac Primary Barrier

18MV	Green cells are for input values provided by the Qualified Expert			
	Yellow cells are not to be changed by the user of the software			
Linac, Primary barrier				
	Input values	*unit*		
P	Design Dose Limit	mSv wk^{-1}	0.1	
d	Distance from POI to source origin	m	7.2	
W	Workload (defined @ 100 cm from source	Gy wk^{-1} or Sv wk^{-1}	600	
U	Use factor		0.25	
T	Occupancy factor		0.2	
TVL	Tenth value layer for shielding material	mm	445	TVLs.xls
	Primary barrier calculation	*equation*		
B	Transmission factor	Pd^2/WUT	1.73E-04	
n	Number of TVL required	$Log_{10}(1/B)$	3.76	
t	Thickness of shielding material required	n TVL	1674	mm

Linac Primary Barrier

	TADR considerations			
	(Time Average Dose Equivalent Rate)			
	Input values	*unit*		
DR_m	Maximum dose output rate @ 1 m	Gy min^{-1}	12	
t_e	Thickness of shielding material employed	mm	1760	
W_{ha}	Maximum workload based on actual time/procedur	Gy h^{-1}	36	
W_{hb}	(IAEA) W above expressed in Gy h^{-1}	Gy h^{-1}	600	
W_h	Smaller of W_{ha} and W_{hb}		36	Gy
		equation		
B_e	Transmission factor - expected	$1/(10^{\wedge}(t_e/TVL))$	0.0001109	
IDR	Instantaneous Dose Rate	$DR_m\ 60B_e/d^2$	1.54E-03	Sv h^{-1}
DR_m	Maximum dose output rate @ 1 m	unit conversion	720	Gy h^{-1}
R_h	Maximum dose in-any-hour	IDR W_h U / DR_m	19.25	µSv

< 20 µSv TADR limit

TABLE 5.3 (or B.2 in #151) — TENTH VALUE LAYER (TVL) FOR COBALT-60 AND X RAY ENERGIES. THESE ARE APPROXIMATE VALUES BASED ON LARGE ATTENUATION.

		Co-60a	4 MVb	6 MVb	10 MVb	15 MVb	18 MVb	20 MVb	24 MVb
	TVL for concrete (density 2350 kg¡¤m-3) in mm								
	Primary beam gamma/ X rays	218	290	343	389	432	445	457	470
TABLE B.7	Leakage gamma and X rays (90)	218	254	279	305	330	330	343	356
	TVL for steel (density 7800 kg¡¤m-3) in mm								
	Primary beam gamma/ X rays	71	91	98	105	108	111	111	107
	Secondary beam gamma/ X rays	69	79	80	85	87	87	88	89
	TVL for lead (density 11360 kg¡¤m-3)in mm								
	Primary beam gamma/ X rays	41	53	55	56	57	56	55	52
	Secondary beam gamma/ X rays	40	47	45	46	47	47	49	51

aCobalt-60 data from NCRP49 [1].
bAdapted from Varian Associates. The TVL of leakage X rays are based on calculations by Nelson and LaRiviere [22].

Leakage & Scatter Barrier

Linac, Secondary barrier				
	Input values for leakage barrier	*unit*		
P	Design Dose Limit	$mSv\ wk^{-1}$	0.02	
d_s	Distance from POI to isocenter	m	7.2	
W	Workload (defined @ 100 cm from source of unit)	$Gy\ wk^{-1}$ or $Sv\ wk^{-1}$	600	
U	Use factor		1	
T	Occupancy factor		0.0625	
TVL_l	Tenth value layer for shielding material	mm	330	TVLs.xls
	Leakage barrier calculation	*equation*		
B	Transmission factor	$1000\ P\ d^2\ /\ W\ T$	2.76E-02	
n	Number of TVL required	$Log_{10}(1/B)$	1.56	
t	Thickness of shielding material required	n TVL	514	mm
	Input values for patient scatter barrier	*unit*		
P	Design Dose Limit	$mSv\ wk^{-1}$	0.02	E
d_{sca}	Distance from source to isocenter	m	1	
d_{sec}	Distance from POI to isocenter	m	7.2	
a	Scatter fraction per 400 cm^2		2.53E-03	aScFraction.x
W	Workload (defined @ 100 cm from source of unit)	$Gy\ wk^{-1}$ or $Sv\ wk^{-1}$	600	
U	Use factor		1	
T	Occupancy factor		0.0625	
F	Maximum field size at isocenter	cm^2	1600	
TVL_p	Tenth value layer for shielding material	mm	288	TVLscatter.xl

