Maze Calculations / Door Design

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Maze Calculation Categories

- Scatter Mechanisms
  - Wall Scatter
  - Patient Scatter
  - Leakage Scatter
- Direct Leakage
  - Conventional secondary barrier calculation
- High Energy Accelerator Mechanisms
  - Neutrons
  - Capture Gammas

Topics

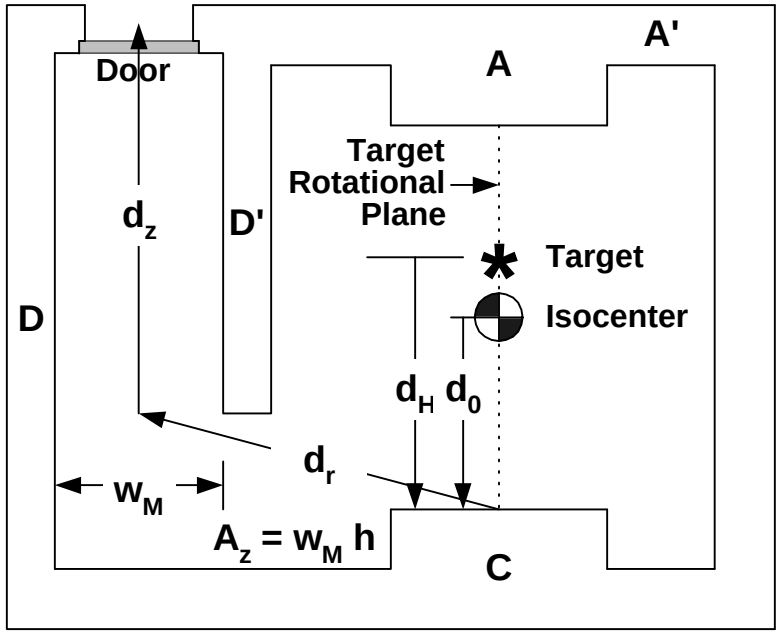
- Specific calculations described in NCRP 151 for each of the maze mechanisms
- Two Detailed Examples
  - Long maze at 6 MV
    - » Illustrates the scatter mechanism calculations
  - Long maze at 18 MV
    - » Illustrates neutron / capture gamma calculations
- Four Less-Detailed Examples
  - Short maze
  - Maze with additional bend
  - Maze with axis of rotation perpendicular to maze
  - Maze with primary barrier instead of direct leakage

Wall Scatter

- 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



- Use factor adjustment
  - U = 0.25 applicable for above gantry orientation with highest dose rate
  - Total dose rate is 2.64 times the dose rate for this gantry angle

Beam Area at Wall

- Beam area at wall (A_0) depends on distance from target
  - $A_0 = F\ (d_H / 1\ m)^2$ (meters^2)
  - F = Maximum field size at isocenter (1 m from target)
  - d_H = Distance from target to wall (also in meters)
- Traditional field size assumption
  - F = 0.40 m x 0.40 m = 0.16 m^2
  - NCRP 151 recommends traditional field size
- Alternative field size assumption with IMRT
  - With IMRT, maximum field typically 15 cm x 15 cm, or 0.0225 m^2
  - Maximum field size 0.16 m^2 without IMRT
  - F = (1-% IMRT) $\times$ 0.16 + % IMRT $\times$ 0.0225

Reflection Coefficient for Concrete (NCRP 151 Tables B.8a and B.8b)

Table B.8a Wall reflection coefficient for concrete, 0º Incidence					
	Angle of reflection measured from normal				
MV	0º	30º	45º	60º	75º
0.25	0.0320	0.0280	0.0250	0.0220	0.0130
0.5	0.0190	0.0170	0.0150	0.0130	0.0080
4	0.0067	0.0064	0.0058	0.0049	0.0031
6	0.0053	0.0052	0.0047	0.0040	0.0027
10	0.0043	0.0041	0.0038	0.0031	0.0021
18	0.0034	0.0034	0.0030	0.0025	0.0016
30	0.0030	0.0027	0.0026	0.0022	0.0015

Table B.8b Wall reflection coefficient for concrete, 45º Incidence					
	Angle of reflection measured from normal				
MV	0º	30º	45º	60º	75º
0.25	0.0360	0.0345	0.0310	0.0250	0.0180
0.5	0.0220	0.0225	0.0220	0.0200	0.0180
4	0.0076	0.0085	0.0090	0.0092	0.0095
6	0.0064	0.0071	0.0073	0.0077	0.0080
10	0.0051	0.0057	0.0058	0.0060	0.0060
18	0.0045	0.0046	0.0046	0.0043	0.0040
30	0.0048	0.0050	0.0049	0.0040	0.0030

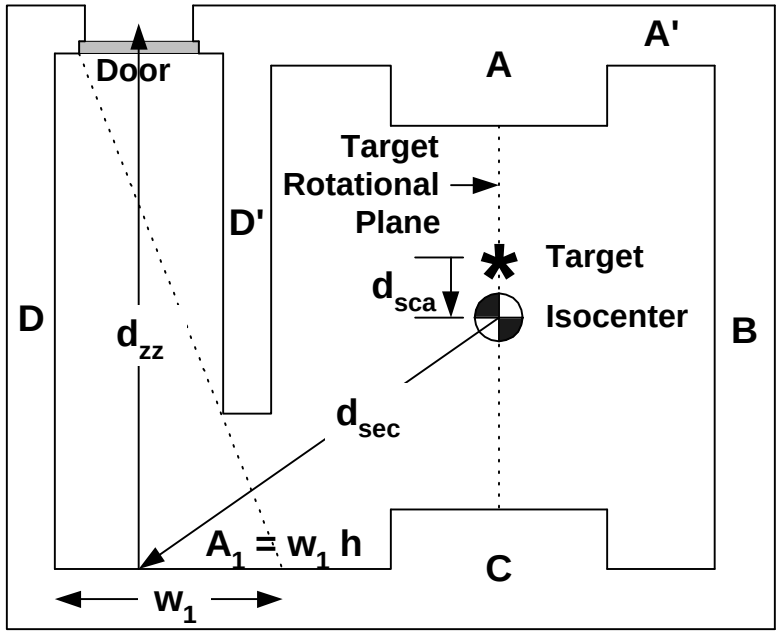
- Reflection coefficient for steel or lead is 2x these values

Patient Scatter

- Unshielded dose rate

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

- where
  - α_1 is reflection coefficient
    - » NCRP 151 Table B.8b with 0.5 MV energy
    - » 0º angle of reflection
  - A_1 is maze wall area seen from door
  - Other constants as before, e.g.,
    - » a = patient scatter fraction
      - See NCRP 151 Table B.4
    - » F = field size in cm²
    - » h = room height



- Use factor adjustment
  - U = 0.25 applicable for above gantry orientation with highest dose rate
  - Total dose rate is 2.64 times the dose rate for this gantry angle

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

- 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 MV	Angle (degrees)							
	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

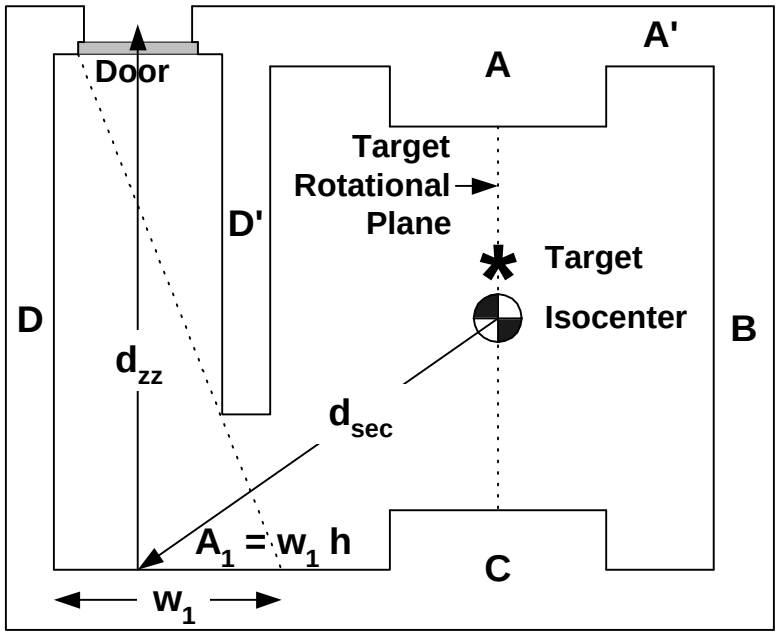
Leakage Scatter

- **Unshielded dose rate**

$$H_{LS} = \frac{10^{-3} W_L U \alpha_1 A_1}{d_{sec}^2 d_{zz}^2}$$

where

- 10^{-3} = head-leakage radiation ratio
- α_1 is reflection coefficient
  - » NCRP 151 Table B.8b with MV = 1.4 at 6 MV, 1.5 at 10 MV
  - » 0º angle of reflection
- A_1 is maze wall area seen from door
- d_{sec} measured from isocenter
  - » Isocenter is average target location



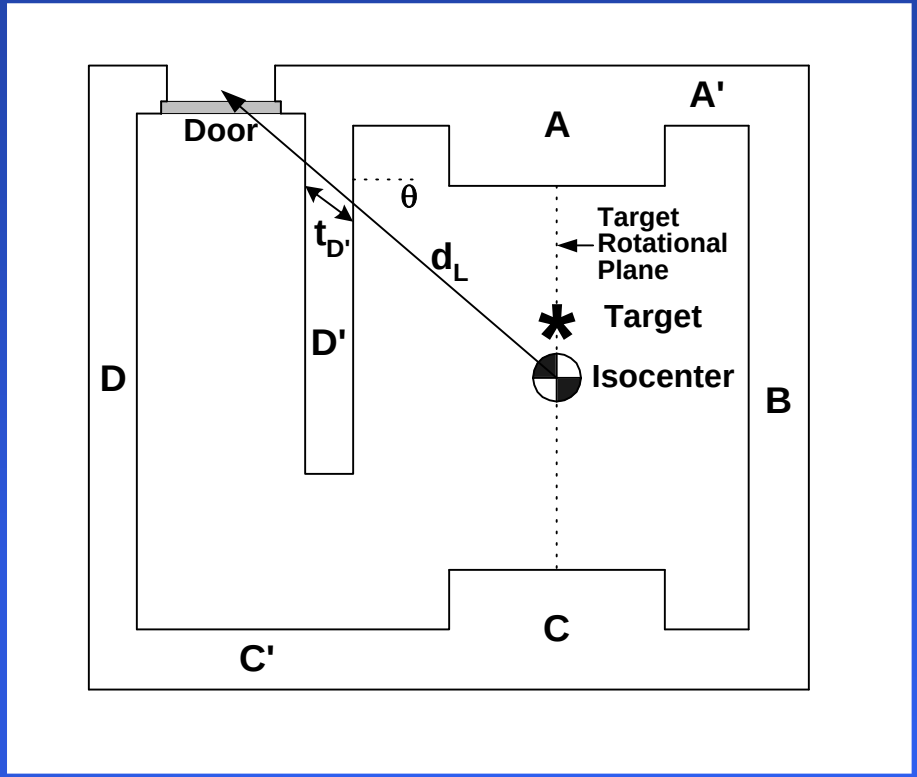
- **Use factor adjustment**
  - NCRP 151 recommends same adjustment as patient and wall scatter
  - U = 1 with no adjustment is assumed in the example calculations here
    - » with d_{sec} measured from isocenter

Direct Leakage

- **Unshielded dose rate**

$$H_{LT} = \frac{10^{-3}\, W_L\, U\, B}{d_L^2}$$

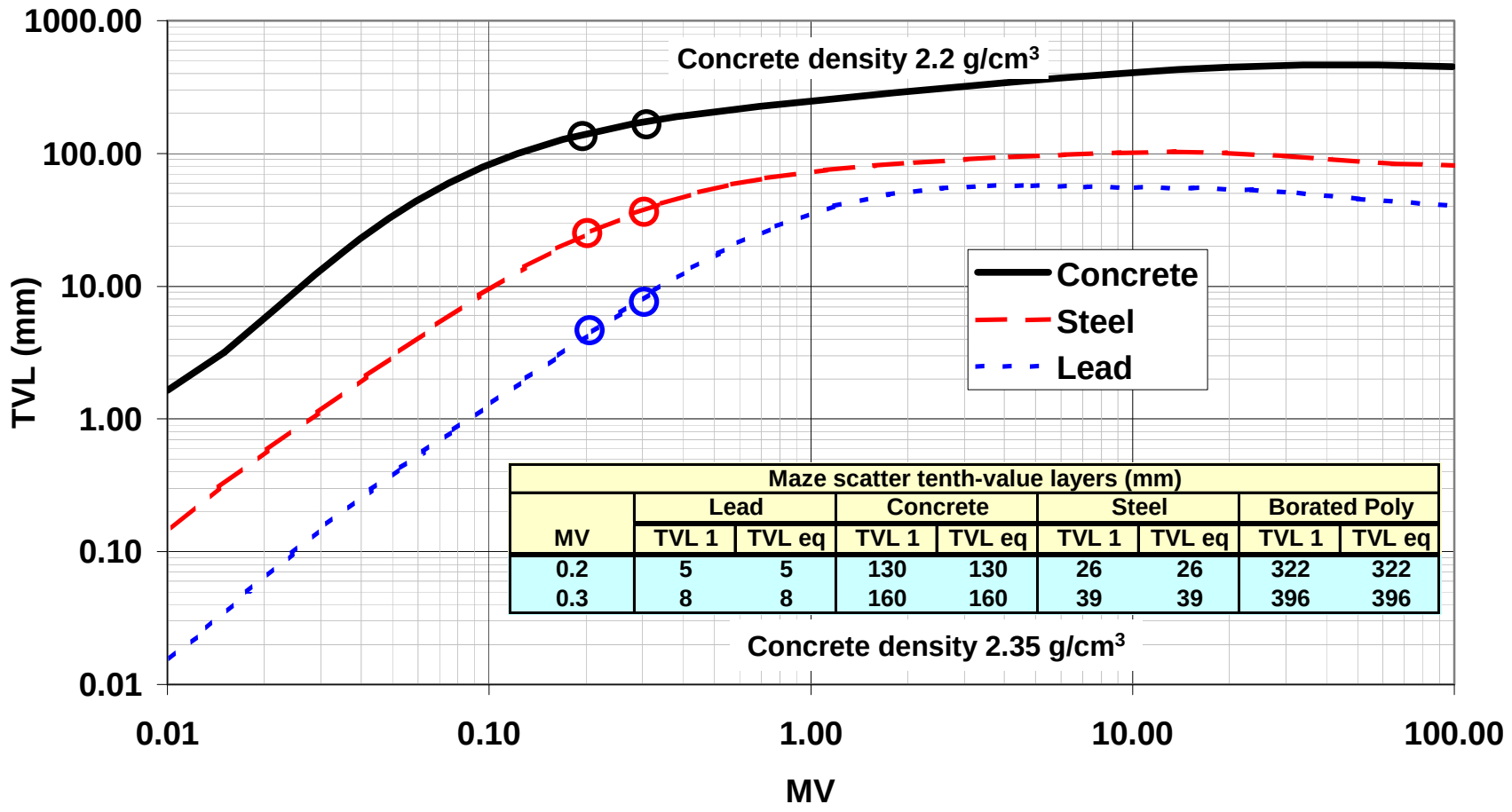
- **Same as standard secondary photon leakage calculation**
  - **B is leakage transmission through wall**
- **Use factor adjustment**
  - **NCRP 151 recommends the same adjustment as patient and wall scatter**
  - **U = 1 with no adjustment is assumed in the example calculations here**



