Linear Accelerator Direct Shielded Doors

An Approach for Calculating the Specialized Shielding Required Adjacent to the Door

Example Calculations

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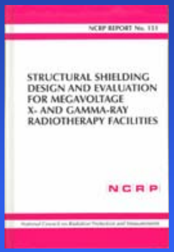
Example Calculations are Based on NCRP Report No. 151

- Report Title: “Structural Shielding Design and Evaluation for Megavoltage X- and Gamma-Ray Radiotherapy Facilities”
  - Released December 31, 2005
- Calculations here illustrate the NCRP 151 recommendations
- Previous NCRP reports are also cited in some cases
  - e.g., NCRP 51 and NCRP 79



NCRP REPORT No. 151

STRUCTURAL SHIELDING DESIGN AND EVALUATION FOR MEGAVOLTAGE X- AND GAMMA-RAY RADIOTHERAPY FACILITIES

NCRP

- Detailed example calculations can be found at: http://www.therapyphysics.com/WC2009_Examples.pdf

Detailed example calculations can be found on web site

Linear Accelerator Energy

- BJR #11 megavoltage (MV) definition used here
  - British Journal of Radiology (BJR) Supplement No. 11
- Comparison of BJR #11 and BJR #17 MV definitions

BJR #11 MV	4	6	10	15	18	20	24
BJR #17 MV	4	6	10	16	23	25	30

NCRP 151 Recommended Workload [1 of 2]

- Workload (W)
  - “Time integral of the absorbed-dose rate determined at the depth of the maximum absorbed dose, 1 m from the source”
- 450 Gy/wk maximum weekly workload cited in NCRP 151
  - Kleck (1994)
    - » Maximum 350 Gy/wk for 6 MV
    - » Maximum 250 Gy/wk at high MV for dual energy
  - Mechalakos (2004)
    - » Maximum 450 Gy/wk for 6 MV single-energy
    - » Maximum 400 Gy/wk for dual energy
  - NCRP 151 Section 7 examples assume 450 Gy/wk at high MV

450 Gy / wk absorbed dose is the default weekly workload

NCRP 151 Recommended Workload [2 of 2]

- 30 patients treated per day is default assumption
  - NCRP 151 default recommendation for busy facility
  - Can also base on a conservative estimate influenced by factors such as historical workload and demographics
    - » e.g. lower patient workload for facility in small town
- 3 Gy absorbed dose per patient treatment default
  - Assumption used in NCRP 151 Section 7 examples
  - Consistent with 450 Gy/wk with 30 patients treated per day
    - » 450 Gy/wk = 5 treatments/wk/patient x 3 Gy/treatment x 30 patients
  - Equivalent to 219 cGy treatment fraction (0.73 tissue maximum ratio)
    - » Intentionally somewhat conservative (compared to ~200 cGy fraction) since no specific allowance for quality or maintenance workload
  - Can be based on direct knowledge of accelerator use instead
    - » But preferable to stick with the NCRP 151 default

450 Gy/wk is consistent with 30 patients & 3 Gy/treatment

Workload Assumptions for Dual Energy Linear Accelerators

- Preferable to assume full 450 Gy/wk workload is at the higher energy
  - Simpler, more conservative calculation
  - Appropriate for new construction
- For existing construction, dual-energy calculation may be appropriate
  - If modifications to existing vault are difficult and size constrained
  - Split 30 patient workload to ensure at least 250 Gy/wk at higher MV
    - » With 17 patients, 255 Gy/wk at higher MV

Mode	Gy/wk/patient	Patients/day	W (Gy/wk)
Single x-ray mode	15	30	450
Dual x-ray mode	15	30	450
High-X mode	15	17	255
Low-X mode	15	13	195

At least 250 Gy/wk at high MV mode

Radiation Protection Limits

- Shielding Design Goal (P)
  - Level of dose equivalent (H) used in the design calculations
  - Applies to barriers designed to limit exposure to people
    - » Limiting exposure to unoccupied locations is not the goal
  - Stated in terms of mSv at the point of nearest occupancy
- NCRP 151 recommended values for shielding design goal
  - 0.10 mSv/week for controlled areas
  - 0.02 mSv/week for uncontrolled areas
- Lower values may be applicable in your country

Controlled Areas

- Limited-access area in which the occupational exposure of personnel to radiation or radioactive material is under the supervision of an individual in charge of radiation protection
- Access, occupancy and working conditions are controlled for radiation protection purposes
- Areas are usually in the immediate areas where radiation is used, such as treatment rooms and control booths, or other areas that require control of access, occupancy, and working conditions for radiation protection purposes
- The workers in these areas are those individuals who are specifically trained in the use of ionizing radiation and whose radiation exposure is usually individually monitored

Uncontrolled Areas

- All other areas in the hospital or clinic and the surrounding environs
- Trained radiation oncology personnel and other trained workers, as well as members of the public, frequent many areas near controlled areas such as examination rooms or restrooms
  - Choice of appropriate occupancy factors ensures the protection of both those who are occupationally exposed as well as others who might be exposed in these areas

Radiation Protection Limits for Locations

- Protected location
  - Walls: 0.3 m beyond the barrier
  - Ceilings: 0.5 m above the floor of the room above the vault
  - Floors: 1.7 m above the floor of the room below
- Permissible dose at protected location depends on occupancy
- *Occupancy factor (T):*

  Fraction of time a particular location may be occupied
- Maximum shielded dose rate at protected location: P/T
  - Assuming occupancy factor T for protected location

Max shielded dose rate traditionally referred to as P/T

NCRP 151 Recommended Occupancy

- T=1: 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
- T= 0.5: Adjacent treatment room, patient examination room adjacent to shielded vault
- T = 0.2: Corridors, employee lounges, staff rest rooms
- T = 0.125: Treatment vault doors
- T = 0.05: Public toilets, unattended vending rooms, storage areas, outdoor areas with seating, unattended waiting rooms, patient holding areas, attics, janitor's closets
- T = 0.025: Outdoor areas with only transient pedestrian or vehicular traffic, unattended parking

Occupancy Factor Selection

- For interior locations, T=1 and T=0.2 are most common
  - T = 1 for work locations
  - T = 0.2 for locations not occupied continuously
- For exterior locations, T = 0.05 is most common
- T < 1 now appropriate for some controlled locations
  - <u>Use with T = 0.125 for vault entrance with caution: any higher occupancy location further away must also be protected</u>
  - T = 0.5 for adjacent vault appears to be reasonable assumption
- Select T = 0.05 for interior locations with caution
  - Should be very unlikely to be occupied (storage, attic, closets)
- T = 0.025 for exterior locations with restricted access
  - NRC hourly limit is more constraining for unrestricted locations

Use Factor

- *Use Factor* (U) is the fraction of the workload for which the primary beam is directed at the barrier in question
- Traditionally U = 0.25 for lateral barriers, ceiling, & floor
- U = 0.1 for tapered portions of ceiling barrier (Example 11)
- Applies to primary barrier calculations, usually not secondary
- NCRP 151 Table 3.1 below consistent with these values
  - TBI may require deviation from these values

90º gantry angle intervals

Angle Interval Center	U (percent)	Standard Deviation (percent)
0º (down)	31.0	3.7
90º and 270º	21.3 (each)	4.7
180º (up)	26.3	3.7

45º gantry angle intervals

Angle Interval Center	U (percent)	Standard Deviation (percent)
0º (down)	25.6	4.2
45º and 315º	5.8 (each)	3.0
90º and 270º	15.9 (each)	5.6
135º and 225º	4.0 (each)	3.3
180º (up)	23.0	4.4