Table 5.5 Scatter fractions of dose, a, at 1 metre for a 400 cm^2 incident beam

(Table B.4 of #151)

Angle (degree)	Co-60[a]	6 MV[b]		10 MV[b]		18 MV[b]		24 MV[b]	
		max a	a at 1.5 cm	max a	a at 2.5 cm	max a	a at 2.5 cm	max a	a at 2.5 cm
10	1.1×10^{-2}	1.68×10^{-2}	1.04×10^{-2}	1.69×10^{-2}	1.66×10^{-2}	2.43×10^{-2}	1.42×10^{-2}	2.74×10^{-2}	1.78×10^{-2}
20	8.0×10^{-2}	1.15×10^{-2}	6.73×10^{-3}	1.03×10^{-2}	5.79×10^{-3}	1.17×10^{-2}	5.39×10^{-3}	1.27×10^{-2}	6.32×10^{-3}
30	6.0×10^{-3}	5.36×10^{-3}	2.77×10^{-3}	6.73×10^{-3}	3.18×10^{-3}	7.13×10^{-3}	2.53×10^{-3}	7.21×10^{-3}	2.74×10^{-3}
45	3.7×10^{-3}	2.97×10^{-3}	1.39×10^{-3}	3.25×10^{-3}	1.35×10^{-3}	3.05×10^{-3}	8.64×10^{-4}	3.06×10^{-3}	8.30×10^{-4}
60	2.2×10^{-3}	1.74×10^{-3}	8.24×10^{-4}	1.84×10^{-3}	7.46×10^{-4}	1.42×10^{-3}	4.24×10^{-4}	1.37×10^{-3}	3.86×10^{-4}
90	9.1×10^{-4}	7.27×10^{-4}	4.26×10^{-4}	7.14×10^{-4}	3.81×10^{-4}	3.75×10^{-4}	1.89×10^{-4}	3.53×10^{-4}	1.74×10^{-4}
135	5.4×10^{-4}	4.88×10^{-4}	3.00×10^{-4}	3.70×10^{-4}	3.02×10^{-4}	2.59×10^{-4}	1.24×10^{-4}	2.33×10^{-4}	1.20×10^{-4}
150	1.5×10^{-4}	3.28×10^{-4}	2.87×10^{-4}	3.16×10^{-4}	2.74×10^{-4}	2.26×10^{-4}	1.20×10^{-4}	2.12×10^{-4}	1.13×10^{-4}

Leakage & Scatter Barrier

	Patient scatter barrier calculation	*equation*		
B	Transmission factor	$P\,d_{sca}^2\,d_{sec}^2 / (a\,W\,U\,T\,F/400)$	2.73E-03	
n	Number of TVL required	$Log_{10}(1/B)$	2.56	
t	Thickness of shielding material required	n TVL	738	mm

TADR considerations

	Input values	*unit*		
DR_m	Maximum dose output rate @ 1 m	Gy min^{-1}	12	
t_e	Thickness of shielding material employed	mm	837	
W_{ha}	Maximum workload based on actual time/procedure	Gy h^{-1}	36	
W_{hb}	(IAEA) W above expressed in Gy h^{-1}	Gy h^{-1}	600	
W_h	Smaller of W_{ha} and W_{hb}		36	Gy

		equation		
B_{el}	Transmission factor - Leakage - expected	$1/(10^{(t_e/TVL_l)})$	0.0029083	
B_{ep}	Transmission factor - pat scat - expected	$1/(10^{(t_e/TVL_p)})$	0.0012409	
IDR_L	Instantaneous Dose Rate due to leakage	$DR_m\,60 B_{el}/ds^2/1000$	4.04E-05	Sv h^{-1}
IDRp	IDR due to patient scatter	$DR_m\,60\,a\,(F/400)\,B_{ep} / (d_{sec}^2\,d_{sca}^2)$	1.74E-04	Sv h^{-1}
IDR	Total IDR	$IDR_p + IDR_L$	2.15E-04	Sv h^{-1}
DR_m	Maximum dose output rate @ 1 m	unit conversion	720	Gy h^{-1}
R_h	Maximum dose in-any-hour	$IDR\,W_h\,U / DR_m$	10.7	µSv