Tenth-Value Layers for Maze Calculation

- Patient and wall scatter TVLs based on 0.2 MV broadbeam transmission
  - TVL read from NCRP 151 Figure A.1
  - Low energy since two bounces
- Leakage scatter TVLs based on 0.3 MV broadbeam transmission
  - 0.3 MV average energy cited in McGinley p. 49
    - » Single bounce vs. two bounces for patient & wall scatter
  - TVL read from NCRP 151 Figure A.1
- Leakage TVL for direct leakage
  - Note that door may not shield direct leakage for short maze

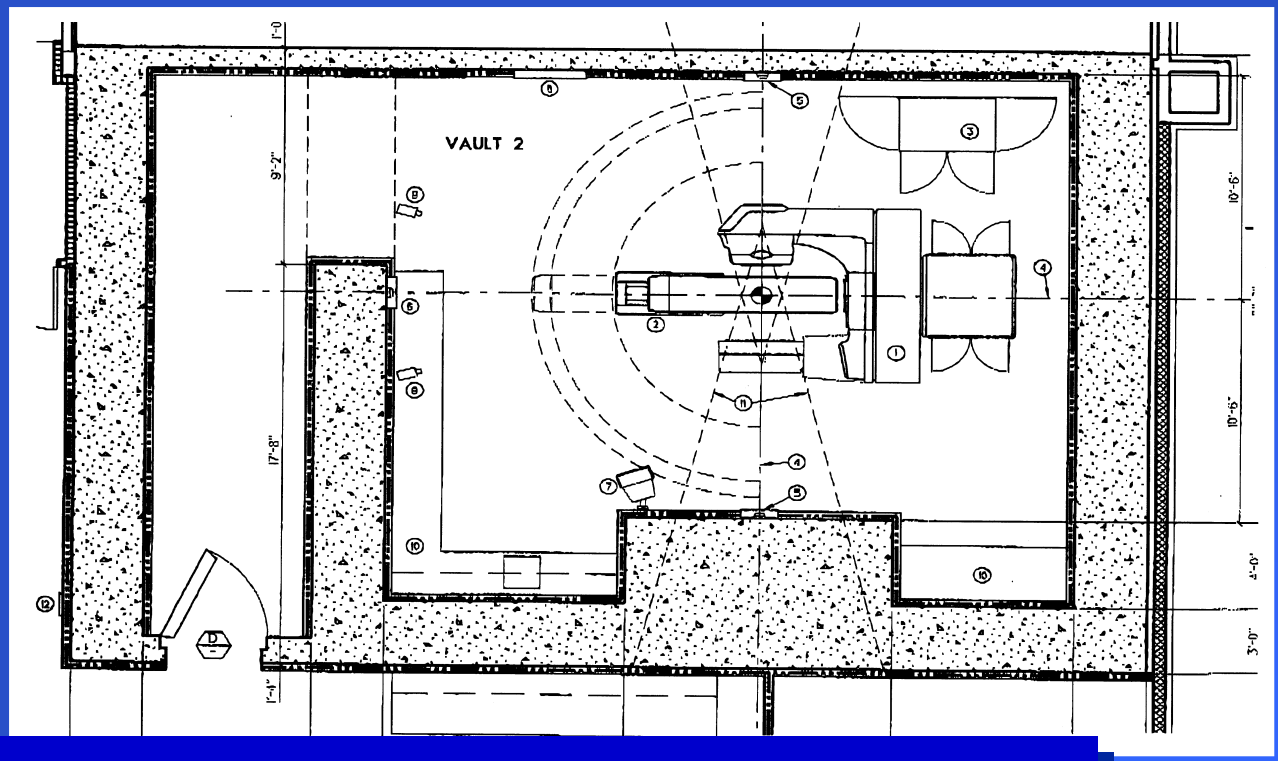
Broad Beam Equilibrium TVLs (NCRP 151 Figure A.1)



Maze scatter tenth-value layers (mm)								
	Lead		Concrete		Steel		Borated Poly	
MV	TVL 1	TVL eq	TVL 1	TVL eq	TVL 1	TVL eq	TVL 1	TVL eq
0.2	5	5	130	130	26	26	322	322
0.3	8	8	160	160	39	39	396	396

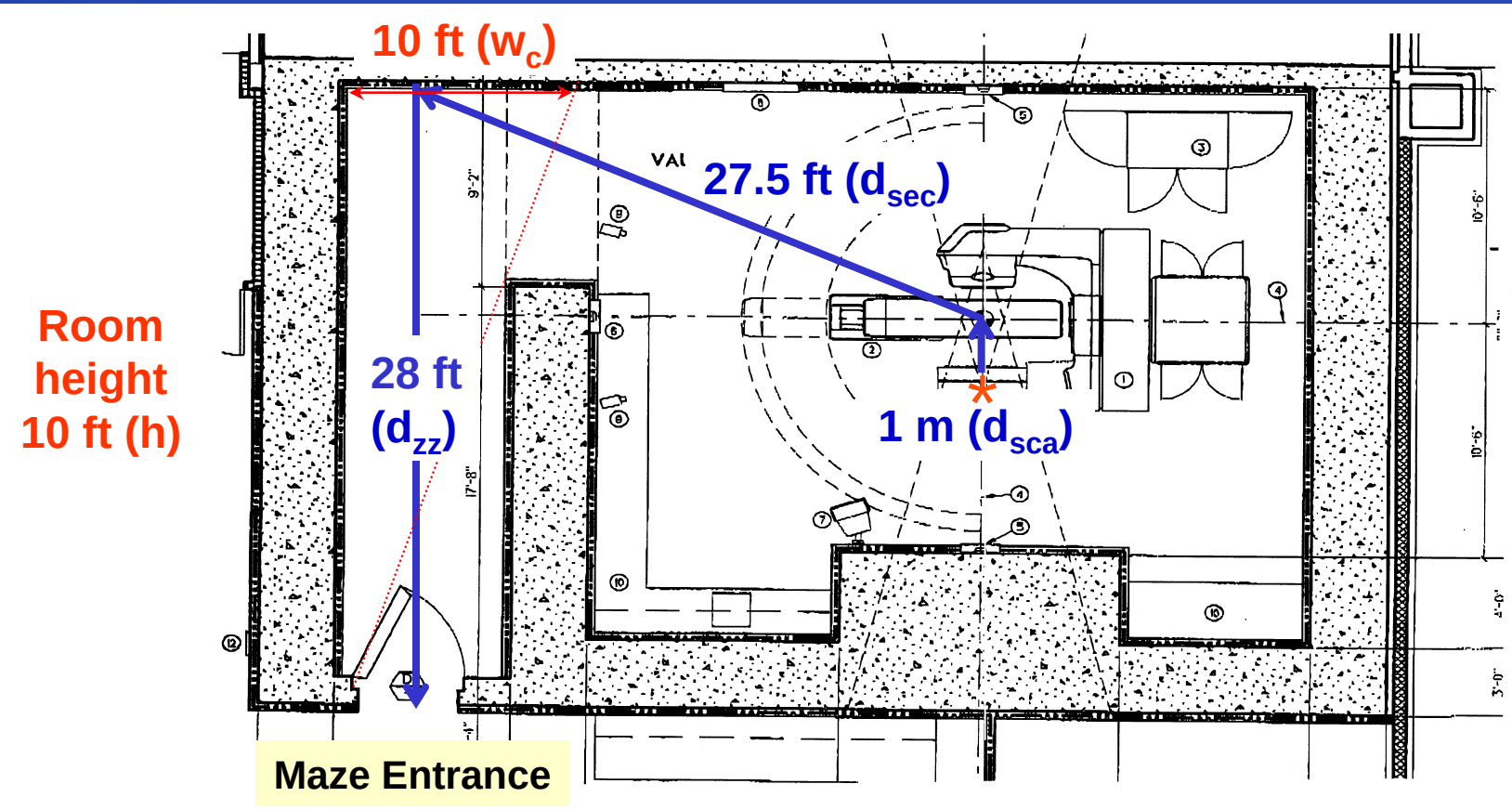
Example 1: Conventional Maze, 6 MV

- Conventional maze similar to NCRP 151 examples
  - Axis of rotation is parallel to maze; maze extends full length of vault
- Machine energy is 6 MV
  - All scatter mechanisms must be calculated
  - Direct leakage must also be calculated
    - » With door also contributing to attenuation of direct leakage
  - Neutron & capture gamma calculation is not needed
    - » < 10 MV



Door: 0.25” lead, hard wood covers

Example 1a: Patient Scatter



Example 1: P/T and Average Field Size Calculation

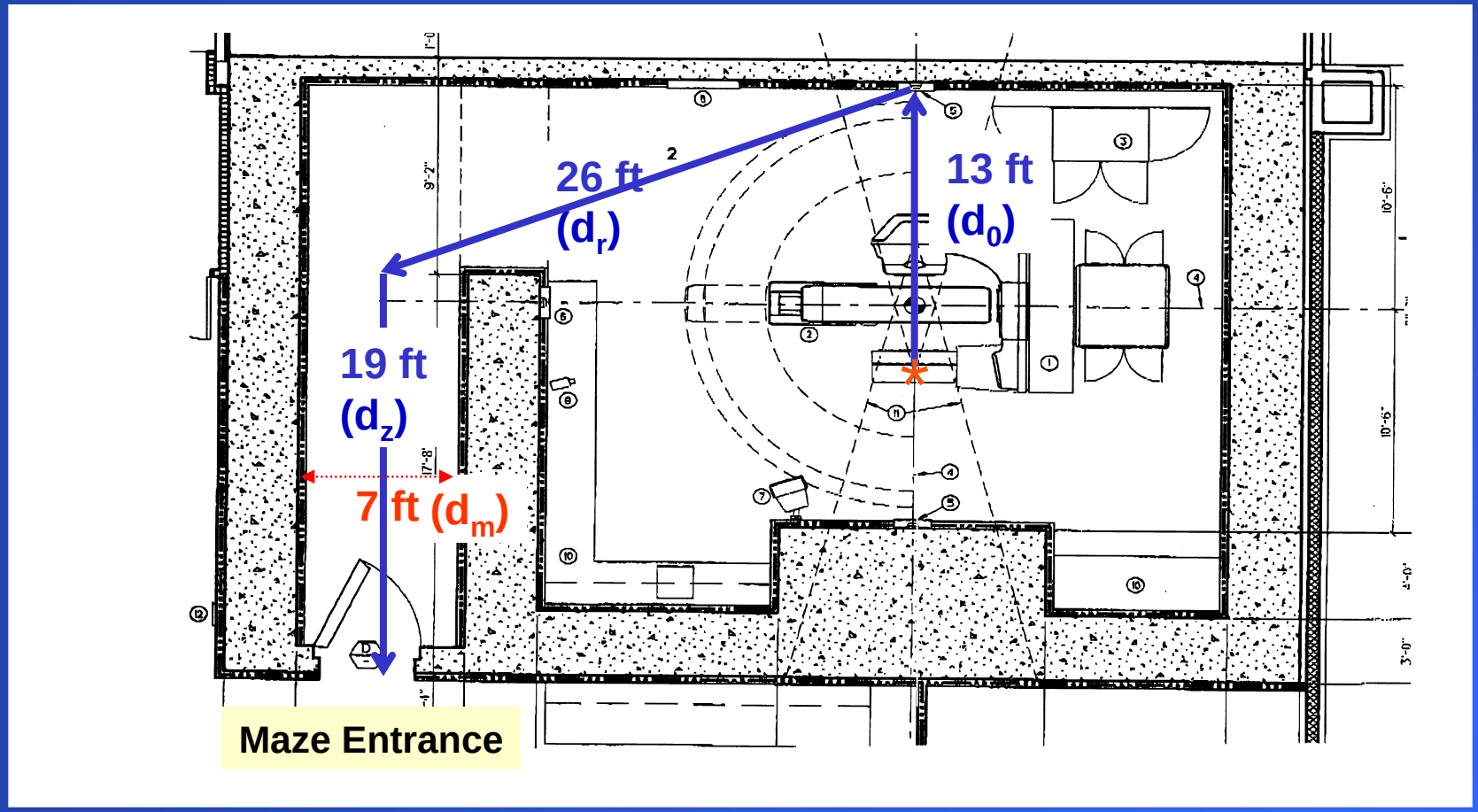
- Protected location is in a controlled area (P= 0.1 msv/wk)
  - NCRP 151 occupancy T=1/8 for extremely low traffic location
  - Higher occupancy appropriate if close proximity to control area
    - » e.g., T=0.5 or T=1 (T=1 is assumed in example)
  - Maximum shielded dose rate (P/T) is 0.1 mSv/wk for T=1
- NCRP 151 examples uses 40 x 40 cm^2 field area for scatter
  - Weighted average field area with / without IMRT also valid
    - » e.g., especially useful for existing vault door calculations
    - » Caution: Safety survey often performed without IMRT

Line	Parameter	Units	Value		Calculation
			w/o IMRT	with IMRT	
a	Max Field Size	cm	40	15	
b	Fraction of Workload		50%	50%	
c	Effective Field Area	cm^2	912.5		$b_1 * a_1$^2 + $b_2 * a_2$^2
d	Effective Field Size	cm	30.2		sqrt (c)