Secondary Barrier Photon Leakage

- Leakage unshielded dose rate

$$H_L = \frac{W \times leakage\ fraction}{d_{sec}^2}$$

  - Assumes H_L in Sv and W in Gy
  - 0.1% leakage fraction is customary
  - Secondary distance d_{sec} in meters
- Calculate shielded dose rate using TVLs in NCRP 151 Table B.7
- Calculation tends to be conservative
  - Typical leakage 5X or more lower than 0.1% requirement
  - Unlike primary barriers, generally no need for extra margin

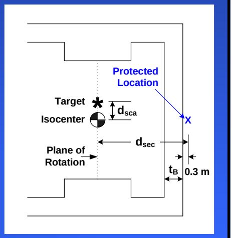


Table 2: Leakage TVLs (mm)

Linac MV	Lead TVL1	Lead TVLe	Concrete TVL1	Concrete TVLe	Steel TVL1	Steel TVLe	Earth TVL1	Earth TVLe	Borated Poly TVL1	Borated Poly TVLe
4	57	57	330	280	96	96	517	439	817	693
6	57	57	340	290	96	96	533	455	842	718
10	57	57	350	310	96	96	549	486	866	767
15	57	57	360	330	96	96	564	517	891	817
18	57	57	360	340	96	96	564	533	891	842
20	57	57	360	340	96	96	564	533	891	842
25	57	57	370	350	96	96	580	549	916	866

NCRP 151 Primary TVL Table B.2

NCRP 151 Table B.7

Varian TVL ratio relative concrete

Est. by density vs. concrete

concrete = 2.35 g / cm^3 [NCRP 151, p. 69]
earth density =1.5 g / cm^3 [NCRP 151, p. 72]
BPE = 0.95 g / cm^3 [NCRP 151, p. 162]

Note: NCRP 51 Figure E.14 indicates lead TVL is maximum near 6 MeV, so using primary TVL for leakage is reasonable

No data in NCRP 151 for steel leakage TVL.
NCRP 51 Figure E.13 implies steel leakage TVL should be less than primary.
Rationale for 96 mm steel TVL based on Varian document #12004 on next chart.

Intensity Modulated Radiation Therapy (IMRT)

- IMRT requires increased monitor units per cGy at isocenter
  - IMRT ratio is the ratio of MU with IMRT per cGy at isocenter
- Percent workload with IMRT impacts shielding
  - 50% typically assumed; 100% if vault is dedicated to IMRT
- Account for IMRT by multiplying workload by IMRT factor
  - IMRT Factor = % IMRT x IMRT ratio + (1 - % IMRT)
- Leakage Workload: W_L = W × IMRT Factor
  - W_L replaces W in leakage unshielded dose calculation with IMRT
- Lower IMRT factor appropriate for neutrons if calculate shielding at the higher MV for a dual MV machine

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IMRT Ratio Typical Values

Manufacturer	IMRT Ratio	Percent IMRT	IMRT Factor Photon	IMRT Factor Neutron
Varian	3	50%	2	1
Siemens	5	50%	3	1.5
NOMOS	10	50%	5.5	2.75
Tomotherapy	16	100%	16	NA

- Typically assume 50% of treatments with IMRT
  - Pessimistic assumption for dual energy machine since most IMRT done at lower energy (e.g., >75% at 6 MV, <25% at 18 MV)
- Neutron IMRT factor (applicable to dual energy) assumes IMRT equally at high and low energy
  - Since most IMRT is done at the lower energy, an even lower neutron IMRT factor may be appropriate

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Neutron Leakage Fraction

- Neutron leakage unshielded dose rate

$$H_n = \frac{W_{Ln} \times H_o}{d_{sec}^2}$$

  - H_n in Sv and W_{Ln} in Gy
  - H_0 is neutron leakage dose equivalent fraction normalized to 1 m from target
- H_o in Table 4 normalized to 1 m
  - Varian* and Siemens** values based on manufacturer data
  - Elekta data from Site Planning Guide***
  - GE data based on NCRP 151 Table B.9 normalized to 1 m

Vendor	MV	Ho @1 m Sv/Gy
Varian	10	4.0E-05
	15	7.0E-04
	18	1.5E-03
	20	1.9E-03
	24	2.0E-03
Siemens	10	2.0E-05
	15	4.2E-04
	18	9.9E-04
	20	1.4E-03
	24	2.3E-03
Elekta / Philips	10	3.0E-04
	15	7.0E-04
	18	1.5E-03
	20	2.0E-03
	24	3.0E-03
GE	12	1.8E-04
	15	6.4E-04
	18	1.1E-03
	25	2.7E-03

* Varian: http://www.varian.com/osup/pdf/12000.pdf [Page 12, Average of 4 positions]
** Siemens: Conservative neutron leakage dose rates in patient plane with Q=10
*** Elekta: Nisy Ipe, "*Neutron Shielding Design and Evaluations*", 2007 AAPM Summer School

Neutron Leakage TVL

- TVL recommendation based on NCRP 79
  - TVL_n = 155 + 56 * Neutron MV for concrete
    - » 211 mm at 1 MV is traditional neutron leakage TVL for concrete
  - TVL_n = 62 + 34 * Neutron MV for borated polyethylene (BPE)
    - » 96 mm at 1 MV is traditional neutron leakage TVL for BPE
  - Estimate other material from concrete or BPE based on hydrogen content
  - Lead and steel provide negligible neutron attenuation

	Concrete		Earth		Borated Poly		
MV	TVL1	TVLe	TVL1	TVLe	TVL1	TVLe	Application
1	211	211	331	331	96	96	Leakage

Secondary Barrier Patient Scatter

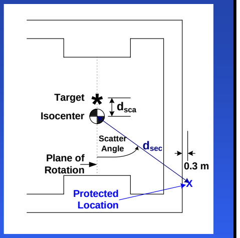
- Patient scatter unshielded dose rate

$$H_{ps} = \frac{a\,WU\,(F/400)}{d_{sca}^{2}\;d_{sec}^{2}}$$

  - a = scatter fraction for 20 x 20 cm
  - F is maximum field area in cm^2
    - » NCRP 151 examples use F=1600 (conservative 40x40 cm field)
  - Effective F is smaller with IMRT
    - » F=225 cm^2 w/ IMRT (15 x 15 cm)

F = (1-% IMRT) × 1600 + % IMRT × 225

  - Typically use F=1600 even if IMRT is used to add conservatism
    - » Safety survey done w/o IMRT
    - » IMRT seldom used at higher MV for dual energy machines
    - » Primary beam adds to patient scatter at small scatter angles



- Scatter fraction as function of MV and scatter angle in NCRP 151 Table 5.4
- Scatter energy as function of MV and scatter angle in NCRP 151 Table B.6

Use Factor (U) and Scatter

- Use Factor is typically taken as 1 for secondary calculations
  - Invariably true for leakage calculations
- Scatter is significant only for secondary barriers immediately adjacent to primary barriers
  - Scatter is negligible for all other orientations
  - NCRP 151 : "However, if the [scatter] calculation is performed with the minimum angle of scatter from the patient to the point of calculation and a use factor of 1 is also used, the barrier thickness will be overestimated due to the conservatively higher scatter fraction from the smaller scattering angles"
- Sometimes appropriate to apply use factor to scatter
  - U = 0.25 may be appropriate if scatter angle < 35º
    - » i.e., secondary barrier immediately adjacent to primary barrier
    - » U=0.25 best used only for retrofit (to avoid unnecessary modifications) or if there are severe space constraints
  - Otherwise U = 1