< 20 µSv TADR limit

TABLE 5.4. FIRST TVL IN MM CONCRETE FOR PATIENT SCATTER RADIATION AT VARIOUS SCATTERED ANGLES (Table B.5a in #151)

scatter angle	Co-60	4MV	6MV	10MV	15MV	18MV	20MV	24MV
15	223	320	367	410	436	449	457	447
30	213	248	261	275	285	288	290	293
45	197	223	229	233	237	238	239	240
60	189	201	205	209	211	211	212	212
90	151	169	171	173	174	174	174	175
135	128	143	144	144	145	145	145	145

Neutron Shielding Materials

- **Hydrogenous materials are most effective for neutrons**

- Concrete (ρ = 2.35 g/cm3)
– Water content is important, at least 5.5% by weight
– 2.2 MeV γ from thermal neutron capture in H
– Average γ energy from neutron capture= 3 MeV
– Maximum γ energy from neutron capture = 10 MeV
– TVL ~ 8.3”

- **Heavy Concrete**

– Higher densities due to high-Z aggregates
– TVLs for photons lower than concrete (inverse ratio of densities)
– Typically TVLs for neutrons about the same as concrete

- **Earth (ρ = 1.1 -1.5 g/cm3)**

– “Dirt cheap”
– Compacted earth is free from cracks and voids
– Considerable variation in composition, density and water content

- **Polyethylene (ρ = 0.92 g/cm3)**

– Very effective because of H content
– 2.2 MeV γ from thermal neutron capture in H

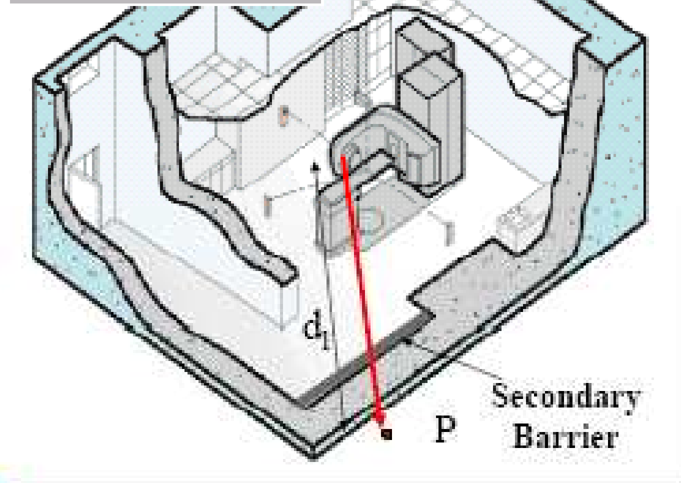
- **Borated Polyethylene (ρ ~ 0.92 g/cm3)**

– Typically 5% boron by weight
– High thermal neutron capture cross section for boron (3840 b/atom)
– 0.478 MeV γ from thermal neutron capture in boron

Neutron transmission of barrier (B_{Ln})

- *P* = Design dose limit at point of interest
- *W* = Workload (dose at 1 m from target)
- *U* = Use Factor
- *T* = Occupancy Factor
- d_l = Distance from the target to point of interest
- *Y* = Leakage neutron yield at 1 m from target (Sv/Gy)

$$B_{Ln} = \frac{P d_l^2}{WYUT}$$



Neutron Dose Equivalent (H_n)

TVL= 5m

- Kersey's Method
- Modified Kersey's method (McKinley & Huffman 2000, Wu & McKinley 2003)

$$H_{n,D} = (H_0)\left(\frac{S_0}{S_1}\right)\left(\frac{d_0}{d_1}\right)^2 10^{-\left(\frac{d_2}{5}\right)}$$

$$H_{n,D} = 2.4 \times 10^{-15}\, \varphi_A \sqrt{\frac{S_0}{S_1}} \left[1.64 \times 10^{-\left(\frac{d_2}{1.9}\right)} + 10^{-\left(\frac{d_2}{TVD}\right)}\right]$$

- $H_{n,D}$= neutron dose equivalent (Sv n^{-1} m^2)
- φ_A= neutron fluence per unit absorbed dose ($m^{-2}Gy^{-1}$) given in Eq. 2.16 NCRP 151
- S_o/S_1= ratio of the inner maze entrance cross sectional area to the cross sectional area along the maze
- TVD= Tenth value distance (m) that varies as the square root for the S_1
- $TVD = 2.06 \sqrt{S_1}$