Example 1a: Patient Scatter Unshielded Dose Rate Calculation

Line	Symbol	Parameter	Units	Value	Calculation
a	MV	Machine X-ray Energy	MV	6	
b	W	Workload	Gy/wk	450	
c	d_{sca}	Distance from target to isocenter	m	1.00	
d	d_{sec}	Distance from isocenter to wall at maze end	ft	27.5	measured
e			m	8.38	d * 0.3048
f	d_{zz}	Distance from wall at maze end to door	ft	28	measured
g			m	8.53	f * 0.3048
h	w_1	Wall width seen from door	ft	10	measured
i			m	3.05	h * 0.3048
j	h	Room height	ft	10	measured
k			m	3.05	j * 0.3048
L	A_1	Scatter area	m^2	9.3	i * k
m	a	Patient scatter fraction ($400\ cm^2$ field)		1.39E-03	NCRP 151 Table B.4 (45º) Function of MV
n	α_1	Reflection Coefficient		2.20E-02	Table B.8b, 0.5 MV, 0º
o	F	Average field area	cm^2	912.5	See above
p	U	Use Factor		0.25	Orientation with highest dose rate
q	H_{PS}	Patient scatter unshielded dose rate	mSv/wk	1.42E-02	1000*m*b*p*(o/400)*L / (c^2 * e^2 * g^2)

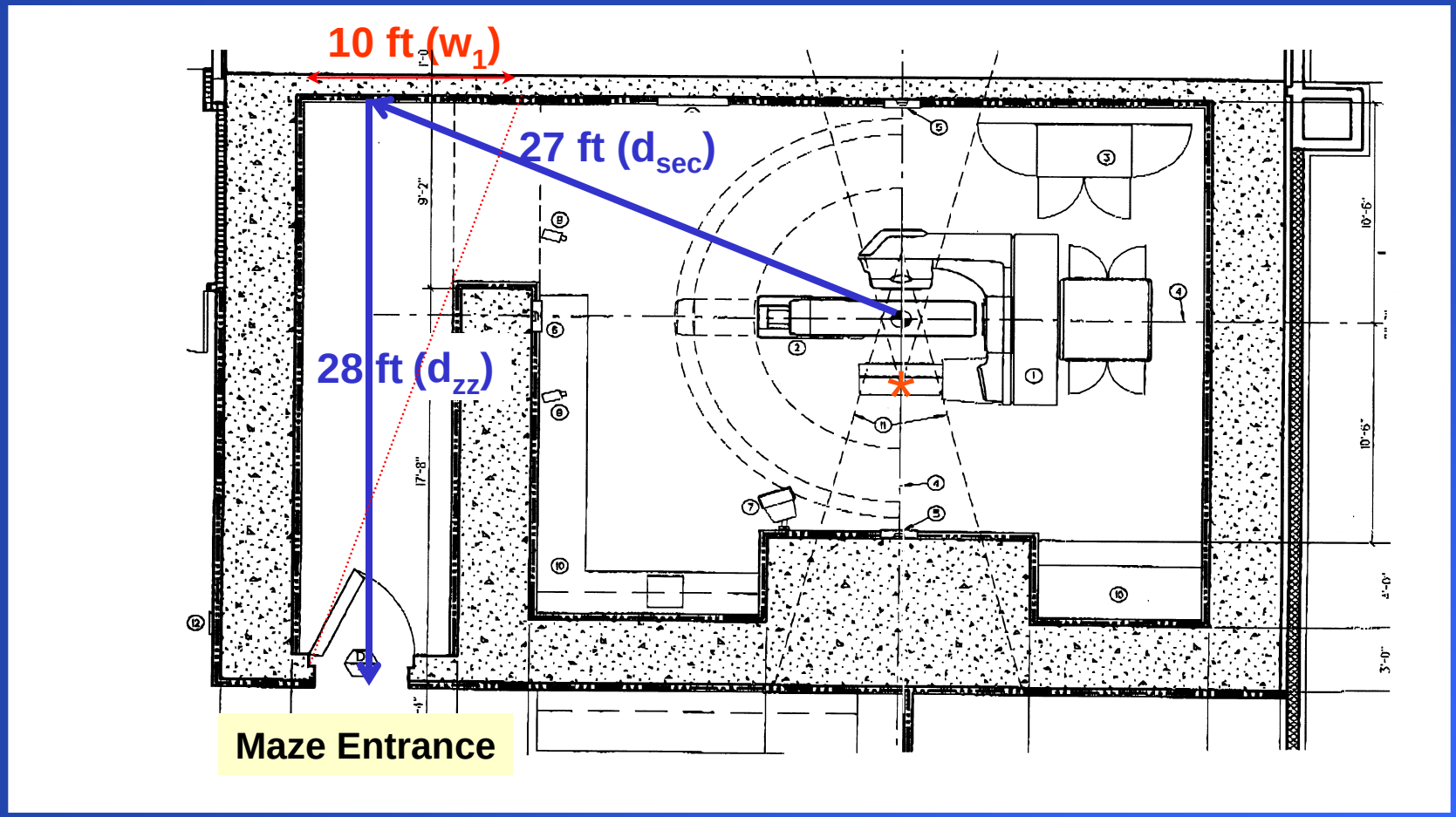
Example 1b: Wall Scatter



Example 1b: Wall Scatter Unshielded Dose Rate Calculation

Line	Symbol	Parameter	Units	Value	Calculation
a	MV	Machine X-ray Energy	MV	6	
b	W	Workload	Gy/wk	450	
c	f	Patient transmission		0.25	0.25 if MV ≤ 10
d	d_0	Distance from target to primary barrier wall	ft	13	measured
e			m	3.96	d * 0.3048
f	d_r	Distance from primary barrier wall to maze inside opening	ft	26	measured
g			m	7.92	f * 0.3048
h	d_z	Distance from maze inside opening to door	ft	19	measured
i			m	5.79	h * 0.3048
j	d_m	Maze width	ft	7	measured
k			m	2.13	j * 0.3048
L	h	Room height	ft	10	measured
m			m	3.05	L * 0.3048
n	α_0	1sr reflection coefficient	$1 / m^2$	0.0027	Table B.8a with 6 MV 75º scatter angle
o		Effective field size	cm	30.2	see above
p	A_0	Beam area at first reflection	m^2	1.43	(e * o/100)^2
q	α_z	2nd bounce scatter fraction / m^2		0.0080	Table B.8a with 0.5 MV 75º scatter angle
r	A_z	Maze cross section	m^2	6.5	j * L
s	U	Use Factor		0.25	Orientation with highest dose rate
t	f H_S	Wall scatter unshielded dose rate	mSv/wk	1.71E-04	1000*m*b*s*(o/400)* L / (e^2 * g^2 * i^2)

Example 1c: Leakage Scatter

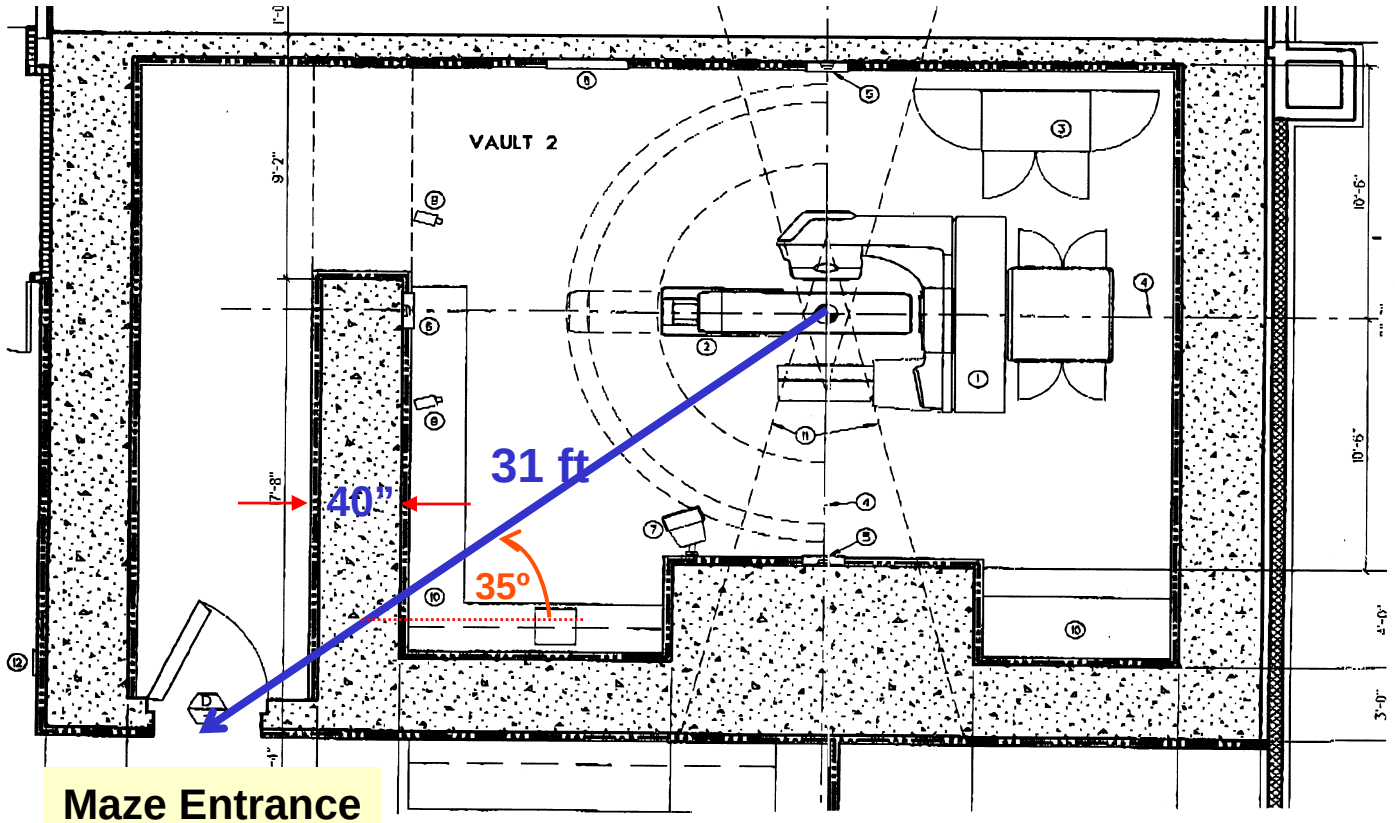


d_{sec} measured from isocenter (the average target location)

Example 1c: Leakage Scatter Unshielded Dose Rate Calculation

Line	Symbol	Parameter	Units	Value	Calculation
a	MV	Machine X-ray Energy	MV	6	
b	W	Workload	Gy/wk	450	
c		Leakage Fraction	%	0.10%	
d		IMRT Factor		2	
e	d_{sec}	Distance from target to wall at maze end	ft	27	measured
f			m	8.23	d * 0.3048
g	d_{zz}	Distance from wall at maze end to door	ft	28	measured
h			m	8.53	f * 0.3048
i	w_1	Wall width seen from door	ft	10	measured
j			m	3.05	h * 0.3048
k	h	Room height	ft	10	measured
L			m	3.05	j * 0.3048
m	α_1	1sr reflection coefficient	$1 / m^2$	0.0183	Table B.8b with 1.4 MV 0º Reflection angle
n	A_1	Scatter area	m^2	9.3	i * k
o	U	Use Factor		1	Calculation does not depend on orientation
p	H_{LS}	Leakage scatter unshielded dose rate	mSv/wk	3.10E-02	1000 * b * o * c * d * m * n / (f^2 * h^2)

Example 1d: Direct Leakage



Example 1d: Direct Leakage Unshielded Dose Rate Calculation

Line	Parameter	Units	Value	Calculation
a	Machine X-ray Energy	MV	6	
b	Workload (W)	Gy/Wk	450	
c	Use Factor	Ratio	1	
d	Leakage Fraction	%	0.10%	
e	IMRT Factor		2	
f	Isocenter to Protected Point Distance	ft	31.0	
g		m	9.4	f * 0.3048
h	Unshielded Dose Rate	mSv/wk	1.01E+01	1000*b*c*d*e / g^2
i	Wall Transmission		7.86E-05	see below
j	Inside of Door Dose Rate	mSv/wk	7.92E-04	h * i

Barrier	Material Thickness	Slant Thickness	Material	Patient Scatter		Photon Trans.
	inches	mm		TVL1 (mm)	TVLe (mm)	
Inside Layer	40	1240	Concrete	340	290	7.86E-05
Layer #2						1.00E+00
Outside Layer						1.00E+00
Slant Angle:	35 deg			6 MV	Total:	7.86E-05

Example 1: Maze Door Transmission Calculation

Maze Patient Scatter Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Lead	5	5	5.37E-02
Layer #2						1.00E+00
Outside Layer						1.00E+00
Slant Angle:		0 deg		0.2 MV	Total:	5.37E-02

Maze Wall Scatter Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Wall Scatter TVL1 (mm)	Wall Scatter TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Lead	5	5	5.37E-02
Layer #2						1.00E+00
Outside Layer						1.00E+00
Slant Angle:		0 deg		0.2 MV	Total:	5.37E-02

Maze Leakage Scatter Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Leakage Scatter TVL1 (mm)	Leakage Scatter TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Lead	8	8	1.61E-01
Layer #2						1.00E+00
Outside Layer						1.00E+00
Slant Angle:		0 deg		0.3 MV	Total:	1.61E-01

Example 1: Maze Door Shielded Dose Rate

Maze Direct Leakage Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Direct Leakage TVL1 (mm)	Direct Leakage TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Lead	57	57	7.74E-01
Layer #2						1.00E+00
Outside Layer						1.00E+00
Slant Angle:		0 deg		6 MV	Total:	7.74E-01

Maze Shielded Dose at Door

Line	Parameter	Units	Patient Scatter	Wall Scatter	Leakage Scatter	Direct Leakage	Calculation
a	Calc. Unshielded Dose Rate	mSv/wk	1.42E-02	1.71E-04	3.10E-02	7.92E-04	
b	Total / Calc. Dose Rate		2.64	2.64	1	1	NCRP 151 p. 37
c	Total Unshielded Dose Rate	mSv/wk	3.76E-02	4.52E-04	3.10E-02	7.92E-04	a * b
d	Energy for TVL	MV	0.2	0.2	0.3	6.0	
e	Transmission		5.37E-02	5.37E-02	1.61E-01	7.74E-01	see above
f	Shielded Dose Rate	mSv/wk	0.00202	0.00002	0.00499	0.00061	c * e
g	Total Shielded Dose Rate	mSv/wk	0.0076				Sum Row f

