Linear Accelerator Direct Shielded Doors

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

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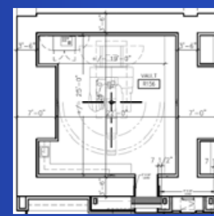
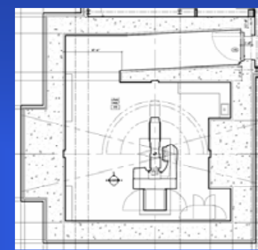
Vault Exterior Size Can be Reduced by Using a Direct Shielded Door Instead of a Maze

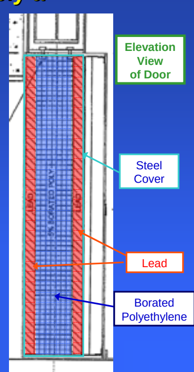




- Linear accelerator vaults have historically included mazes
- Trend is toward increased use of direct shielded doors
  - ~50% of new construction in USA

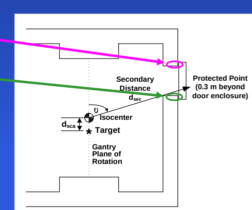
A Direct Shielded Door is Simply a Secondary Barrier

- Typically 25 to 28 cm thick borated polyethylene for 18 MV machine
  - Attenuates leakage neutrons
  - Approximately half of the polyethylene need not have boron added
    - » Just as effective and less costly
  - Not required if less than 10 MV
- 15 cm thick lead is typical, with half on inside and half outside the polyethylene
  - Distributes weight in the door
  - Lead on outside attenuates capture gammas from polyethylene
  - Lead on inside reduces neutron energy, improving neutron capture by polyethylene
- 6 mm thick steel covers



Limited Overlap of the Door with the Entrance Requires Specialized Shielding

- Far side of entrance sees direct leakage and scatter
- Near side of entrance resembles maze geometry
  - Not directly visible from target
  - Implies maze neutrons and capture gamma are present
  - Direct leakage through wall
- Less expensive to add shielding to wall than to increase door overlap



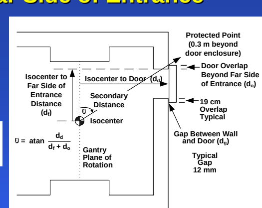
An approach to quantify this shielding is described here

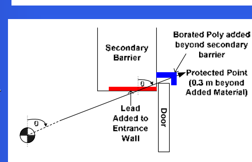
Direct-Shielded Door: Far Side of Entrance

- 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

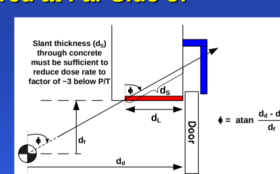




Length of Lead Required at Far Side of Entrance

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

$$d_S = \frac{d_L}{\cos(\phi)} \qquad \phi = \text{atan}\,\frac{d_d - d_L}{d_f}$$



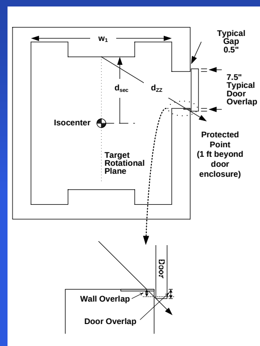
  - d_L is the length of the lead added to the wall
  - d_g is gap between the wall & door
  - d_f is isocenter to far side of entrance distance (in plane of rotation)
  - d_d is isocenter to door distance (perpendicular to plane of rotation)
- Select d_L sufficiently large so that slant distance d_S through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

Direct-Shielded Door: Near Side of Entrance Wall Scatter

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

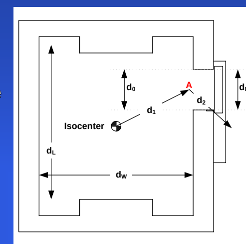
$$f\,H_S = f\,\frac{W\,U\,\alpha_0\,A_0\,\alpha_z\,A_z}{d_H^2\;d_r^2\;d_z^2}$$

- 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 (m²) at wall
  - α_z = 2nd reflection coefficient
    - 0.5 MV at 75º in Table B.8a
  - A_z = Maze cross section (m²)
    - w_M x maze height



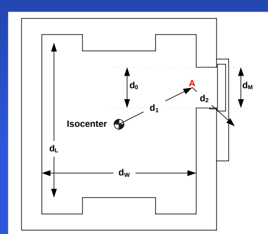
Direct-Shielded Door: Near Side of Entrance Neutrons / Capture Gammas

- 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



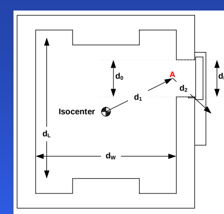
Neutron Fluence Calculation

- Neutrons / m² / 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 (m²)