NCRP 151 Table B.4
Patient Scatter Fraction for 400 cm^2 Field

- Scatter fraction increases as angle decreases
- Scatter fraction vs MV may increase or decrease
  - Tends to increase with MV at small scatter angles
  - Decreases with increasing MV at large scatter angles

Linac	Angle (degrees)							
MV	10	20	30	45	60	90	135	150
4	1.04E-02	6.73E-03	2.77E-03	2.09E-03	1.24E-03	6.39E-04	4.50E-04	4.31E-04
6	1.04E-02	6.73E-03	2.77E-03	1.39E-03	8.24E-04	4.26E-04	3.00E-04	2.87E-04
10	1.66E-02	5.79E-03	3.18E-03	1.35E-03	7.46E-04	3.81E-04	3.02E-04	2.74E-04
15	1.51E-02	5.54E-03	2.77E-03	1.05E-03	5.45E-04	2.61E-04	1.91E-04	1.78E-04
18	1.42E-02	5.39E-03	2.53E-03	8.64E-04	4.24E-04	1.89E-04	1.24E-04	1.20E-04
20	1.52E-02	5.66E-03	2.59E-03	8.54E-04	4.13E-04	1.85E-04	1.23E-04	1.18E-04
24	1.73E-02	6.19E-03	2.71E-03	8.35E-04	3.91E-04	1.76E-04	1.21E-04	1.14E-04

Scatter Tenth Value Layers

- From NCRP 151 Table B.5 and Figure A.1

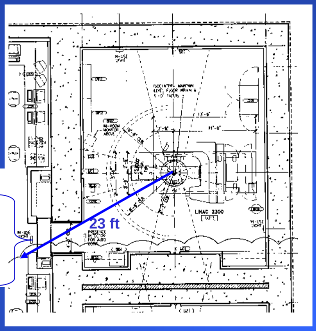
	Concrete Scatter TVL (mm)				
	Scatter Angle (degrees)				
MV	15	30	45	60	90
4	270	250	240	220	180
6	280	260	240	220	190
10	300	270	250	230	190
15	320	280	250	230	210
18	330	280	260	230	210
20	340	290	260	240	210
24	350	300	270	250	210

	Recommended Steel Scatter TVL (mm)					
	Scatter Angle (degrees)					
MV	20	30	45	60	75	90
4	78	72	68	63	58	50
6	83	78	70	64	58	53
10	84	78	71	65	58	54
15	89	82	74	67	62	59
18	92	84	76	68	62	61
20	93	86	78	70	63	61
24	95	88	81	73	66	61

Lead Scatter tenth-value layers (mm)												
	20		30		45		60		75		90	
MV	TVL1	TVLe	TVL1	TVLe	TVL1	TVLe	TVL1	TVLe	TVL1	TVLe	TVL1	TVLe
4	46	46	33	37	24	31	18	25	13	19	9	13
6	50	50	38	44	28	34	19	26	14	19	10	15
10	51	51	43	45	31	36	21	27	15	19	12	16
15	54	54	50	50	41	41	31	31	24	24	21	21
18	55	55	51	51	43	43	32	32	24	24	22	22
20	56	56	52	52	45	45	34	34	26	26	22	22
25	57	57	54	54	48	48	39	39	29	29	22	22

Example 1: Direct Shielded Door — Door Thickness

Door
0.25 steel inner face
2.5” lead
10” borated poly
2.5” lead
0.25” steel outer face



Example 1: Direct Shielded Door Thickness Calculation [1 of 2]

Line	Parameter	Units	Value	Calculation
a	Design Dose Limit (P)	mSv/wk	0.1	
b	Occupancy Factor (T)		1	
c	P/T	mSv/wk	0.100	a / b
d	Machine X-ray Energy	MV	18	
e	Vendor		Varian	

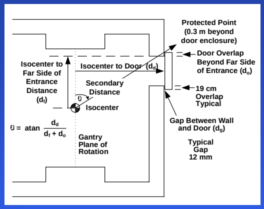
Line	Parameter	Units	Value		Calculation
			w/o IMRT	with IMRT	
a	Max Field Size	cm	40	40	
b	Fraction of Workload		50%	50%	
c	Effective Field Area	cm^2	1600.0		b_1*a_1^2 + b_2*a_2^2
d	Effective Field Size	cm	40.0		sqrt (c)
e	Scatter Angle	deg	60		
f	Machine X-ray Energy	MV	18		
g	Scatter / 400 cm^2		4.24E-04		Function of e & f
h	Scatter Fraction		0.00170		g * c / 400

Example 1: Direct Shielded Door Thickness Calculation [2 of 2]

Line	Parameter	Units	Photon Leakage	Photon Scatter	Neutron Leakage	Calculation
a	Workload / Treatment	Gy/pt	3	3	3	NCRP 151 default
b	Patients per Day	pt/day	30	30	30	NCRP 151 default
c	Workload (W)	Gy/wk	450	450	450	5 * a * b
d	Use Factor	Ratio	1	1	1	
e	Fraction		1.00E-03	1.70E-03	1.5E-03	18 MV values
f	IMRT Factor		2	1	1	
g	Isocenter to Protected Point Distance	ft	23.0	23.0	23.0	
h		m	7.0	7.0	7.0	g * 0.3048
i	Unshielded Dose Rate	mSv/wk	1.83E+01	1.55E+01	1.37E+01	1000*c*d*e*f/h^2
j	Transmission		8.44E-04	8.44E-07	8.81E-04	see below
k	Shielded Dose Rate	mSv/wk	0.0154	0.0000	0.0121	i * j
L	Total Shielded Dose Rate	mSv/wk	0.0276			Sum row k

Barrier	Material Thickness	Slant Thickness	Material	Photon Leakage			Scatter			Neutron	
	inches	mm		TVL1 (mm)	TVLe (mm)	Trans.	TVL1 (mm)	TVLe (mm)	Trans.	TVL (mm)	Trans.
Inside Layer	0.25	7	Steel	96	96	8.39E-01	68	68	7.80E-01	N/A	1.00E+00
Layer #2	2.5	73	Lead	57	57	5.17E-02	32	32	5.11E-03	N/A	1.00E+00
Layer #3	10	293	Borated Poly	891	842	4.48E-01	230	230	5.31E-02	96	8.81E-04
Layer #4	2.5	73	Lead	57	57	5.17E-02	32	32	5.11E-03	N/A	1.00E+00
Outside Layer	0.25	7	Steel	96	96	8.39E-01	68	68	7.80E-01	N/A	1.00E+00
Slant Angle (degrees):		30		18 MV	Total:	8.44E-04		Total:	8.44E-07	Total:	8.81E-04

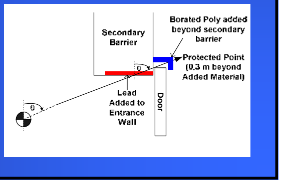
Direct-Shielded Door: Far Side of Entrance



- Direct leakage path occurs at the far lateral edge of the door
- Slant thickness through the wall at the corner (d_C) is given by

$$d_C = \frac{d_o}{\cos(\theta)} - \frac{d_g}{\sin(\theta)} \qquad \theta = \text{atan}\,\frac{d_d}{d_f + d_o}$$

  - d_o is the door overlap
  - d_g is gap between the wall & door
- Shielding next to door
  - Compensates for slant thickness (d_C) being inadequate for direct leakage and scatter
  - Lead provides shielding needed for x-ray leakage & patient scatter
  - Borated polyethylene provides shielding for neutron leakage

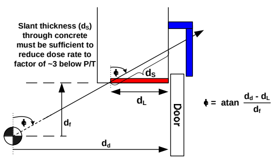


Length of Lead Required at Far Side of Entrance

- Slant thickness (d_S) through the wall not benefiting from additional shielding