0.0076 mSv/wk is less than
P/T = 0.100 mSv/wk

Example 1: Wall Adjacent to Maze Door Transmission Calculation

Maze Patient Scatter Transmission for Wall Adjacent to Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Photon Trans.
Inside Layer	6	152	Concrete	130	130	6.73E-02
Layer #2						1.00E+00
Outside Layer						1.00E+00
	Slant Angle:	0 deg		0.2 MV	Total:	6.73E-02

Maze Wall Scatter Transmission for Wall Adjacent to Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Photon Trans.
Inside Layer	6	152	Concrete	130	130	6.73E-02
Layer #2						1.00E+00
Outside Layer						1.00E+00
	Slant Angle:	0 deg		0.2 MV	Total:	6.73E-02

Maze Leakage Scatter Transmission for Wall Adjacent to Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Photon Trans.
Inside Layer	6	152	Concrete	160	160	1.12E-01
Layer #2						1.00E+00
Outside Layer						1.00E+00
	Slant Angle:	0 deg		0.3 MV	Total:	1.12E-01

Example 1: Wall Adjacent to Maze Door Shielded Dose Rate

Maze Direct Leakage Transmission for Wall Adjacent to Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Photon Trans.
Inside Layer	6	152	Concrete	340	290	2.98E-01
Layer #2						1.00E+00
Outside Layer						1.00E+00
Slant Angle:		0 deg		6 MV	Total:	2.98E-01

Maze Shielded Dose at Wall Adjacent to Door

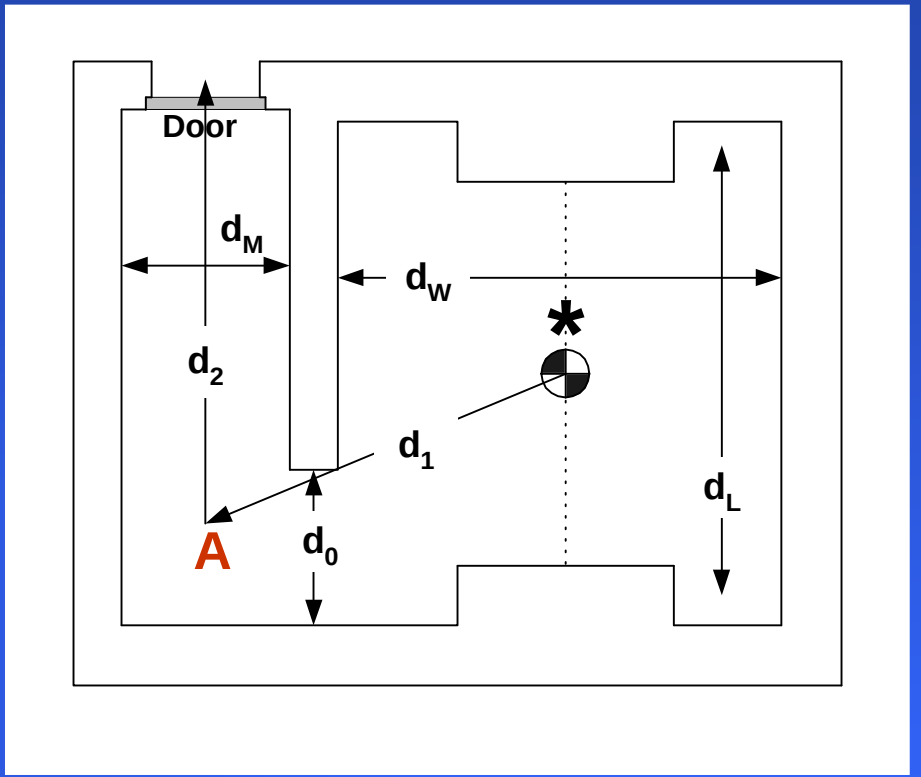
Line	Parameter	Units	Patient Scatter	Wall Scatter	Leakage Scatter	Direct Leakage	Calculation
a	Calc. Unshielded Dose Rate	mSv/wk	1.42E-02	1.71E-04	3.10E-02	7.92E-04	
b	Total / Calc. Dose Rate		2.64	2.64	1	1	NCRP 151 p. 37
c	Total Unshielded Dose Rate	mSv/wk	3.76E-02	4.52E-04	3.10E-02	7.92E-04	a * b
d	Energy for TVL	MV	0.2	0.2	0.3	6.0	
e	Transmission		6.73E-02	6.73E-02	1.12E-01	2.98E-01	see above
f	Shielded Dose Rate	mSv/wk	0.0025	0.0000	0.0035	0.0002	c * e
g	Total Shielded Dose Rate	mSv/wk	0.0063				Sum Row f

Maze Calculations for High Energy Accelerators

- Neutrons and capture gammas dominate the shielded dose
- Direct leakage may also be significant
  - Particularly with thin maze wall
- Scatter mechanisms continue to apply
  - But are invariably negligible for MV > 10

Maze Neutron and Capture Gammas

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

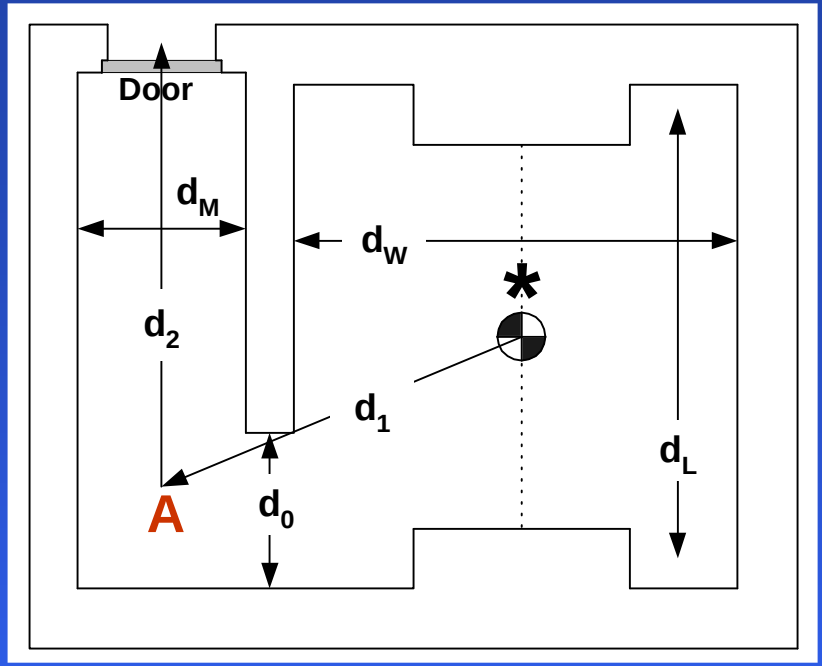


Neutron Fluence Calculation

- **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 (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

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

Vendor	Model	MV	Q_n N/Gy
Varian	1800	18	1.22E+12
Varian	1800	15	7.60E+11
Varian	1800	10	6.00E+10
Varian	2100C	18	9.60E+11
Varian	2300CD	18	9.50E+11
Varian	2500	24	7.70E+11
Siemens	KD	20	9.20E+11
Siemens	KD	18	8.80E+11
Siemens	MD	15	2.00E+11
Siemens	MD2	10	8.00E+10
Siemens	Primus	10	2.00E+10
Siemens	Primus	15	2.10E+11
Philips	SL25	25	2.37E+12
Philips	SL20	20	6.90E+11
Philips	SL20	18	4.60E+11
Philips	SL25	18	4.60E+11
GE	Saturne41	12	2.40E+11
GE	Saturne41	15	4.70E+11
GE	Saturne43	18	1.50E+12
GE	Saturne43	25	2.40E+12

Maze Capture Gamma Unshielded Dose Rate Calculation

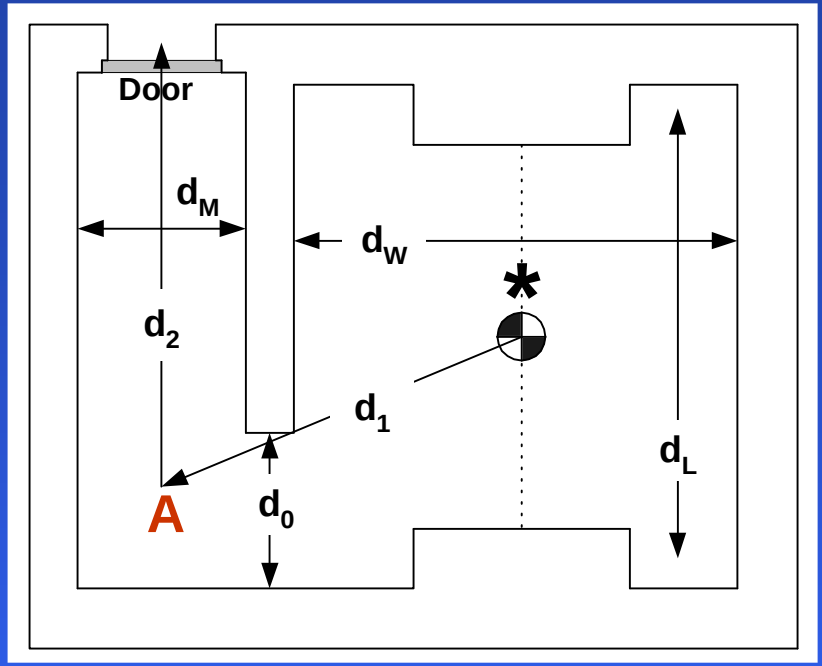
- Capture gamma dose at door per workload at isocenter (Sv/Gy)

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

- 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 at door

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

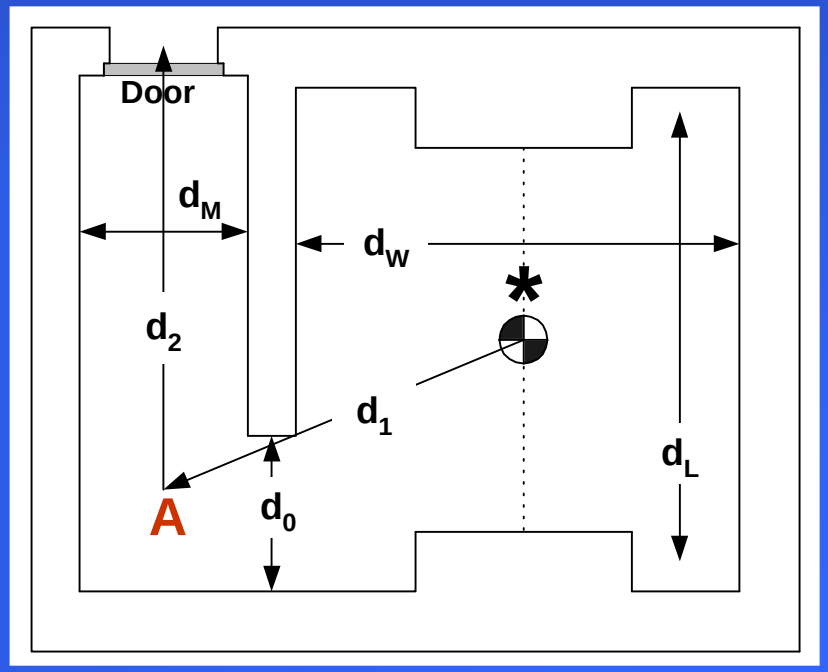
  - W_{Ln} is neutron leakage workload

Maze Neutron Unshielded Dose Rate Calculation

- **Maze neutron dose-equivalent at door per neutron leakage workload at isocenter (Sv/Gy)**

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

- **where**
  - 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. = $2.06\ S^{1/2}$



- **Weekly neutron dose-equivalent at door**

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

Maze Door Neutron Shielding TVL

- 45 mm TVL_n for borated polyethylene
  - "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]
- 161 TVL_n for concrete wall adjacent to door
  - " the average neutron energy at the maze entrance is reported to be ~100 keV" [also NCRP 151 p. 46]
  - NCRP 79 TVL_n for concrete with 0.1 MV neutron energy
    - » $TVL_n = 155 + 56 * 0.1 = 161$ mm

Maze Capture Gamma TVL

- NCRP 151
  - "for very short mazes ... a lead TVL of 6.1 cm may be required"
  - "mazes longer than 5 m ...TVL of only about 0.6 cm lead"
- Reading between the lines
  - Use 61 mm TVL for lead (NCRP 79) regardless of maze length
  - "The average energy of neutron capture gamma rays is 3.6 MeV"
    - » Assumed to apply to long mazes ($d_2 > 5$ m)
    - » Use NCRP 151 Figure A.1 TVLs at 3.6 MV for concrete / steel
  - "can range as high as 10 MeV" for very short mazes
    - » Short maze assumed to be $d_2 \leq 2.5$ m
    - » Use primary 10 MV TVLs (except 61 mm for lead vs. 57 mm 10 MV TVL)
  - "conservatively safe if one assumes that all neutron captures result in 7.2 MeV gamma rays" for direct-shielded doors
    - » Assumed to be conservatively safe for $2.5 \text{ m} < d_2 \leq 5$ m maze also
    - » Interpolate NCRP 151 Table B.2 TVLs at 7.2 MV for concrete / steel

Maze Capture Neutron and Gamma TVL Summary

Maze Neutron tenth-value layers (mm)

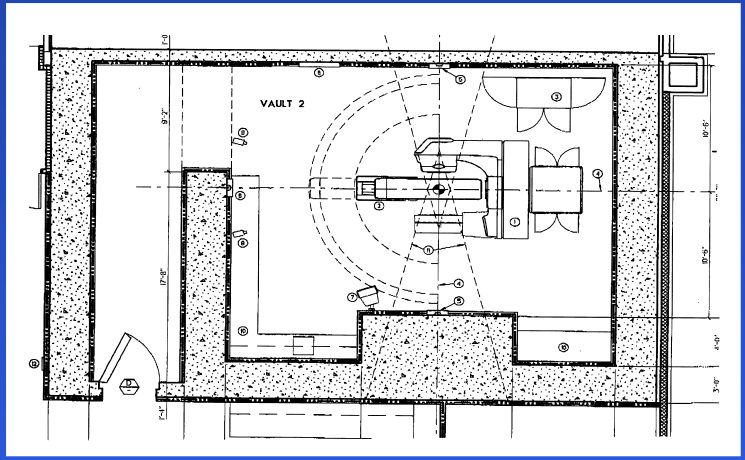
MV	Lead		Concrete		Steel		Borated Poly	
	TVL 1	TVL eq	TVL 1	TVL eq	TVL 1	TVL eq	TVL 1	TVL eq
0.1	N/A	N/A	161	161	N/A	N/A	45	45