Neutron Source Strength(Q_n)

- The neutron yields are summarized in Appendix B: Table B-9
- Siemens18 MV had a <u>lower</u> Q_n (0.88) than the Varian 18 MV (1.22)

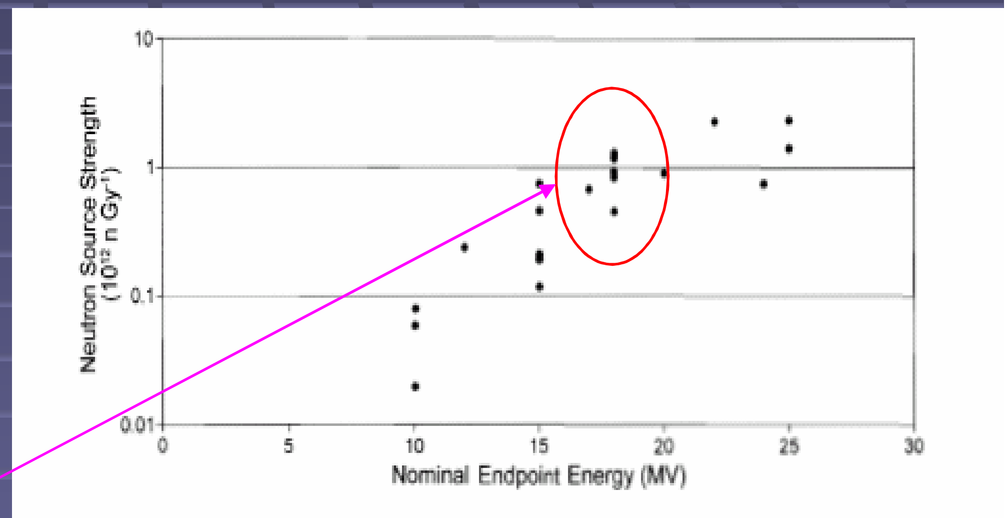
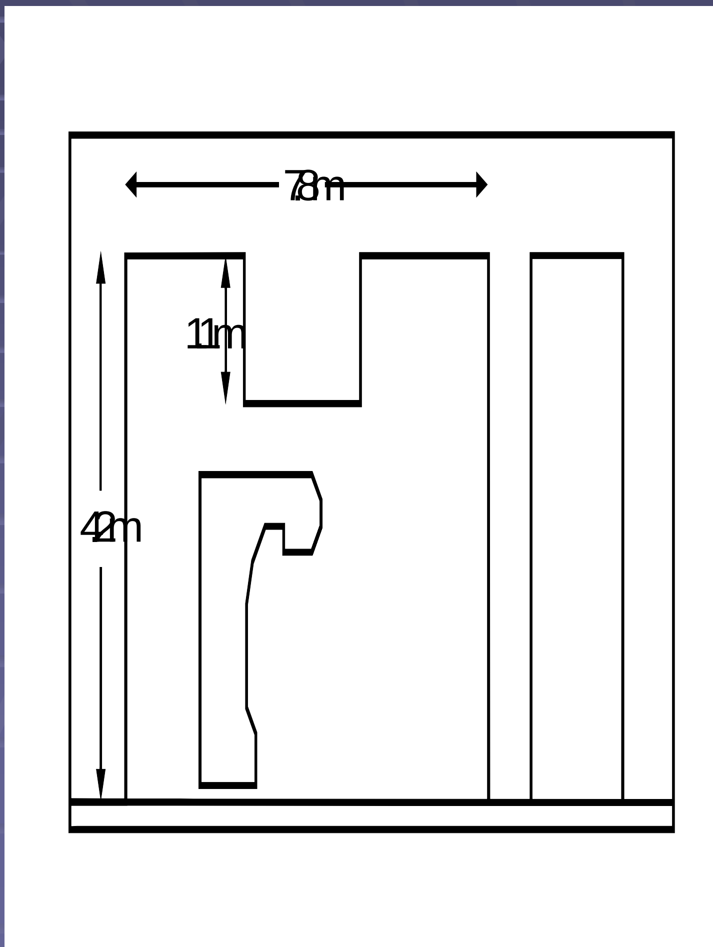
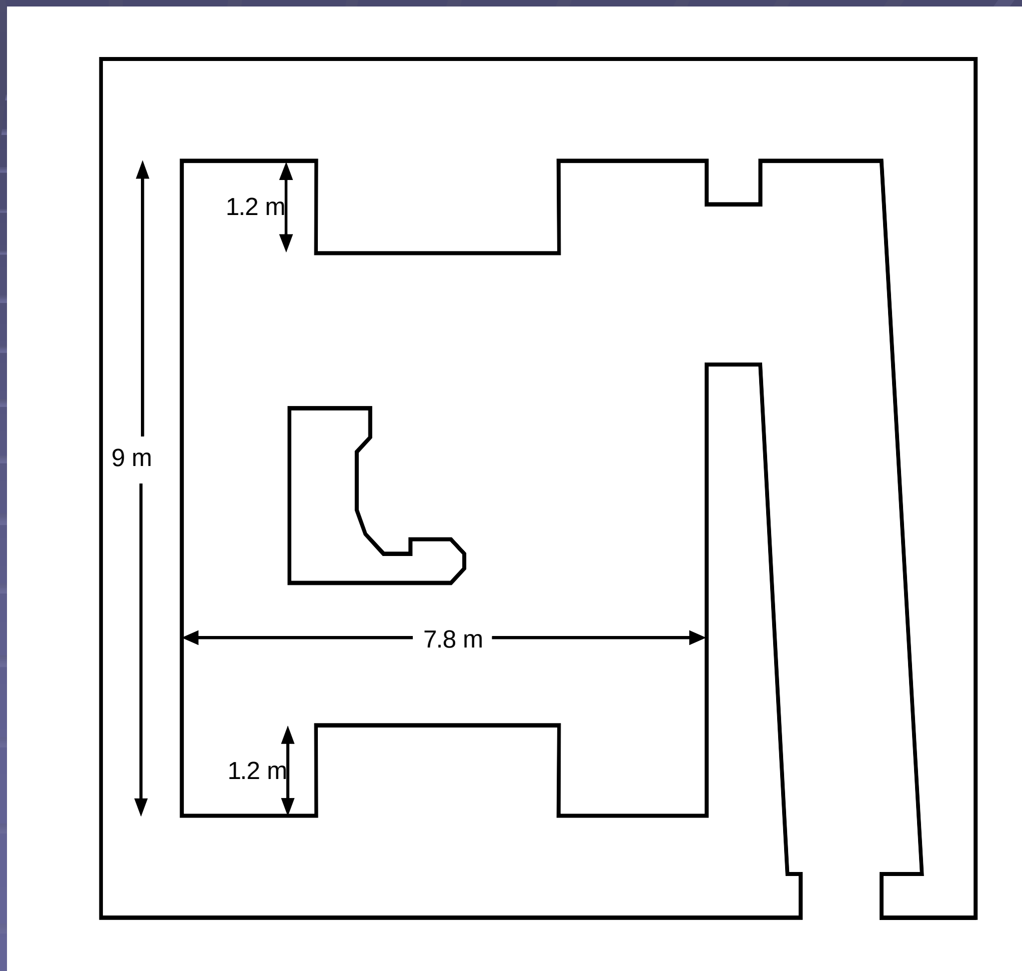