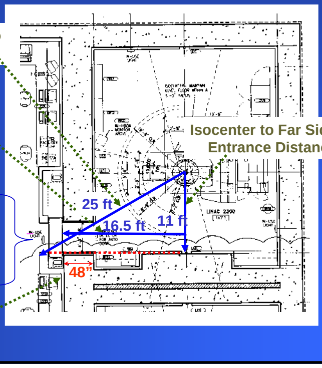
$$d_S = \frac{d_L}{\cos(\phi)}$$

$$\phi = \text{atan}\,\frac{d_d - d_L}{d_f}$$



  - d_L is the length of the lead added to the wall
  - d_g is gap between the wall & door
  - d_f is isocenter to far side of entrance distance (in plane of rotation)
  - d_d is isocenter to door distance (perpendicular to plane of rotation)
- Select d_L sufficiently large so that slant distance d_S through wall provides adequate shielding
  - Preferably factor of 3 margin to allow for scatter from door & HVAC penetration

Example 2: Direct Shielded Door — Additional Shielding for Far Side of Door



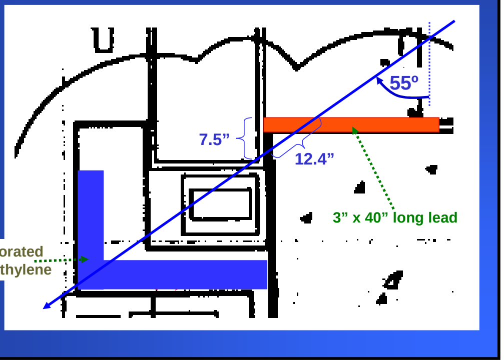
Secondary Distance to Far Side of Entrance

Isocenter to Inside Face of Door Distance

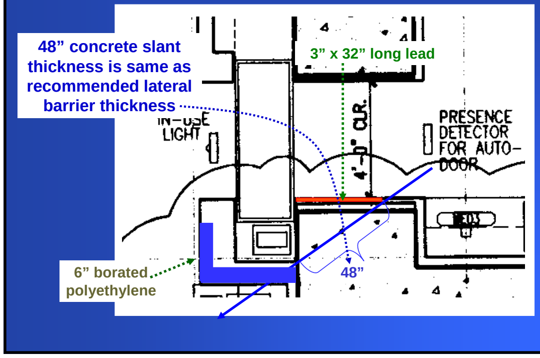
Isocenter to Far Side of Entrance Distance

Secondary Barrier Thickness on Far Side of Entrance

Example 2: Direct Shielded Door — Additional Shielding for Far Side of Door



Example 2: Direct Shielded Door — Additional Shielding for Far Side of Door



48” concrete slant thickness is same as recommended lateral barrier thickness

3” x 32” long lead

6” borated polyethylene

Example 2: Direct Shielded Door Far Side of Entrance Shielded Dose Rate Calculation [1 of 3]

Far Side of Door Distance, Thickness, and Length Calculations

Line	Parameter	Units	Value	Calculation
a	Door Overlap	in	7.5	
b	Gap Between Barrier and Door	in	0.5	
c	Distance from Isocenter to Far Side of Entrance	ft	11	
d		in	132	c * 12
e	Distance from Isocenter to Inside Face of Door	ft	16.5	
f		in	198	e * 12
g	Slant Angle at Far Side of Entrance	deg	54.8	atan(f / (a + d))
h	Slant Thickness at Corner	in	12.4	a / cos(g) - b / sin(g)
i		mm	315	25.4 * h
j	Thickness of Lead Added to Wall	in	3	Selected value
k	Slant Thickness through Lead	mm	132	25.4 * j / cos(g)
L	Slant Thickness through Concrete	in	183	i - k
m	Concrete Thickness	in	4.15	L * cos(g) / 25.4
n	Borated Poly Thickness	in	6	Selected value
o	Borated Poly Slant Thickness	mm	186	25.4 * n / sin(g)
p	Minimum Desired Slant Thickness	in	42	Dose rate < P/T / 3
q	Minimum Length of Added Lead	in	35	p * sin(g)

- Thicknesses selected to make shielded dose rate less than dose limit

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Example 2: Direct Shielded Door Far Side of Entrance Shielded Dose Rate Calculation [2 of 3]

Far Side of Door Scatter Fraction Calculation

Line	Parameter	Units	Value		Calculation
			w/o IMRT	with IMRT	
a	Max Field Size	cm	40	40	
b	Fraction of Workload		50%	50%	
c	Effective Field Area	cm^2	1600.0		b_1*a_1^2 + b_2*a_2^2
d	Effective Field Size	cm	40.0		sqrt (c)
e	Scatter Angle	deg	54.8		
f	Machine X-ray Energy	MV	18		
g	Scatter / 400 cm^2		5.42E-04		Function of e & f
h	Scatter Fraction		0.00217		g * c / 400

Example 2: Direct Shielded Door Far Side of Entrance Shielded Dose Rate Calculation [3 of 3]

Line	Parameter	Units	Photon Leakage	Photon Scatter	Neutron Leakage	Calculation
a	Workload / Treatment	Gy/pt	3	3	3	NCRP 151 default
b	Patients per Day	pt/day	30	30	30	NCRP 151 default
c	Workload (W)	Gy/wk	450	450	450	5 * a * b
d	Use Factor	Ratio	1	1	1	
e	Fraction		1.00E-03	2.17E-03	1.50E-03	18 MV values
f	IMRT Factor		2	1	1	
g	Isocenter to Protected Point Distance	ft	25.0	25.0	25.0	
h		m	7.6	7.6	7.6	g * 0.3048
i	Unshielded Dose	mSv/wk	1.55E+01	1.68E+01	1.16E+01	1000*c*d*e*f/h^2
j	Transmission		8.31E-04	6.14E-06	1.55E-03	see below
k	Shielded Dose	mSv/wk	0.013	0.000	0.018	i * j
L	Total Shielded Dose	mSv/wk	0.031			Sum row k

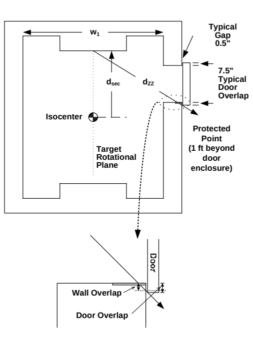
Barrier	Material Thickness	Slant Thickness	Material	Photon Leakage			Scatter			Neutron	
	inches	mm		TVL1 (mm)	TVLe (mm)	Trans.	TVL1 (mm)	TVLe (mm)	Trans.	TVL (mm)	Trans.
Inside Layer	3	132	Lead	57	57	4.77E-03	36	36	2.01E-04	N/A	1.00E+00
Layer #2	4.1	183	Concrete	360	340	2.90E-01	244	244	1.78E-01	211	1.36E-01
Layer #3	6	186	Borated Poly	891	842	6.01E-01	244	244	1.72E-01	96	1.14E-02
Layer #4						1.00E+00			1.00E+00		1.00E+00
Outside Layer						1.00E+00			1.00E+00		1.00E+00
Slant Angle (degrees):		54.8		18 MV	Total:	8.31E-04		Total:	6.14E-06	Total:	1.55E-03

Direct-Shielded Door: Near Side of Entrance Wall Scatter

- Geometry similar to short maze
  - Scatter is significant only if < 10 MV
- Unshielded dose rate

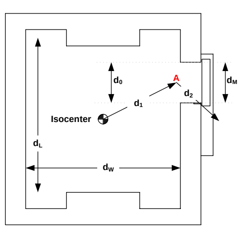
$$f\,H_S = f\,\frac{W\,U\,\alpha_0\,A_0\,\alpha_z\,A_z}{d_H^2\,d_r^2\,d_z^2}$$