Capture Gamma tenth-value layers (mm)

MV	Lead		Concrete		Steel		Borated Poly		Distance Pt. A to Door
	TVL 1	TVL eq	TVL 1	TVL eq	TVL 1	TVL eq	TVL 1	TVL eq	
3.6	61	61	330	330	95	95	817	817	$d_2 > 5$ m
7.2	61	61	390	350	103	103	965	866	2.5 m < d_2 < 5 m
10	61	61	410	370	110	110	1015	916	$d_2 <$ 2.5 m

Example 2: Conventional Maze, 18 MV

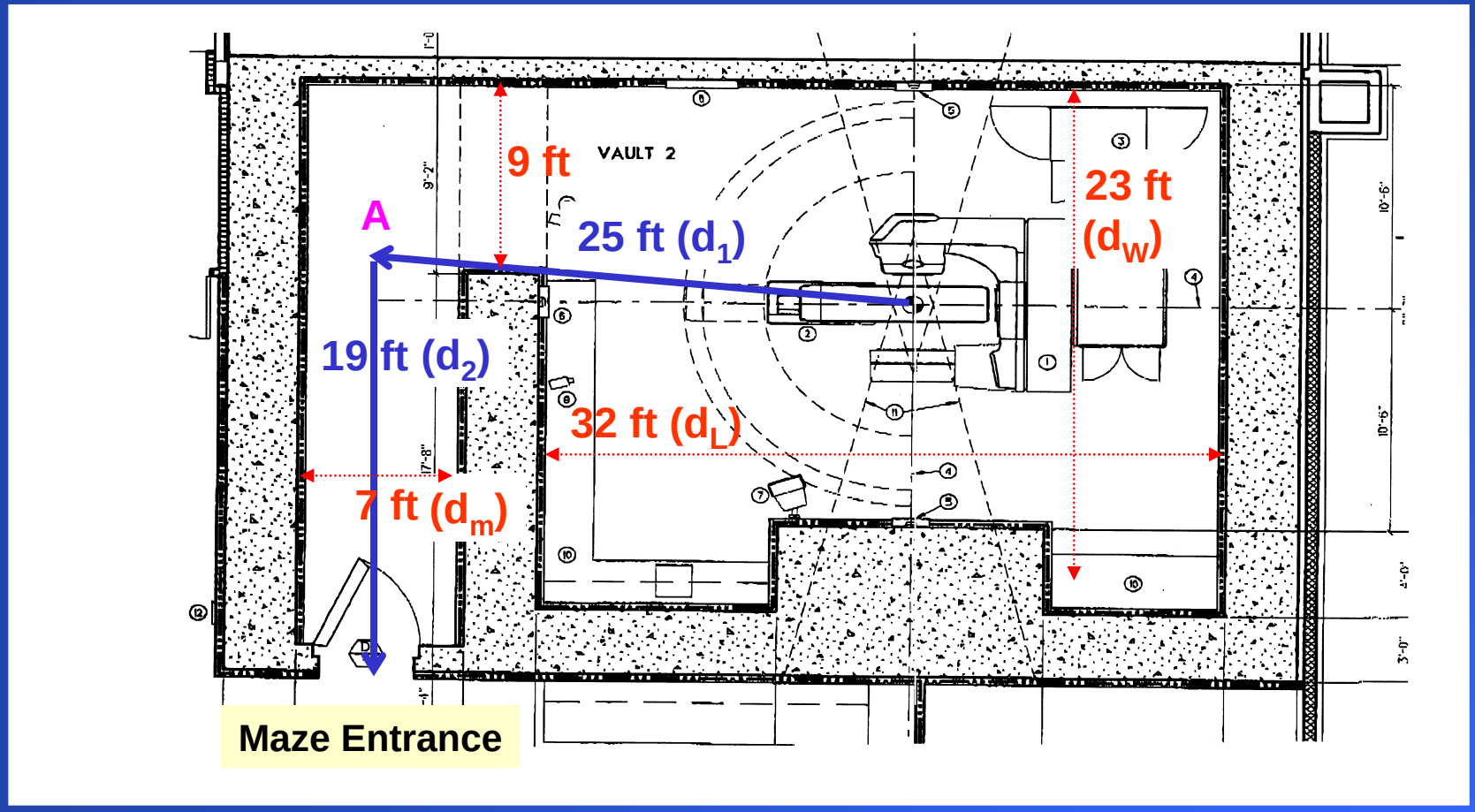
- Same maze layout as Example 1
  - Conventional maze similar to examples in NCRP 151



- Mechanisms included in door calculation
  - Neutron mechanisms dominate shielded dose
  - Direct leakage must be calculated
    - » With door also contributing to attenuation of direct leakage
  - Scatter mechanisms need not be calculated
    - » Calculations are included to illustrate that scatter is negligible

Door: 1” lead, 3” borated polyethylene with 0.25” steel covers

Example 2e: Maze with Secondary Leakage Through Door — Maze Neutrons



Examples 2a to 2d (patient scatter, wall scatter, leakage scatter, direct leakage) follow 2e (neutrons / capture gammas)

Example 2e: 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	25	measured
f			m	7.62	e * 0.3048
g	d_L	Vault Average Length	ft	32	measured
h			m	9.75	g * 0.3048
i	d_W	Vault Average Width	ft	23	measured
j			m	7.01	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	238.9	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	$n /m^2/Gy$	5.60E+09	c*n* [d/(4*π* f^2) + (5.4*d+1.3)/(2*π*m)]

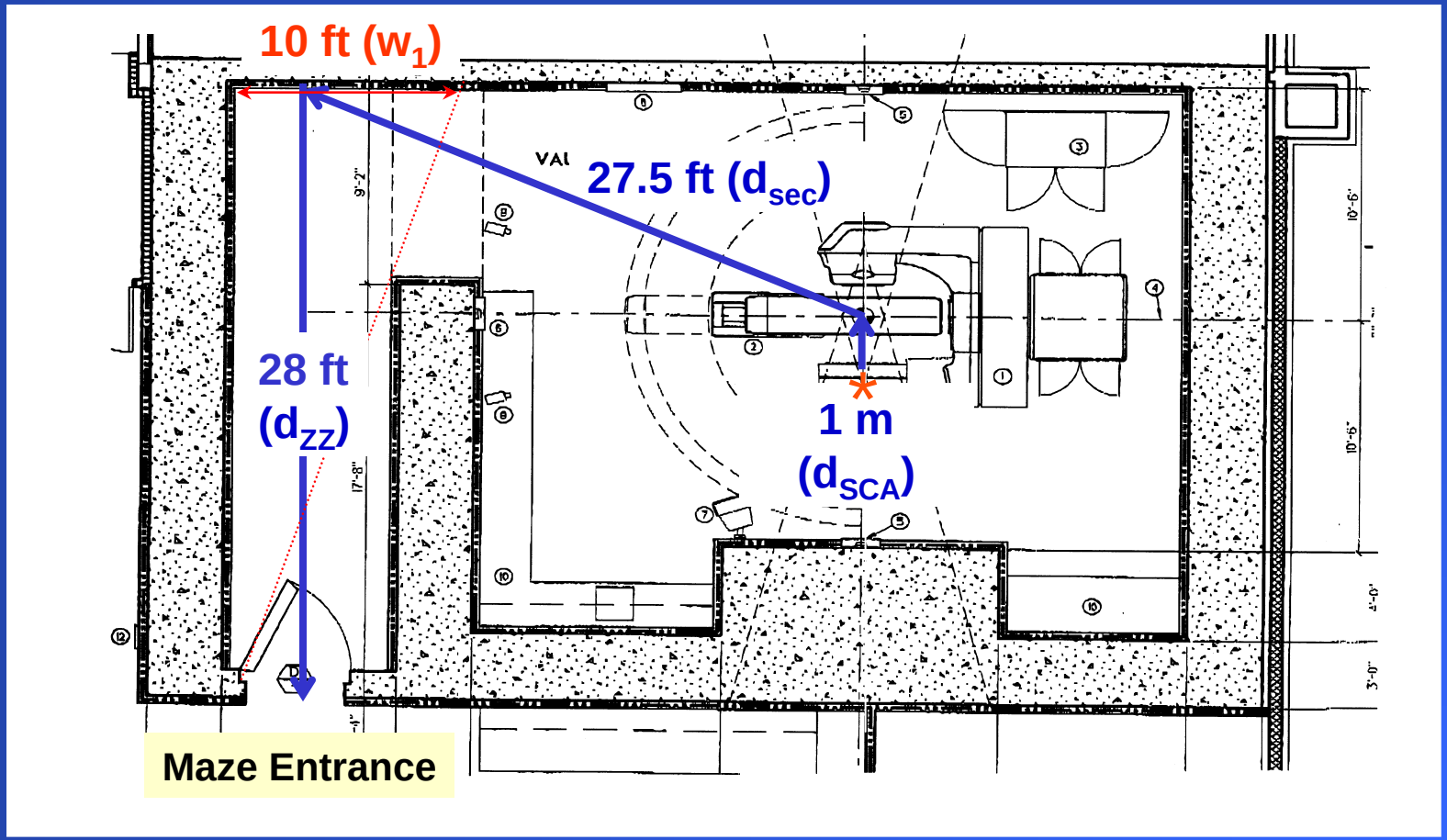
Example 2e: Capture Gamma Unshielded Dose Rate Calculation

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	5.60E+09	see above
d	d_2	Distance from maze opening (Point A) to door	ft	19	measured
e			m	5.79	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		6.9E-16	Constant
h	h_φ	Capture Gamma Unshielded Dose at Door per Dose at Isocenter	Sv/Gy	3.27E-07	g * c * 10^(-e / f)
i	H_{cg}	Capture Gamma Unshielded Dose Rate	mSv/wk	1.47E-01	1000 * a * h

Example 2e: Maze Neutron Unshielded Dose Rate Calculation

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	5.60E+09	See above
c	d_2	Distance from maze opening (Point A) to door	ft	19	measured
d			m	5.79	c * 0.3048
e	d_0	Inner Maze Entrance Width	ft	9	measured
f			m	2.74	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	8.36	f * h
j	d_m	Maze Width	ft	7	measured
k			m	2.13	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	6.50	i * m
o	TVD_n	Maze Neutron Tenth-Value Distance	m	5.25	2.06 * sqrt(n)
p	$H_{n,D}$	Neutron Unshielded Dose-Equivalent at Door per Dose at Isocenter	Sv/Gy	1.23E-06	2.4E-15 * b * sqrt(i / n) * [1.64*10^(-d/1.9)+10^(-d/o)]
q	H_n	Neutron Unshielded Dose-Equivalent Rate at Door	Sv/wk	5.52E-01	1000 * a * p

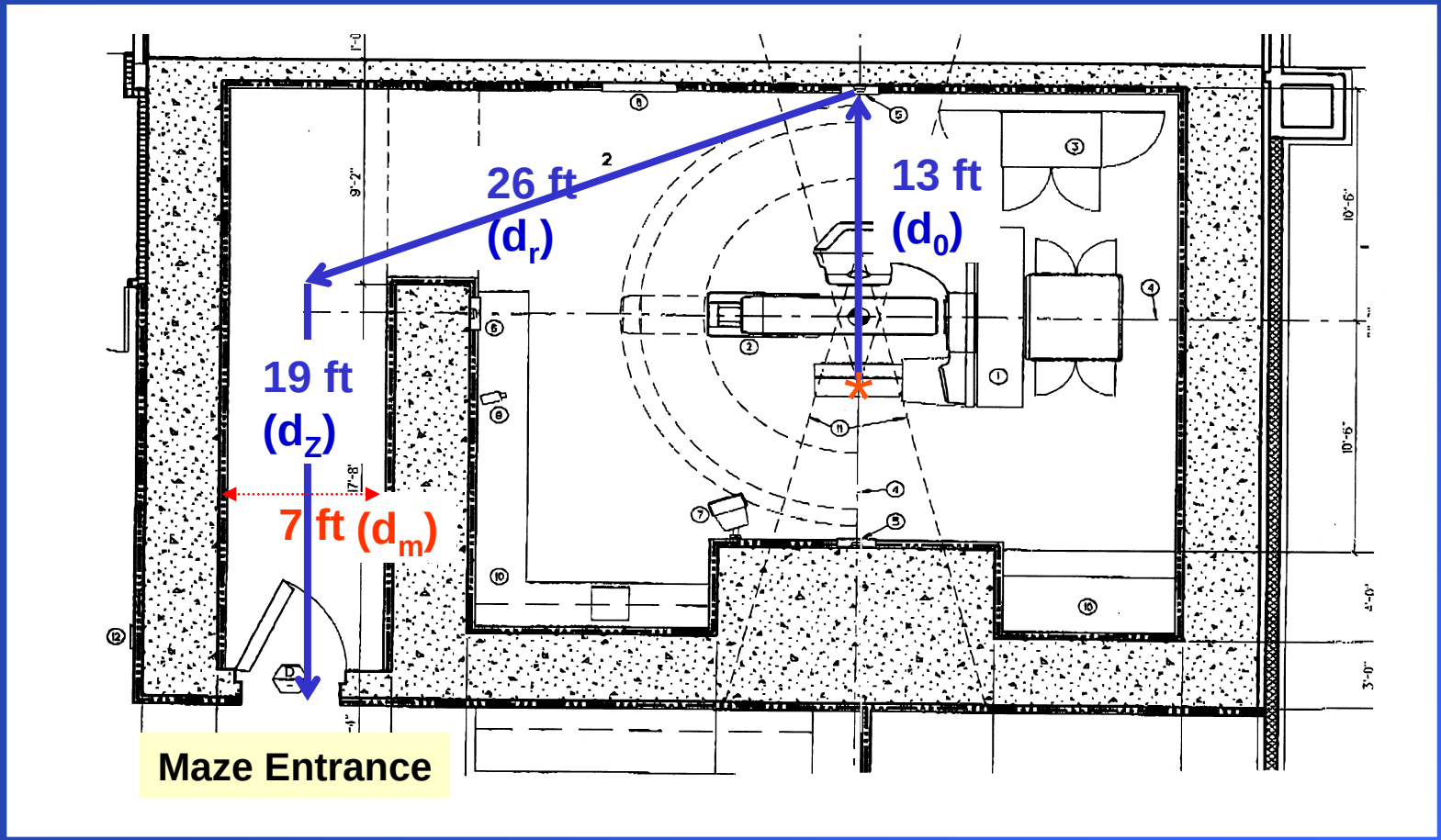
Example 2a: Maze with Secondary Leakage Through Door — Patient Scatter