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



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

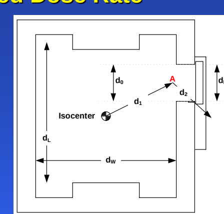
Vendor	MV	Qn N/Gy
Varian	10	6.0E+10
	15	7.6E+11
	18	9.6E+11
	20	9.6E+11
	24	7.7E+11
Siemens	10	8.0E+10
	15	2.0E+11
	18	8.8E+11
	20	9.2E+11
	24	1.5E+12
Elekta / Philips	10	1.4E+11
	15	3.2E+11
	18	6.9E+11
	20	9.6E+11
	24	1.4E+12
GE	12	2.4E+11
	15	4.7E+11
	18	1.5E+12
	25	2.4E+12

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 m² 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

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

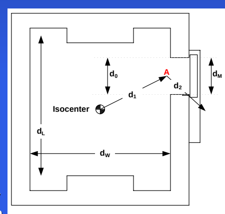
  - W_{Ln} is neutron leakage workload

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

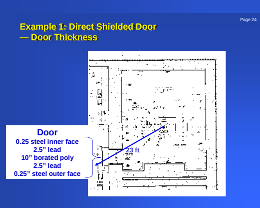
Short Maze Tenth Value Layers (TVLs)

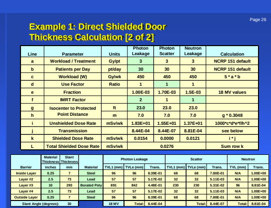
- Capture Gamma TVL
  - NCRP 151: "for very short mazes ... a lead TVL of 6.1 cm may be required"
  - NCRP 151: "can range as high as 10 MeV" for very short mazes
    - » Use primary 10 MV TVLs for material other than lead
- Neutron TVL
  - "maze door shielding, a conservatively safe recommendation is 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 Calculations Can be Found on TherapyPhysics.com Web Site

- Shielding Example URL
  - http://www.therapyphysics.com/WC2009_Examples.pdf





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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

Approaches to Reduce the Amount of Supplementary Shielding

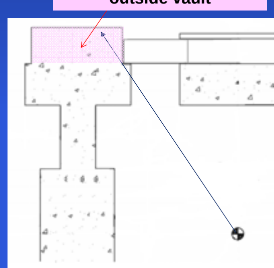
- Concrete wall extension outside vault on far side of door
  - Reduces the supplemental shielding required at the far side of the entrance
- Concrete wall extension inside vault on near side of door
  - Makes entrance half-way between maze and traditional direct shielded door
  - Reduces the amount of lead and borated polyethylene in the door
  - Reduces specialized shielding required next to the door

These approaches reduce shielding but may increase vault size

Concrete Wall Extension Outside Vault

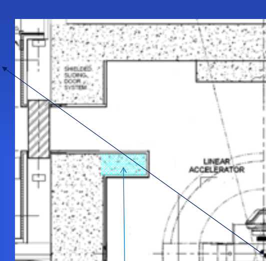
- Wall extension adds concrete at corner
  - Can eliminate lead in far entrance wall
    - » If concrete extends sufficiently far
  - May also eliminate need for borated polyethylene
- Single extension can provide shielding for two vaults if the vaults are back-to-back
- May not be easily compatible with all vendor designs
- Consumes floor space outside vault

Concrete wall extension outside vault



Concrete Wall Extension Inside Vault

- Wall extension adds concrete prior to door
  - Can significantly reduce door thickness
  - Can eliminate lead & borated poly in far entrance wall
- Shielding in both sides of entrance wall is calculated using "near side" approach
  - Geometry used for direct leakage calculation is different for near and far side
  - Capture gamma and maze neutron calculation is the same for near and far side

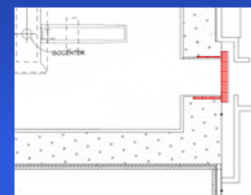


Concrete wall extension inside vault

Direct Shielded Doors for Other Types of Vaults: Tomotherapy and Cyberknife

Direct Shielded Door for Tomotherapy Vault

- 6 MV machine, so no need to shield neutrons
  - Borated polyethylene not required
- High IMRT ratio (16) & % IMRT (100%) increases need for photon shielding
  - Door requires ~20 cm lead vs. typical ~15 cm
  - Far side of entrance requires ~8 cm lead vs. typical ~5 cm



- Near side of entrance requires shielding for scatter only
  - No neutrons or capture gammas
  - Shielding comparable or less than typical high conventional high MV linac vault (~3 cm) despite high leakage workload

Direct Shielded Door for Cyberknife Vault

- 6 MV machine, so no need to shield neutrons
  - Borated polyethylene not required
- Lateral barriers require combined primary and secondary calculation
  - Including door & far side of entrance
  - Very low (0.05) Use Factor for primary calculations
  - Door ~20 cm lead vs. typical ~15 cm

- Near side of entrance shielded for scatter only (unless near side is visible from target)
- Example above requires combined primary and secondary calculation for both sides of entrance
  - Entrance is located near isocenter so both walls are visible from target

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