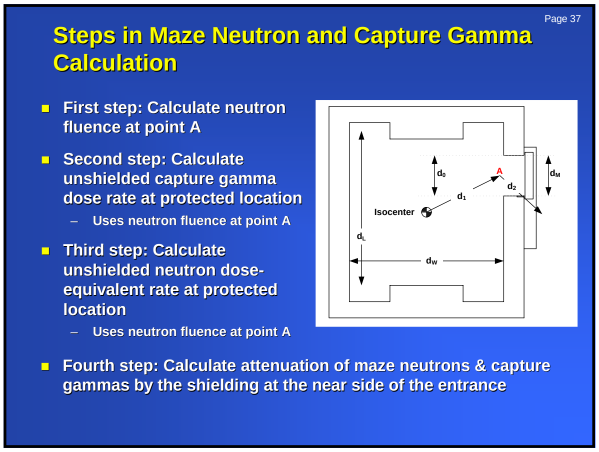
- where
  - f = patient transmission (0.25)
  - α_0 = first reflection coefficient
    - NCRP 151 Table B.8a vs. MV
    - 75º angle of reflection typical
  - A_0 = beam area (m^2) at wall
  - α_z = 2nd reflection coefficient
    - 0.5 MV at 75º in Table B.8a
  - A_z = Maze cross section (m^2)
    - w_M x maze height



Direct-Shielded Door: Near Side of Entrance Neutrons / Capture Gammas

- Geometry similar to short maze
  - Therefore reasonable to apply maze calculation
- Geometry is not exactly the same as a short maze
  - Also reasonable to include margin since maze calculation may underestimate neutron dose rate
- Neutrons & capture gammas dominate scatter for MV ≥ 10
- Requires less material than far side of entrance
  - Lower unshielded dose rate
  - Lower energy





Steps in Maze Neutron and Capture Gamma Calculation

- First step: Calculate neutron fluence at point A
- Second step: Calculate unshielded capture gamma dose rate at protected location
  - Uses neutron fluence at point A
- Third step: Calculate unshielded neutron dose-equivalent rate at protected location
  - Uses neutron fluence at point A
- Fourth step: Calculate attenuation of maze neutrons & capture gammas by the shielding at the near side of the entrance

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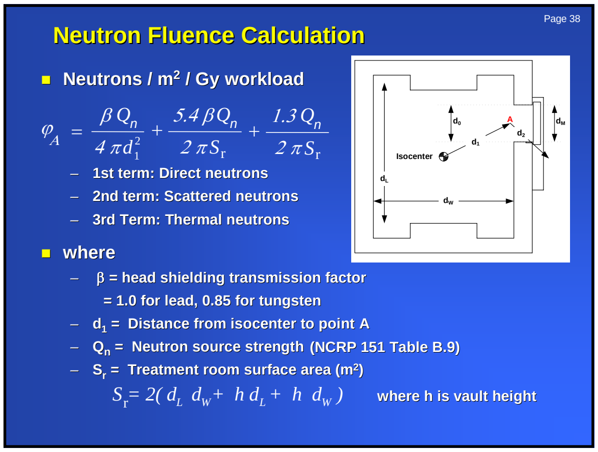

Neutron Fluence Calculation

- Neutrons / m^2 / Gy workload

$$\varphi_A = \frac{\beta Q_n}{4\pi d_1^2} + \frac{5.4\,\beta Q_n}{2\pi S_r} + \frac{1.3\,Q_n}{2\pi S_r}$$

  - 1st term: Direct neutrons
  - 2nd term: Scattered neutrons
  - 3rd Term: Thermal neutrons
- where
  - β = head shielding transmission factor
    = 1.0 for lead, 0.85 for tungsten
  - d_1 = Distance from isocenter to point A
  - Q_n = Neutron source strength (NCRP 151 Table B.9)
  - S_r = Treatment room surface area (m^2)

$$S_r = 2(d_L\, d_W + h\, d_L + h\, d_W)$$ where h is vault height

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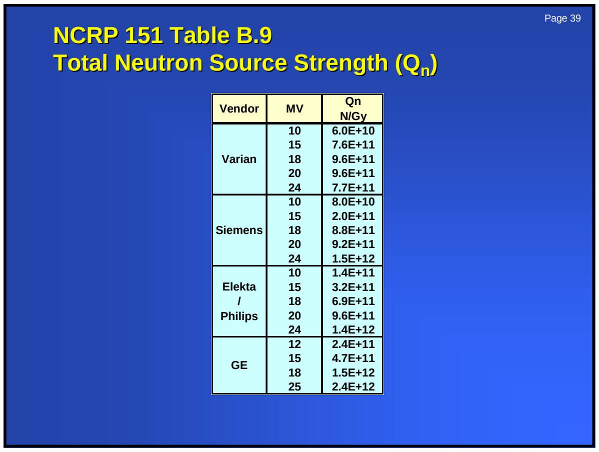
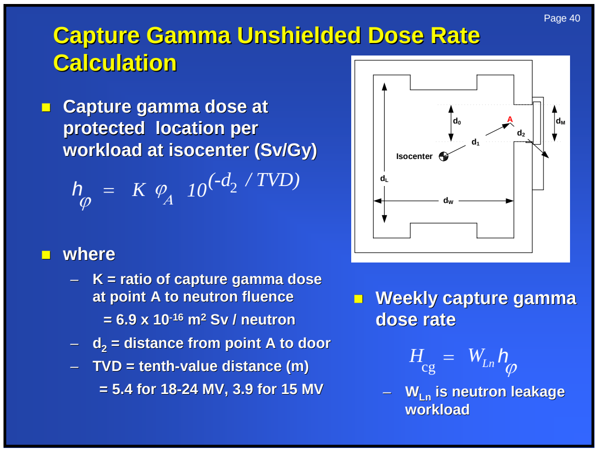


NCRP 151 Table B.9
Total Neutron Source Strength (Q_n)

Vendor	MV	Qn N/Gy
Varian	10	6.0E+10
	15	7.6E+11
	18	9.6E+11
	20	9.6E+11
	24	7.7E+11
Siemens	10	8.0E+10
	15	2.0E+11
	18	8.8E+11
	20	9.2E+11
	24	1.5E+12
Elekta / Philips	10	1.4E+11
	15	3.2E+11
	18	6.9E+11
	20	9.6E+11
	24	1.4E+12
GE	12	2.4E+11
	15	4.7E+11
	18	1.5E+12
	25	2.4E+12



Capture Gamma Unshielded Dose Rate Calculation

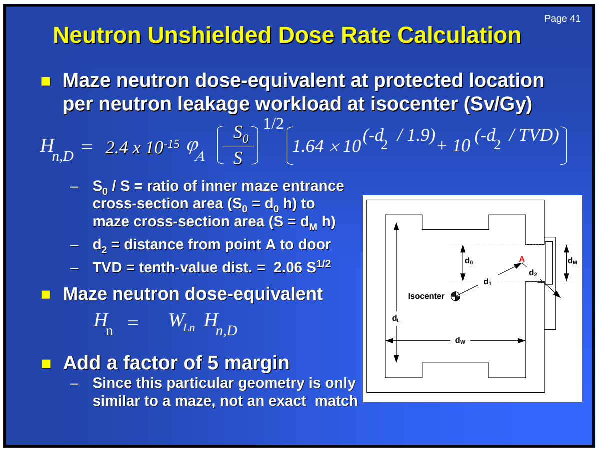
- Capture gamma dose at protected location per workload at isocenter (Sv/Gy)

$$h_\varphi = K\,\varphi_A\,10^{(-d_2/TVD)}$$

- where
  - K = ratio of capture gamma dose at point A to neutron fluence
    = 6.9 x 10^{-16} m^2 Sv / neutron
  - d_2 = distance from point A to door
  - TVD = tenth-value distance (m)
    = 5.4 for 18-24 MV, 3.9 for 15 MV
- Weekly capture gamma dose rate

$$H_{cg} = W_{Ln}\, h_\varphi$$

  - W_{Ln} is neutron leakage workload



Neutron Unshielded Dose Rate Calculation

- Maze neutron dose-equivalent at protected location per neutron leakage workload at isocenter (Sv/Gy)

$$H_{n,D} = 2.4 \times 10^{-15}\,\varphi_A \left(\frac{S_0}{S}\right)^{1/2} \left[1.64 \times 10^{(-d_2/1.9)} + 10^{(-d_2/TVD)}\right]$$