Example 2a: Patient Scatter Unshielded Dose Rate Calculation

Line	Symbol	Parameter	Units	Value	Calculation
a	MV	Machine X-ray Energy	MV	18	
b	W	Workload	Gy/wk	450	
c	d_{sca}	Distance from target to isocenter	m	1.00	
d	d_{sec}	Distance from isocenter to wall at maze end	ft	27.5	measured
e			m	8.38	d * 0.3048
f	d_{zz}	Distance from wall at maze end to door	ft	28	measured
g			m	8.53	f * 0.3048
h	w_1	Wall width seen from door	ft	10	measured
i			m	3.05	h * 0.3048
j	h	Room height	ft	10	measured
k			m	3.05	j * 0.3048
L	A_1	Scatter area	m^2	9.3	i * k
m	a	Patient scatter fraction ($400\ cm^2$ field)		8.64E-04	NCRP 151 Table B.4 (45º) Function of MV
n	α_1	2nd bounce scatter fraction / m^2		2.20E-02	Table B.8b, 0.5 MV, 0º
o	F	Average field area	cm^2	912.5	See above
p	U	Use Factor		0.25	Orientation with highest dose rate
q	H_{PS}	Patient scatter unshielded dose rate	mSv/wk	8.86E-03	1000*m*b*p*(o/400)*L / (c^2 * e^2 * g^2)

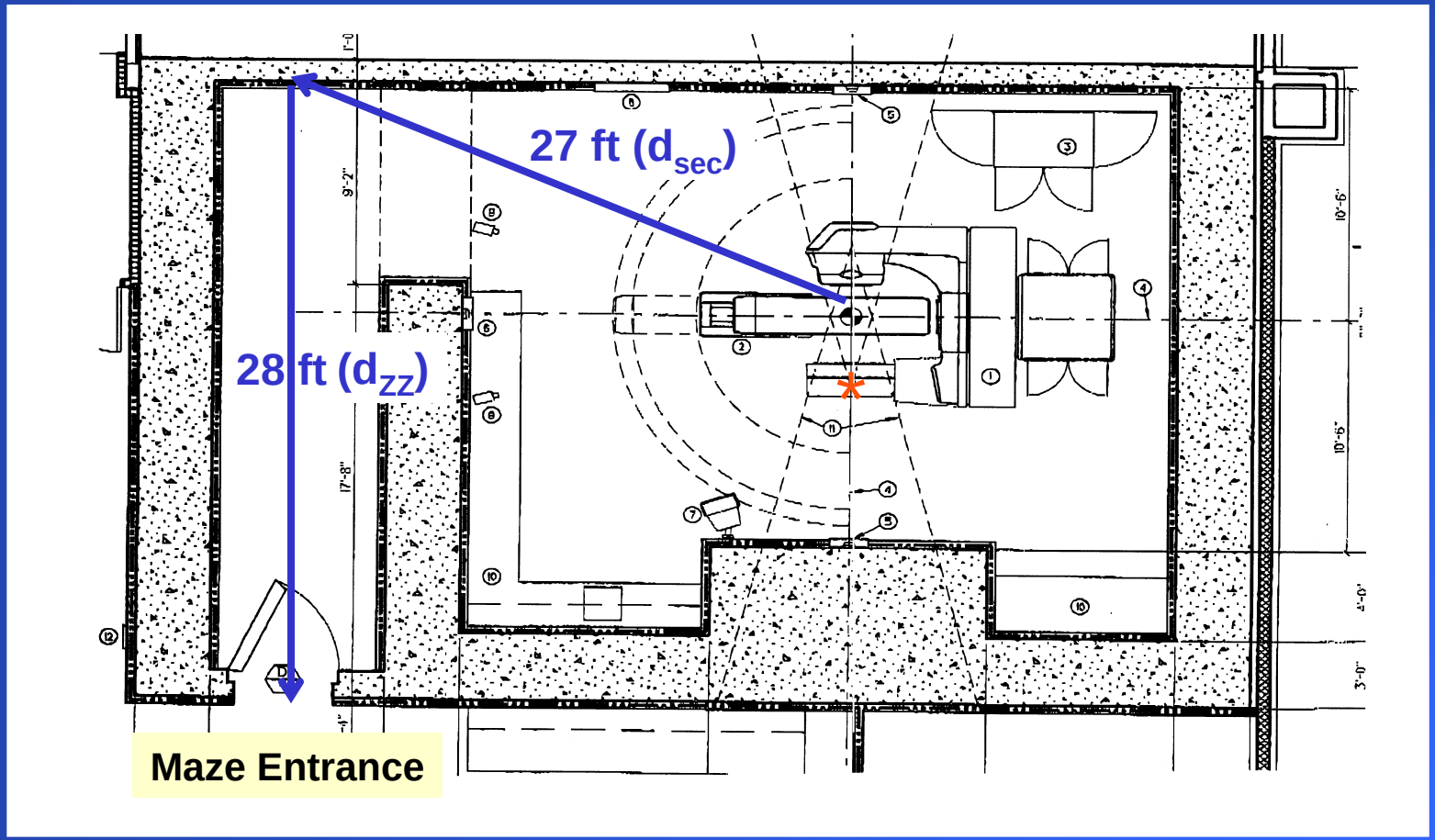
Example 2b: Maze with Secondary Leakage Through Door — Wall Scatter



Example 2b: Wall Scatter Unshielded Dose Rate Calculation

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	13	measured
e			m	3.96	d * 0.3048
f	d_r	Distance from primary barrier wall to maze inside opening	ft	26	measured
g			m	7.92	f * 0.3048
h	d_z	Distance from maze inside opening to door	ft	19	measured
i			m	5.79	h * 0.3048
j	d_m	Maze width	ft	7	measured
k			m	2.13	j * 0.3048
L	h	Room height	ft	10	measured
m			m	3.05	L * 0.3048
n	α_0	1sr reflection coefficient	$1 / m^2$	0.0016	Table B.8a with 18 MV 75º scatter angle
o		Effective field size	cm	30.2	see above
p	A_0	Beam area at first reflection	m^2	1.43	(e * o/100)^2
q	α_z	2nd bounce scatter fraction / m^2		0.0080	Table B.8a with 0.5 MV 75º scatter angle
r	A_z	Maze cross section	m^2	6.5	j * L
s	U	Use Factor		0.25	Orientation with highest dose rate
t	f H_S	Wall scatter unshielded dose rate	mSv/wk	1.10E-04	1000*m*b*s*(o/400)* L / (e^2 * g^2 * i^2)

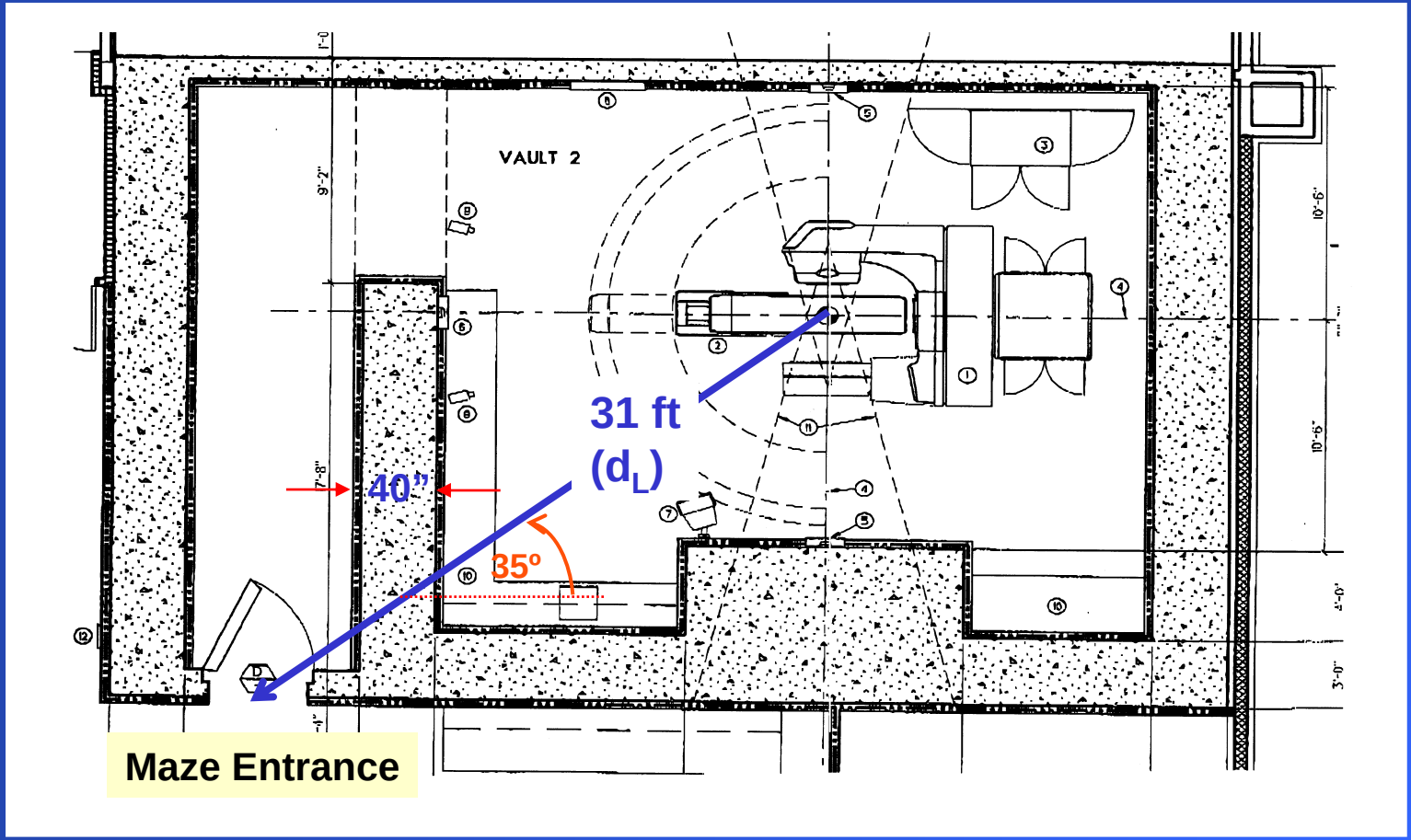
Example 2c: Maze with Secondary Leakage Through Door — Leakage Scatter



Example 2c: Leakage Scatter Unshielded Dose Rate Calculation

Line	Symbol	Parameter	Units	Value	Calculation
a	MV	Machine X-ray Energy	MV	18	
b	W	Workload	Gy/wk	450	
c		Leakage Fraction	%	0.10%	
d		IMRT Factor		2	
e	d_{sec}	Distance from target to wall at maze end	ft	27	measured
f			m	8.23	d * 0.3048
g	d_{zz}	Distance from wall at maze end to door	ft	28	measured
h			m	8.53	f * 0.3048
i	w_1	Wall width seen from door	ft	10	measured
j			m	3.05	h * 0.3048
k	h	Room height	ft	10	measured
L			m	3.05	j * 0.3048
m	α_1	1sr reflection coefficient	$1 / m^2$	0.0179	Table 8b with 1.5 MV 0º Reflection angle
n	A_1	Scatter area	m^2	9.3	i * k
o	U	Use Factor		1	Calculation does not depend on orientation
p	H_{LS}	Leakage scatter unshielded dose rate	mSv/wk	3.03E-02	1000 *b *o *c *d *m *n / (f^2 * h^2)

Example 2d: Maze with Secondary Leakage Through Door — Direct Leakage



Example 2d: Direct Leakage Unshielded Dose Rate Calculation

Line	Parameter	Units	Value	Calculation
a	Machine X-ray Energy	MV	18	
b	Workload (W)	Gy/Wk	450	
c	Use Factor	Ratio	1	
d	Leakage Fraction	%	0.10%	
e	IMRT Factor		2	
f	Isocenter to Protected Point Distance	ft	31.0	
g		m	9.4	f * 0.3048
h	Unshielded Dose	mSv/wk	1.01E+01	1000*b*c*d*e / g^2
i	Wall Transmission		2.58E-04	see below
j	Dose at Inside of Door	mSv/wk	2.60E-03	h * i

Barrier	Material Thickness	Slant Thickness	Material	Direct Leakage		Photon Trans.
	inches	mm		TVL1 (mm)	TVLe (mm)	
Inside Layer	40	1240	Concrete	360	340	2.58E-04
Layer #2						1.00E+00
Outside Layer						1.00E+00
Slant Angle: 35 deg				18 MV	Total:	2.58E-04

Example 2: Maze Door Transmission Calculation [1 of 2]

Maze Patient Scatter Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Steel	25	25	5.57E-01
Layer #2	3	76	Borated Poly	322	322	5.80E-01
Layer #3	1	25	Lead	5	5	8.32E-06
Outside Layer	0.25	6	Steel	25	25	5.57E-01
Slant Angle:		0 deg		0.2 MV	Total:	1.50E-06

Maze Wall Scatter Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Wall Scatter TVL1 (mm)	Wall Scatter TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Steel	25	25	5.57E-01
Layer #2	3	76	Borated Poly	322	322	5.80E-01
Layer #3	1	25	Lead	5	5	8.32E-06
Outside Layer	0.25	6	Steel	25	25	5.57E-01
Slant Angle:		0 deg		0.2 MV	Total:	1.50E-06

Maze Leakage Scatter Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Leakage Scatter TVL1 (mm)	Leakage Scatter TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Steel	39	39	6.87E-01
Layer #2	3	76	Borated Poly	396	396	6.42E-01
Layer #3	1	25	Lead	8	8	6.68E-04
Outside Layer	0.25	6	Steel	39	39	6.87E-01
Slant Angle:		0 deg		0.3 MV	Total:	2.03E-04

Example 2: Maze Door Transmission Calculation [2 of 2]

Maze Direct Leakage Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Direct Leakage TVL1 (mm)	Direct Leakage TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Steel	110	110	8.76E-01
Layer #2	3	76	Borated Poly	842	842	8.12E-01
Layer #3	1	25	Lead	57	57	3.58E-01
Outside Layer	0.25	6	Steel	110	110	8.76E-01
Slant Angle:		0 deg		18 MV	Total:	2.23E-01

Neutron Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Maze Neutrons TVL1 (mm)	Maze Neutrons TVLe (mm)	Neutron Trans.
Inside Layer	0.25	6	Steel	N/A	N/A	1.00E+00
Layer #2	3	76	Borated Poly	45	45	2.03E-02
Layer #3	1	25	Lead	N/A	N/A	1.00E+00
Outside Layer	0.25	6	Steel	N/A	N/A	1.00E+00
Slant Angle:		0 deg		0.1 MV	Total:	2.03E-02