Fig. B.1. Graph of neutron source strength (Q_n) (neutrons per gray of x-ray absorbed dose at isocenter) as a function of nominal endpoint energy for data presented in Table B.9.

Capture Gamma Dose at Maze door





Linac Neutron Dose at Maze Door

Capture Gamma Dose at Maze door

1. Determination of the neutron fluence at point A

	A Surface Area of treatment room	*unit*	
	Follow the example shown in Figure a		
	Height of room	m	4.2
	Protruding thickness of primary barrier for ceiling	m	1.1
	Room width to maze wall	m	7.8
	Length of room	m	9.0
	Protruding thickness of primary barrier for wall 1	m	1.2
	Protruding thickness of primary barrier for wall 2	m	1.2
	Calculation for room surface area S		
S	see example: S=2x[7.8x(4.2-0.55)+(9-0.6-0.6)x(4.2-0.55)+(9-0.6-0.6)x7.8)		236 m^2

B Neutron fluence

Input values for neutron fluence calculation

Q_N	Neutron source strength	neutrons per x-ray Gy at isocenter		1.22E+12	QN.xls
d_1	Distance from isocenter to point A		m	6.4	
d_2	Distance from point A to maze door		m	8.5	

Calculation for φ_A at inner maze point A

φ_A	Total neutron fluence per isocenter x-ray Gy	$Q_N*[1/(4\pi d_1^2)+6.66/(2\pi S)]$		7859960036	$n\text{-}m^{-2}$

C Calculation for capture gamma dose Dφ in Gy @ door per Gy @isocenter

Dφ	Capture γ dose at door Wu method	$5.7\times10^{-16} \times \varphi_A \times 10$^$(-d_2/6.2)$		1.91E-07	Gy per Gy
	TVDn=3.9 for 15MV, 5.5 for above		m	5.5	
Dφ	Capture γ McG2 method	$6.9\times10^{-16} \times \varphi_A \times 10$^$(-d_2/TVDn)$		1.54E-07	Gy per Gy

Input values for calculation of neutron dose at the maze door

A_r	Cross-sectional area of inner maze entrance		m^2	10.2	
S_1	Cross-sectional area of maze		m^2	8.76	

TABLE 5.7 APPARENT NEUTRON SOURCE STRENGTH QN IN 1012 NEUTRONS PER X RAY¡¤GY AT ISOCENTRE [14]

(Table B.9 in #151)

Manufacturer	Model	Stated MV	NAP MV	QN
Varian	1800	10	unknown	0.06
GE	Saturne 41	12	11.2	0.24
GE	Saturne 41	15	12.5	0.47
Varian	2100 EX	15	13	0.50*
Philips	SL-20	17	17	0.69
Varian	1800	15	13	0.76
Siemens	KD	20	16.5	0.92
Varian	1800	18	16.8	1.22
GE	Saturne 43	18	14	1.5
Philips	SL-25	22	20.4	2.37
GE	Saturne 43	25	18.5	2.4

*Wu and McGinley [29]

NAP is the nominal accelerating potential defined in the TG21 protocol [35]

	D Calculation for neutron dose at the maze door			
T_N	Tenth value length for maze neutron	$2.06*SQRT(S_1)$	6.1	
D_n	Neutron dose equivalent in Sv per x-ray Gy at isocenter			
	$2.4\times10^{-15}\times\varphi_A\times\sqrt{(A_r/S_1)}\times[1.64\times10^{\wedge}(-d_2/1.9)+10^{\wedge}(-d_2/T_N)]$		8.23E-07	Sv per Gy
	Input value for calculation of weekly capture gamma and neutron dose			
W	Workload	$Gy\ wk^{-1}$ or $Sv\ wk^{-1}$	600	
	E Capture gamma dose at maze door both methods	$W \times D_\varphi$	1.14E-04	9.27E-05
	Capture gamma dose at maze door	$W \times D_\varphi$	1.14E-04	$Sv\ wk^{-1}$
	Neutron dose at maze door	$W \times D_n$	4.94E-04	$Sv\ wk^{-1}$
		sum of both	6.08E-04	$Sv\ wk^{-1}$
	G Photon dose due to head leakage and scatter from previous sheet		6.94E-05	$Sv\ wk^{-1}$

D_{gp}	Grand total for photon before door	$W \times D\varphi + D_{pd}$		1.84E-04	$Sv\ wk^{-1}$
	Door shielding evaluation	in inch converted to mm			
	Proposed steel frame thickness		0.5	12.7	mm
t_l	Proposed lead thickness		0.5	12.7	mm
t_b	Proposed BPE thickness		4	101.6	mm
	TVL in steel for photon at door				
T_{lp}	TVL in lead for photon at door McG2 p76	mm		6.1	
	TVL in BPE for photon at door				
	TVL in steel for neutron at door				
	TVL in lead for neutron at door				
T_{bn}	TVL in BPE for neutron at door McG2 p.66	mm		45	
	note TVLs are quite dependent on maze length				
	final neutron dose due to BPE alone at door	$W\ D_n\ 10$^$(-t_b/T_{bn})$		2.72601E-06	$Sv\ wk^{-1}$
	final photon dose due to lead alone at door	$D_{gp}\ 10$^$(-t_l/T_{lp})$		1.52188E-06	$Sv\ wk^{-1}$
	Grand total of dose after door n and ph			4.24789E-06	$Sv\ wk^{-1}$
		unit conversion		0.004	$mSv\ wk^{-1}$
		unit conversion		0.42	$mrem\ wk^{-1}$

Questions?

Thank you very much for your attention!