  - S_0 / S = ratio of inner maze entrance cross-section area ($S_0 = d_0$ h) to maze cross-section area (S = d_M h)
  - d_2 = distance from point A to door
  - TVD = tenth-value dist. = 2.06 $S^{1/2}$
- Maze neutron dose-equivalent

$$H_n = W_{Ln}\, H_{n,D}$$

- Add a factor of 5 margin
  - Since this particular geometry is only similar to a maze, not an exact match

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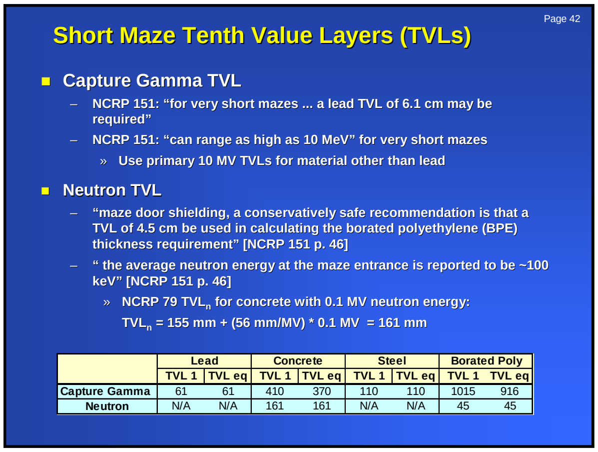
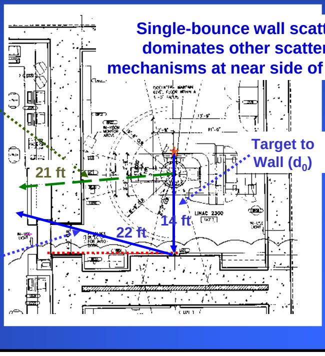


Short Maze Tenth Value Layers (TVLs)

- Capture Gamma TVL
  - NCRP 151: "for very short mazes ... a lead TVL of 6.1 cm may be required"
  - NCRP 151: "can range as high as 10 MeV" for very short mazes
    - » Use primary 10 MV TVLs for material other than lead
- Neutron TVL
  - "maze door shielding, a conservatively safe recommendation is that a TVL of 4.5 cm be used in calculating the borated polyethylene (BPE) thickness requirement" [NCRP 151 p. 46]
  - " the average neutron energy at the maze entrance is reported to be ~100 keV" [NCRP 151 p. 46]
    - » NCRP 79 TVL_n for concrete with 0.1 MV neutron energy:
      TVL_n = 155 mm + (56 mm/MV) * 0.1 MV = 161 mm

	Lead		Concrete		Steel		Borated Poly	
	TVL 1	TVL eq	TVL 1	TVL eq	TVL 1	TVL eq	TVL 1	TVL eq
Capture Gamma	61	61	410	370	110	110	1015	916
Neutron	N/A	N/A	161	161	N/A	N/A	45	45

Example 3: Direct Shielded Door— Additional Shielding for Near Side of Door (Wall Scatter)



Single-bounce wall scatter dominates other scatter mechanisms at near side of door

Secondary Distance (d)

Target to Wall (d_0)

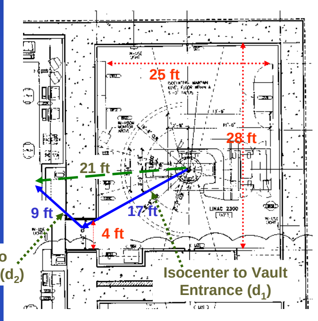
21 ft

14 ft

22 ft

Wall to Near Side of Door (d_r)

Example 3: Direct Shielded Door— Additional Shielding for Near Side of Door (Neutrons / Capture Gammas)



25 ft

28 ft

21 ft

9 ft

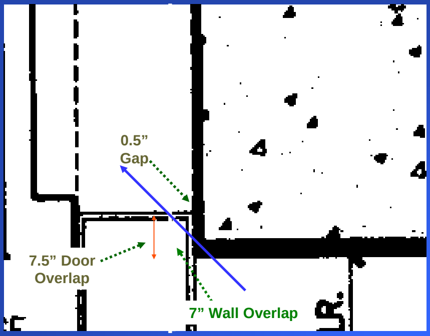
17 ft

4 ft

Entrance to Protected Pt (d_2)

Isocenter to Vault Entrance (d_1)

Example 3: Direct Shielded Door — Gap Between Wall and Door

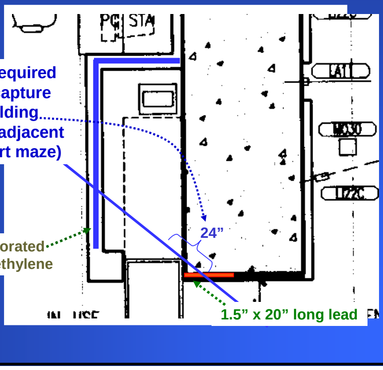


0.5” Gap

7.5” Door Overlap

7” Wall Overlap

Example 3: Direct Shielded Door — Additional Shielding for Near Side of Door



24” concrete required neutron and capture gamma shielding (similar to wall adjacent to door for short maze)

24”

3” borated polyethylene

1.5” x 20” long lead

Example 3: Direct Shielded Door Near Side of Entrance Shielded Dose Rate Calculation [1 of 9]

Near Side of Door Material Thickness Calculation

Line	Parameter	Units	Value	Calculation
a	Door Overlap	in	7.5	
b	Gap Between Barrier and Door	in	0.5	
c	Angle at Near Side Wall	deg	45.0	
d	Wall Overlap Beyond Entrance	in	7.0	(a*tan(c) - b)/ tan(c)
e	Thickness of Lead Added to Wall	in	1.5	
f	Remaining Concrete Wall	in	5.5	d - e
g	Material Added beyond Wall	in	3	

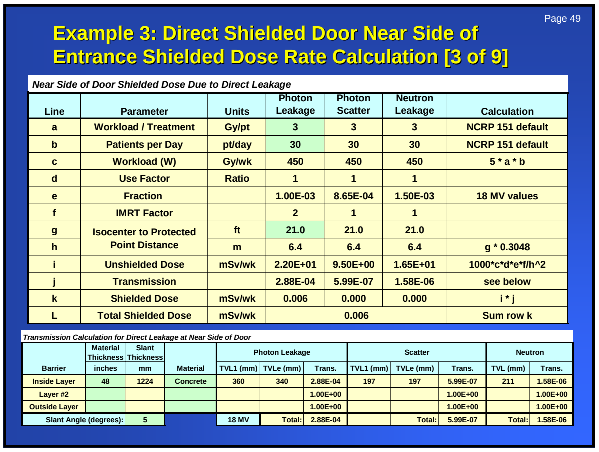
- Material added to wall selected as required to make shielded dose rate less than dose limit