Capture Gamma Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Capture Gamma TVL1 (mm)	Capture Gamma TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Steel	95	95	8.57E-01
Layer #2	3	76	Borated Poly	817	817	8.07E-01
Layer #3	1	25	Lead	61	61	3.83E-01
Outside Layer	0.25	6	Steel	95	95	8.57E-01
Slant Angle:		0 deg		3.6 MV	Total:	2.27E-01

Example 2: Maze Door Shielded Dose Rate

Line	Parameter	Units	Patient Scatter	Wall Scatter	Leakage Scatter	Direct Leakage	Neutrons	Capture Gammas	Calculation
a	Calc. Unshield Dose Rate	mSv/wk	8.86E-03	1.10E-04	3.03E-02	2.60E-03	5.52E-01	1.47E-01	
b	Total / Calc. Dose Rate		2.64	2.64	1	1	1	1	NCRP 151 Eq. 2.14
c	Total Unshield Dose Rate	mSv/wk	2.34E-02	2.89E-04	3.03E-02	2.60E-03	5.52E-01	1.47E-01	a * b
d	Energy for TVL	MV	0.2	0.2	0.3	18.0	0.1	3.6	
e	Transmission		1.57E-06	1.57E-06	2.03E-04	2.23E-01	2.03E-02	2.27E-01	see above
f	Shielded Dose Rate	mSv/wk	0.0000	0.0000	0.0000	0.0006	0.0112	0.0335	c * e
g	Total Shielded Dose Rate	mSv/wk	0.0452						Sum Row f

- Shielded dose typically dominated by neutrons and capture gammas
- Direct leakage may be significant or not, depending on maze wall width (not very large in this case)
- Scatter is negligible for high energy
  - Scatter calculation not really required for greater than 10 MV

Example 2: Wall Adj. to Maze Door Transmission Calc. [1 of 2]

Maze Patient Scatter Transmission for Wall Adjacent to Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Photon Trans.
Inside Layer	12	305	Concrete	130	130	4.52E-03
Layer #2						1.00E+00
Layer #3						1.00E+00
Outside Layer						1.00E+00
Slant Angle:		0 deg		0.2 MV	Total:	4.52E-03

Maze Wall Scatter Transmission for Wall Adjacent to Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Photon Trans.
Inside Layer	12	305	Concrete	130	130	4.52E-03
Layer #2						1.00E+00
Layer #3						1.00E+00
Outside Layer						1.00E+00
Slant Angle:		0 deg		0.2 MV	Total:	4.52E-03

Maze Leakage Scatter Transmission for Wall Adjacent to Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Photon Trans.
Inside Layer	12	305	Concrete	160	160	1.24E-02
Layer #2						1.00E+00
Layer #3						1.00E+00
Outside Layer						1.00E+00
Slant Angle:		0 deg		0.3 MV	Total:	1.24E-02

Example 2: Wall Adj. to Maze Door Transmission Calc. [2 of 2]

Maze Direct Leakage Transmission for Wall Adjacent to Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Photon Trans.
Inside Layer	12	305	Concrete	360	340	1.27E-01
Layer #2						1.00E+00
Layer #3						1.00E+00
Outside Layer						1.00E+00
Slant Angle:		0 deg		18 MV	Total:	1.27E-01

Neutron Transmission for Wall Adjacent to Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Neutron Trans.
Inside Layer	12	305	Concrete	161	161	1.28E-02
Layer #2						1.00E+00
Layer #3						1.00E+00
Outside Layer						1.00E+00
Slant Angle:		0 deg		0.1 MV	Total:	1.28E-02

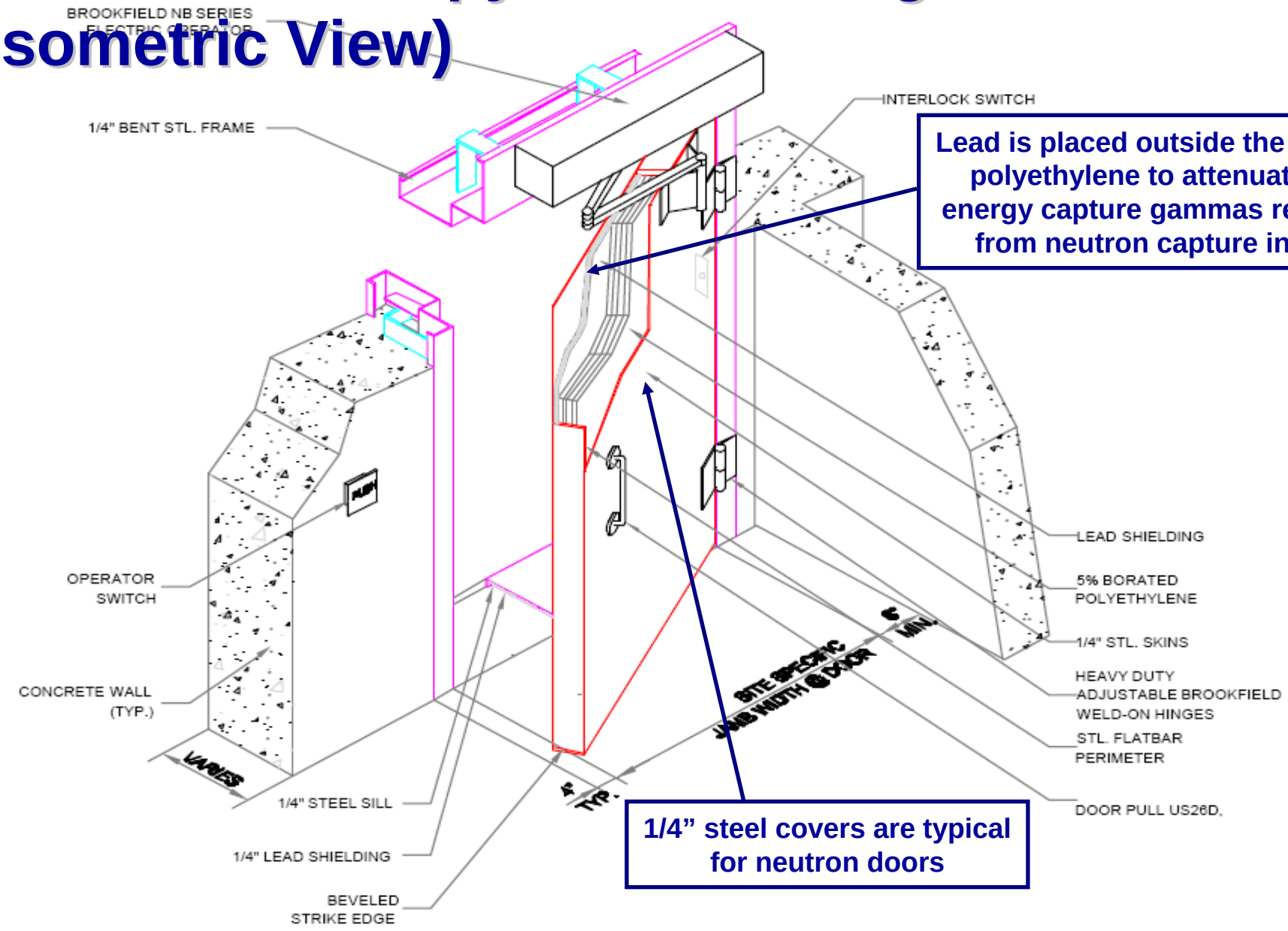
Capture Gamma Transmission for Wall Adjacent to Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Photon Trans.
Inside Layer	12	305	Concrete	330	330	1.19E-01
Layer #2						1.00E+00
Layer #3						1.00E+00
Outside Layer						1.00E+00
Slant Angle:		0 deg		3.6 MV	Total:	1.19E-01

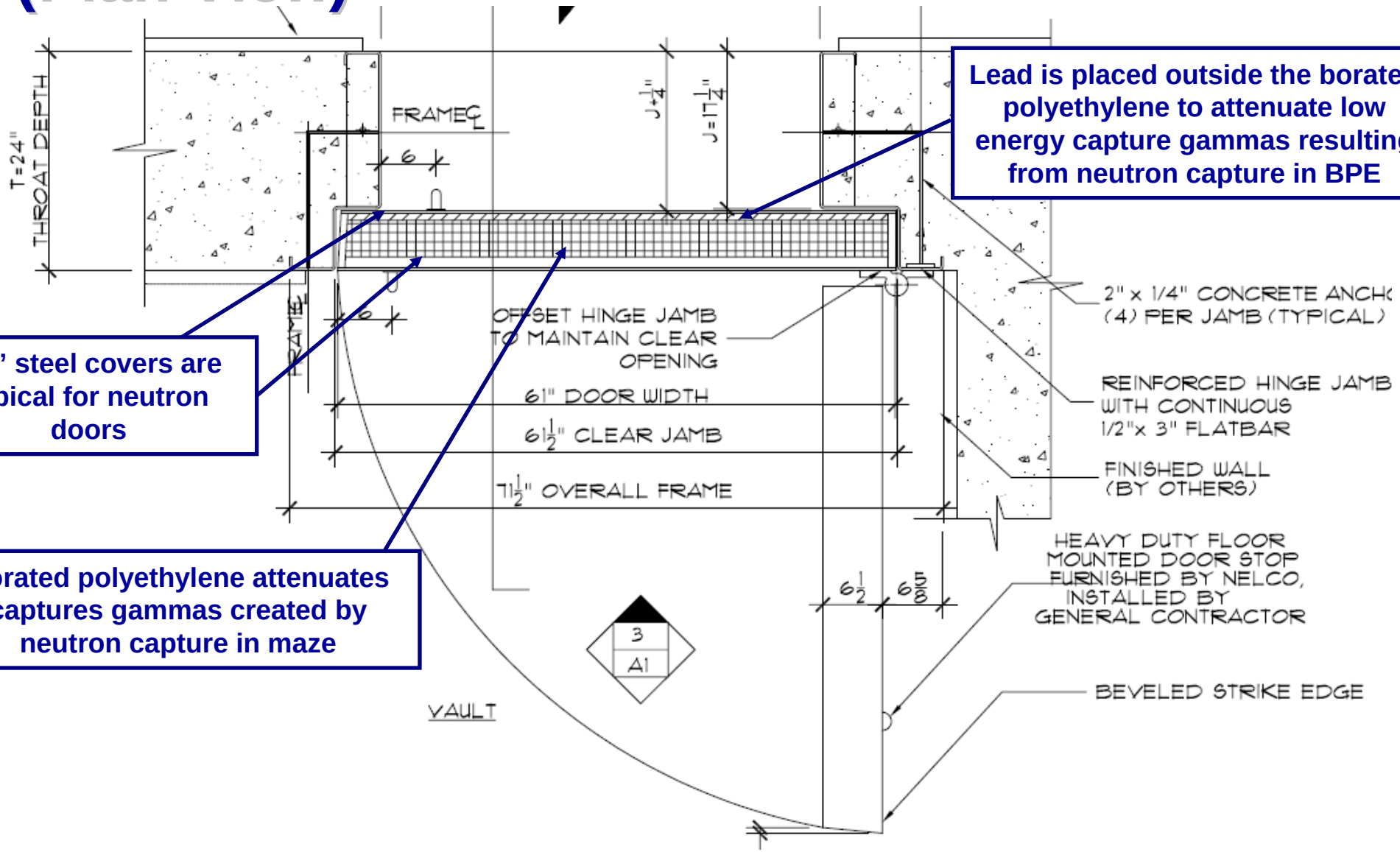
Example 2: Wall Adjacent to Maze Door Shielded Dose Rate

Line	Parameter	Units	Patient Scatter	Wall Scatter	Leakage Scatter	Direct Leakage	Neutrons	Capture Gammas	Calculation
a	Calc. Unshield Dose Rate	mSv/wk	8.86E-03	1.10E-04	3.03E-02	2.60E-03	5.52E-01	1.47E-01	
b	Total / Calc. Dose Rate		2.64	2.64	1	1	1	1	NCRP 151 Eq. 2.14
c	Total Unshield Dose Rate	mSv/wk	2.34E-02	2.89E-04	3.03E-02	2.60E-03	5.52E-01	1.47E-01	a * b
d	Energy for TVL	MV	0.3	0.3	0.5	18.0	0.1	3.6	
e	Transmission		4.52E-03	4.52E-03	1.24E-02	1.27E-01	1.28E-02	1.19E-01	see above
f	Shielded Dose Rate	mSv/wk	0.0001	0.0000	0.0004	0.0003	0.0071	0.0175	c * e
g	Total Shielded Dose Rate	mSv/wk	0.0254						Sum Row f

Radiation Therapy Offset Swing Door (Isometric View)



Radiation Therapy Offset Swing Door (Plan View)