---

Example 3: Direct Shielded Door Near Side of Entrance Shielded Dose Rate Calculation [2 of 9]

Near Side of Door Scatter Fraction Calculation

Line	Parameter	Units	Value		Calculation
			w/o IMRT	with IMRT	
a	Max Field Size	cm	40	40	
b	Fraction of Workload		50%	50%	
c	Effective Field Area	cm^2	1600.0		b_1*a_1^2 + b_2*a_2^2
d	Effective Field Size	cm	40.0		sqrt (c)
e	Scatter Angle	deg	85		
f	Machine X-ray Energy	MV	18		
g	Scatter / 400 cm^2		2.16E-04		Function of e & f
h	Scatter Fraction		0.00086		g * c / 400



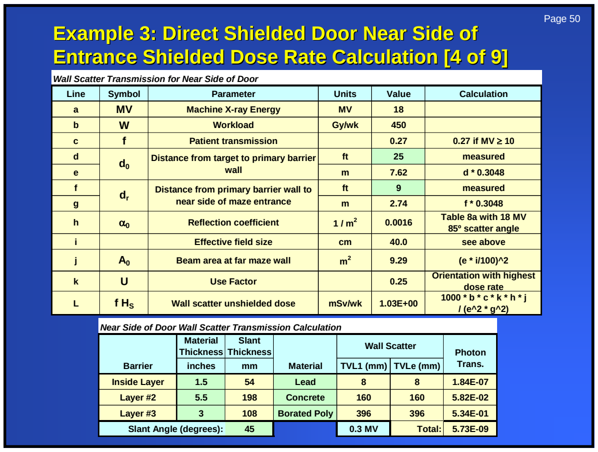
Example 3: Direct Shielded Door Near Side of Entrance Shielded Dose Rate Calculation [3 of 9]

Near Side of Door Shielded Dose Due to Direct Leakage

Line	Parameter	Units	Photon Leakage	Photon Scatter	Neutron Leakage	Calculation
a	Workload / Treatment	Gy/pt	3	3	3	NCRP 151 default
b	Patients per Day	pt/day	30	30	30	NCRP 151 default
c	Workload (W)	Gy/wk	450	450	450	5 * a * b
d	Use Factor	Ratio	1	1	1	
e	Fraction		1.00E-03	8.65E-04	1.50E-03	18 MV values
f	IMRT Factor		2	1	1	
g	Isocenter to Protected Point Distance	ft	21.0	21.0	21.0	
h		m	6.4	6.4	6.4	g * 0.3048
i	Unshielded Dose	mSv/wk	2.20E+01	9.50E+00	1.65E+01	1000*c*d*e*f/h^2
j	Transmission		2.88E-04	5.99E-07	1.58E-06	see below
k	Shielded Dose	mSv/wk	0.006	0.000	0.000	i * j
L	Total Shielded Dose	mSv/wk	0.006			Sum row k

Transmission Calculation for Direct Leakage at Near Side of Door

	Material Thickness	Slant Thickness		Photon Leakage			Scatter			Neutron	
Barrier	inches	mm	Material	TVL1 (mm)	TVLe (mm)	Trans.	TVL1 (mm)	TVLe (mm)	Trans.	TVL (mm)	Trans.
Inside Layer	48	1224	Concrete	360	340	2.88E-04	197	197	5.99E-07	211	1.58E-06
Layer #2						1.00E+00			1.00E+00		1.00E+00
Outside Layer						1.00E+00			1.00E+00		1.00E+00
Slant Angle (degrees):		5		18 MV	Total:	2.88E-04		Total:	5.99E-07	Total:	1.58E-06



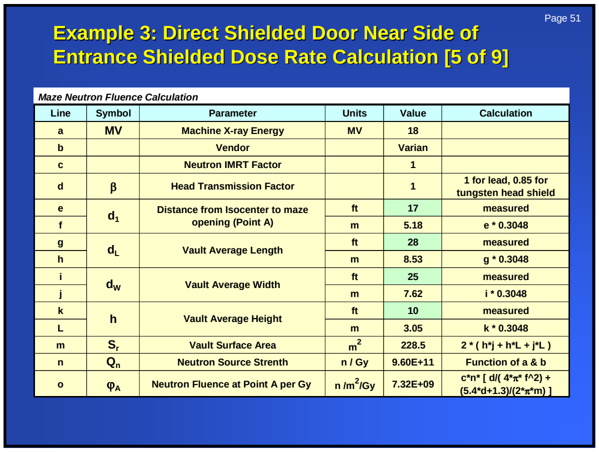
Example 3: Direct Shielded Door Near Side of Entrance Shielded Dose Rate Calculation [4 of 9]

Wall Scatter Transmission for Near Side of Door

Line	Symbol	Parameter	Units	Value	Calculation
a	MV	Machine X-ray Energy	MV	18	
b	W	Workload	Gy/wk	450	
c	f	Patient transmission		0.27	0.27 if MV ≥ 10
d	d_0	Distance from target to primary barrier wall	ft	25	measured
e			m	7.62	d * 0.3048
f	d_r	Distance from primary barrier wall to near side of maze entrance	ft	9	measured
g			m	2.74	f * 0.3048
h	α_0	Reflection coefficient	1 / m^2	0.0016	Table 8a with 18 MV 85º scatter angle
i		Effective field size	cm	40.0	see above
j	A_0	Beam area at far maze wall	m^2	9.29	(e * i/100)^2
k	U	Use Factor		0.25	Orientation with highest dose rate
L	$f\ H_S$	Wall scatter unshielded dose	mSv/wk	1.03E+00	1000 * b * c * k * h * j / (e^2 * g^2)

Near Side of Door Wall Scatter Transmission Calculation

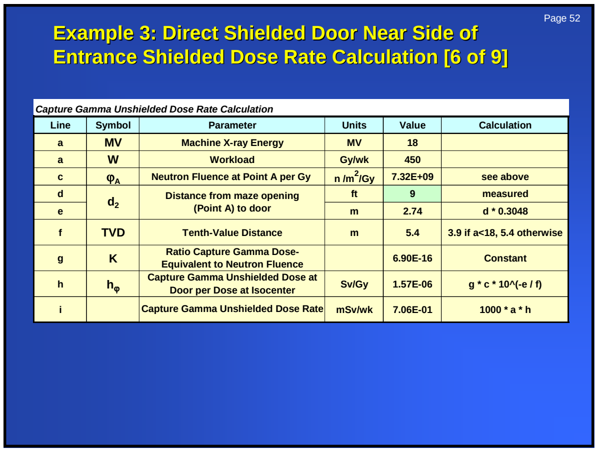
	Material Thickness	Slant Thickness		Wall Scatter		Photon Trans.
Barrier	inches	mm	Material	TVL1 (mm)	TVLe (mm)	
Inside Layer	1.5	54	Lead	8	8	1.84E-07
Layer #2	5.5	198	Concrete	160	160	5.82E-02
Layer #3	3	108	Borated Poly	396	396	5.34E-01
Slant Angle (degrees):		45		0.3 MV	Total:	5.73E-09



Example 3: Direct Shielded Door Near Side of Entrance Shielded Dose Rate Calculation [5 of 9]

Maze Neutron Fluence Calculation

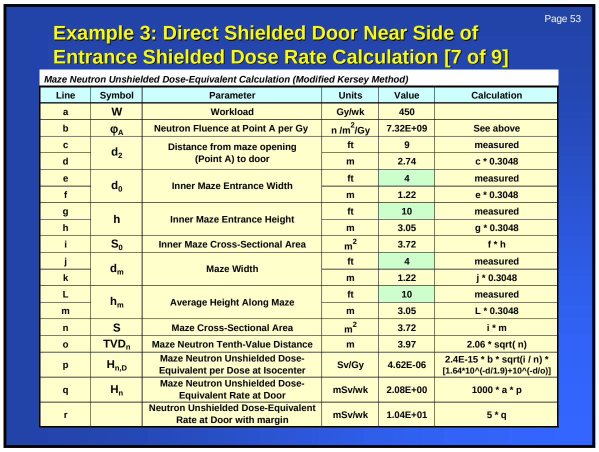
Line	Symbol	Parameter	Units	Value	Calculation
a	MV	Machine X-ray Energy	MV	18	
b		Vendor		Varian	
c		Neutron IMRT Factor		1	
d	β	Head Transmission Factor		1	1 for lead, 0.85 for tungsten head shield
e	d_1	Distance from Isocenter to maze opening (Point A)	ft	17	measured
f			m	5.18	e * 0.3048
g	d_L	Vault Average Length	ft	28	measured
h			m	8.53	g * 0.3048
i	d_W	Vault Average Width	ft	25	measured
j			m	7.62	i * 0.3048
k	h	Vault Average Height	ft	10	measured
L			m	3.05	k * 0.3048
m	S_r	Vault Surface Area	m^2	228.5	2 * (h*j + h*L + j*L)
n	Q_n	Neutron Source Strenth	n / Gy	9.60E+11	Function of a & b
o	φ_A	Neutron Fluence at Point A per Gy	n /m^2/Gy	7.32E+09	c*n* [d/(4*π* f^2) + (5.4*d+1.3)/(2*π*m)]



Example 3: Direct Shielded Door Near Side of Entrance Shielded Dose Rate Calculation [6 of 9]

Capture Gamma Unshielded Dose Rate Calculation

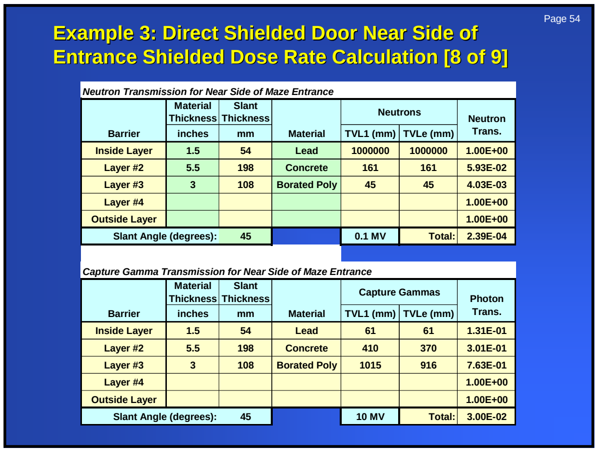
Line	Symbol	Parameter	Units	Value	Calculation
a	MV	Machine X-ray Energy	MV	18	
a	W	Workload	Gy/wk	450	
c	φ_A	Neutron Fluence at Point A per Gy	n /m^2/Gy	7.32E+09	see above
d	d_2	Distance from maze opening (Point A) to door	ft	9	measured
e			m	2.74	d * 0.3048
f	TVD	Tenth-Value Distance	m	5.4	3.9 if a<18, 5.4 otherwise
g	K	Ratio Capture Gamma Dose-Equivalent to Neutron Fluence		6.90E-16	Constant
h	h_φ	Capture Gamma Unshielded Dose at Door per Dose at Isocenter	Sv/Gy	1.57E-06	g * c * 10^(-e / f)
i		Capture Gamma Unshielded Dose Rate	mSv/wk	7.06E-01	1000 * a * h



Example 3: Direct Shielded Door Near Side of Entrance Shielded Dose Rate Calculation [7 of 9]

Maze Neutron Unshielded Dose-Equivalent Calculation (Modified Kersey Method)

Line	Symbol	Parameter	Units	Value	Calculation
a	W	Workload	Gy/wk	450	
b	φ_A	Neutron Fluence at Point A per Gy	n /m^2/Gy	7.32E+09	See above
c	d_2	Distance from maze opening (Point A) to door	ft	9	measured
d			m	2.74	c * 0.3048
e	d_0	Inner Maze Entrance Width	ft	4	measured
f			m	1.22	e * 0.3048
g	h	Inner Maze Entrance Height	ft	10	measured
h			m	3.05	g * 0.3048
i	S_0	Inner Maze Cross-Sectional Area	m^2	3.72	f * h
j	d_m	Maze Width	ft	4	measured
k			m	1.22	j * 0.3048
L	h_m	Average Height Along Maze	ft	10	measured
m			m	3.05	L * 0.3048
n	S	Maze Cross-Sectional Area	m^2	3.72	i * m
o	TVD_n	Maze Neutron Tenth-Value Distance	m	3.97	2.06 * sqrt(n)
p	$H_{n,D}$	Maze Neutron Unshielded Dose-Equivalent per Dose at Isocenter	Sv/Gy	4.62E-06	2.4E-15 * b * sqrt(i / n) * [1.64*10^(-d/1.9)+10^(-d/o)]
q	H_n	Maze Neutron Unshielded Dose-Equivalent Rate at Door	mSv/wk	2.08E+00	1000 * a * p
r		Neutron Unshielded Dose-Equivalent Rate at Door with margin	mSv/wk	1.04E+01	5 * q



Example 3: Direct Shielded Door Near Side of Entrance Shielded Dose Rate Calculation [8 of 9]

Neutron Transmission for Near Side of Maze Entrance

	Material Thickness	Slant Thickness		Neutrons		Neutron Trans.
Barrier	inches	mm	Material	TVL1 (mm)	TVLe (mm)	
Inside Layer	1.5	54	Lead	1000000	1000000	1.00E+00
Layer #2	5.5	198	Concrete	161	161	5.93E-02
Layer #3	3	108	Borated Poly	45	45	4.03E-03
Layer #4						1.00E+00
Outside Layer						1.00E+00
Slant Angle (degrees):		45		0.1 MV	Total:	2.39E-04

Capture Gamma Transmission for Near Side of Maze Entrance

	Material Thickness	Slant Thickness		Capture Gammas		Photon Trans.
Barrier	inches	mm	Material	TVL1 (mm)	TVLe (mm)	
Inside Layer	1.5	54	Lead	61	61	1.31E-01
Layer #2	5.5	198	Concrete	410	370	3.01E-01
Layer #3	3	108	Borated Poly	1015	916	7.63E-01
Layer #4						1.00E+00
Outside Layer						1.00E+00
Slant Angle (degrees):		45		10 MV	Total:	3.00E-02

Example 3: Direct Shielded Door Near Side of Entrance Shielded Dose Rate Calculation [9 of 9]

Maze Shielded Dose at Door

Line	Parameter	Units	Wall Scatter	Direct Leakage	Neutrons	Capture Gammas
a	Calc. Unshielded Dose	mSv/wk	1.03E+00	6.36E-03	1.04E+01	7.06E-01
b	Total / Calc. Dose Rate		2.64	1	1	1
c	Unshielded Dose Rate	mSv/wk	2.73E+00	6.36E-03	1.04E+01	7.06E-01
b	Energy for TVL	MV	0.3	18	0.1	10.0
c	Transmission		5.73E-09	1.00E+00	2.39E-04	3.00E-02
d	Shielded Dose	mSv/wk	0.0000	0.0064	0.0025	0.0212
e	Total Shielded Dose	mSv/wk	0.0300			

Contact Information

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