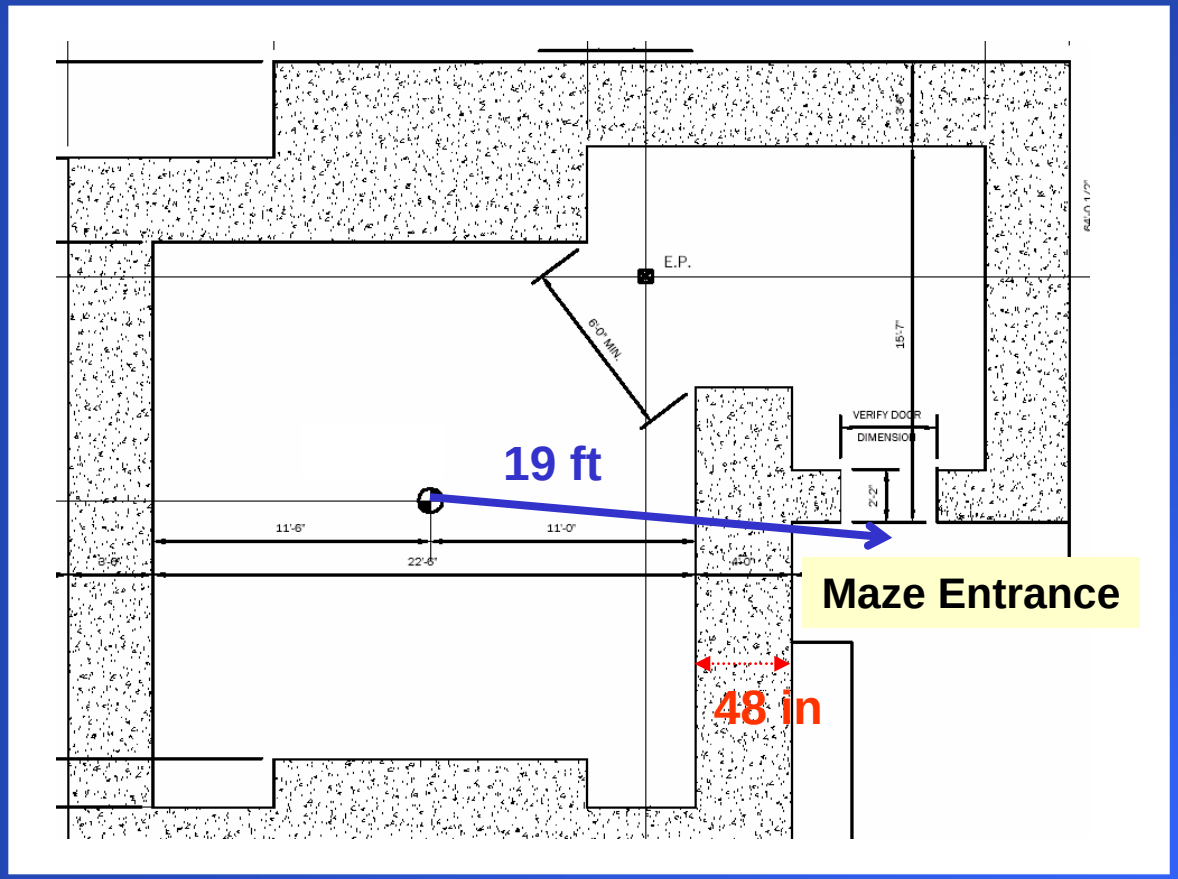


Lead is placed outside the borated polyethylene to attenuate low energy capture gammas resulting from neutron capture in BPE

1/4” steel covers are typical for neutron doors

Borated polyethylene attenuates captures gammas created by neutron capture in maze

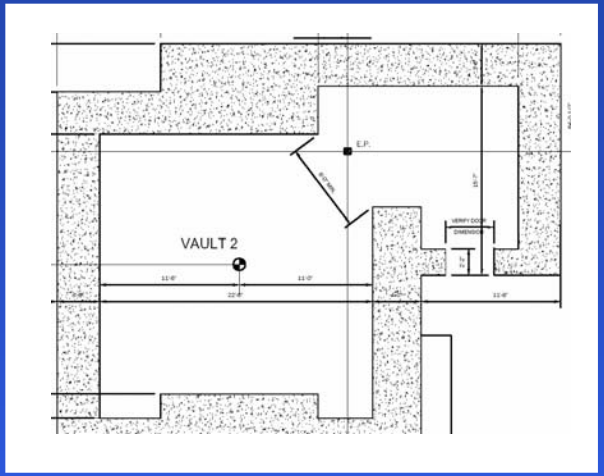
Example 3: Short Maze



Door for short maze does not provide shielding for direct leakage
Door: 3” lead, 6” borated polyethylene with 0.25” steel covers

Example 3: Short Maze

- Shorter maze than illustrated in NCRP 151 example
  - Axis of rotation is parallel to maze
  - Maze extends only part of vault length
- Unshielded dose calculated the same as for conventional maze
  - 18 MV machine, so this includes neutrons and capture gammas
  - Distances are shorter so unshielded dose is higher
  - Higher capture gamma energy assumed
- Key difference is direct leakage
  - Door does not provide attenuation of direct leakage



Example 3: Maze Door Transmission Calculation [1 of 2]

Maze Patient Scatter Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Steel	25	25	5.57E-01
Layer #2	1.5	38	Lead	5	5	2.40E-08
Layer #3	6	152	Borated Poly	322	322	3.36E-01
Layer #4	1.5	38	Lead	5	5	2.40E-08
Outside Layer	0.25	6	Steel	25	25	5.57E-01
Slant Angle:		0 deg		0.2 MV	Total:	6.01E-17

Maze Wall Scatter Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Wall Scatter TVL1 (mm)	Wall Scatter TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Steel	25	25	5.57E-01
Layer #2	1.5	76	Lead	5	5	5.75E-16
Layer #3	6	13	Borated Poly	322	322	9.13E-01
Layer #4	1.5	6	Lead	5	5	5.37E-02
Outside Layer	0.25	6	Steel	25	25	5.57E-01
Slant Angle:		0 deg		0.2 MV	Total:	8.76E-18

Maze Leakage Scatter Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Leakage Scatter TVL1 (mm)	Leakage Scatter TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Steel	39	39	6.87E-01
Layer #2	1.5	38	Lead	8	8	1.73E-05
Layer #3	6	152	Borated Poly	396	396	4.12E-01
Layer #4	1.5	38	Lead	8	8	1.73E-05
Outside Layer	0.25	6	Steel	39	39	6.87E-01
Slant Angle:		0 deg		0.3 MV	Total:	5.81E-11

Example 3: Maze Door Transmission Calculation [2 of 2]

Maze Direct Leakage Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Direct Leakage TVL1 (mm)	Direct Leakage TVLe (mm)	Photon Trans.
Inside Layer			Steel	110	110	1.00E+00
Layer #2			Lead	57	57	1.00E+00
Layer #3			Borated Poly	842	842	1.00E+00
Layer #4			Lead	57	57	1.00E+00
Outside Layer			Steel	110	110	1.00E+00
Slant Angle:		0 deg		18 MV	Total	1.00E+00

Neutron Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Maze Neutrons TVL1 (mm)	Maze Neutrons TVLe (mm)	Neutron Trans.
Inside Layer	0.25	6	Steel	N/A	N/A	1.00E+00
Layer #2	1.5	38	Lead	N/A	N/A	1.00E+00
Layer #3	6	152	Borated Poly	45	45	4.11E-04
Layer #4	1.5	38	Lead	N/A	N/A	1.00E+00
Outside Layer	0.25	6	Steel	N/A	N/A	1.00E+00
Slant Angle:		0 deg		0.1 MV	Total:	4.11E-04

Capture Gamma Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Capture Gamma TVL1 (mm)	Capture Gamma TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Steel	110	110	8.76E-01
Layer #2	1.5	38	Lead	61	61	2.37E-01
Layer #3	6	152	Borated Poly	1015	916	7.08E-01
Layer #4	1.5	38	Lead	61	61	2.37E-01
Outside Layer	0.25	6	Steel	110	110	8.76E-01
Slant Angle:		0 deg		10 MV	Total:	3.06E-02

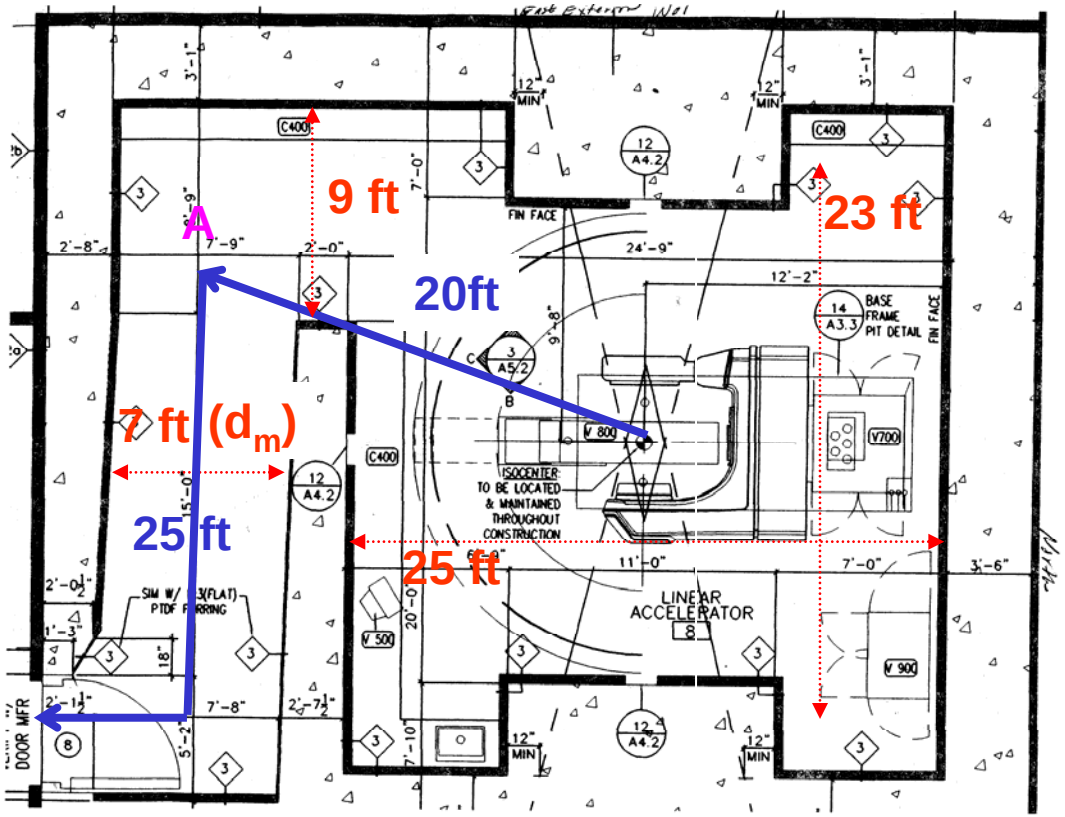
No shielding by door

Example 3: Maze Door Shielded Dose Rate

Line	Parameter	Units	Patient Scatter	Wall Scatter	Leakage Scatter	Direct Leakage	Neutrons	Capture Gammas	Calculation
a	Calc. Unshield Dose Rate	mSv/wk	6.07E-02	2.12E-03	1.71E-01	7.97E-03	3.63E+00	7.55E-01	
b	Total / Calc. Dose Rate		2.64	2.64	1	1	1	1	NCRP 151 Eq. 2.14
c	Total Unshield Dose Rate	mSv/wk	1.60E-01	5.60E-03	1.71E-01	7.97E-03	3.63E+00	7.55E-01	a * b
d	Energy for TVL	MV	0.2	0.2	0.3	18.0	0.1	10.0	
e	Transmission		6.28E-17	9.16E-18	5.81E-11	1.00E+00	4.11E-04	3.06E-02	see above
f	Shielded Dose Rate	mSv/wk	0.0000	0.0000	0.0000	0.0080	0.0015	0.0231	c * e
g	Total Shielded Dose Rate	mSv/wk	0.0325						Sum Row f

- Scatter negligible for high energy machine
- Usually dominated by fast neutrons and capture gammas
- Direct leakage may be significant or not, depending on maze wall width (not very large in this case)

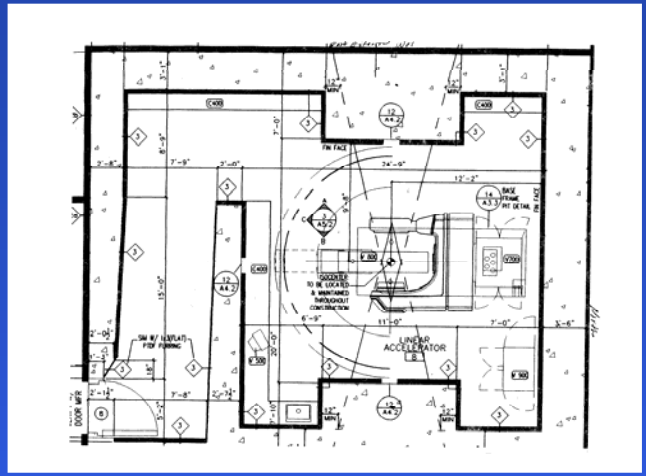
Example 4: Maze with Second Bend



Long maze with extra bend reduces neutrons at door
Door: 1” lead, 1” borated polyethylene with 0.25” steel covers

Example 4: Maze with Additional Bend

- Conventional maze similar to examples in NCRP 151
- Maze includes additional bend
  - Less scatter since walls barely visible from door
  - Neutron distance d_2 measured along center line to door
  - Factor of three reduction in neutron dose rate with extra bend
    - » NCRP 151 wording is ambiguous about Kersey vs. Modified Kersey
  - No comparable reduction for capture gammas identified



- 18 MV machine energy
  - Scatter calculations included to illustrate 6 MV calculations

Example 4: Maze Door Transmission Calculation [1 of 2]

Maze Patient Scatter Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Steel	25	25	5.57E-01
Layer #2	1	25	Borated Poly	322	322	8.34E-01
Layer #3	0.5	13	Lead	5	5	2.88E-03
Outside Layer	0.25	6	Steel	25	25	5.57E-01
Slant Angle:		0 deg		0.2 MV	Total:	7.47E-04

Maze Wall Scatter Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Wall Scatter TVL1 (mm)	Wall Scatter TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Steel	25	25	5.57E-01
Layer #2	1	25	Borated Poly	322	322	8.34E-01
Layer #3	0.5	13	Lead	5	5	2.88E-03
Outside Layer	0.25	6	Steel	25	25	5.57E-01
Slant Angle:		0 deg		0.2 MV	Total:	7.47E-04

Maze Leakage Scatter Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Leakage Scatter TVL1 (mm)	Leakage Scatter TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Steel	39	39	6.87E-01
Layer #2	1	25	Borated Poly	396	396	8.63E-01
Layer #3	0.5	13	Lead	8	8	2.59E-02
Outside Layer	0.25	6	Steel	39	39	6.87E-01
Slant Angle:		0 deg		0.3 MV	Total:	1.05E-02

Example 4: Maze Door Transmission Calculation [2 of 2]

Maze Direct Leakage Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Direct Leakage TVL1 (mm)	Direct Leakage TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Steel	110	110	8.76E-01
Layer #2	1	25	Borated Poly	842	842	9.33E-01
Layer #3	0.5	13	Lead	57	57	5.99E-01
Outside Layer	0.25	6	Steel	110	110	8.76E-01
Slant Angle:		0 deg		18 MV	Total:	4.28E-01

Neutron Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Maze Neutrons TVL1 (mm)	Maze Neutrons TVLe (mm)	Neutron Trans.
Inside Layer	0.25	6	Steel	N/A	N/A	1.00E+00
Layer #2	1	25	Borated Poly	45	45	2.73E-01
Layer #3	0.5	13	Lead	N/A	N/A	1.00E+00
Outside Layer	0.25	6	Steel	N/A	N/A	1.00E+00
Slant Angle:		0 deg		0.1 MV	Total:	2.73E-01

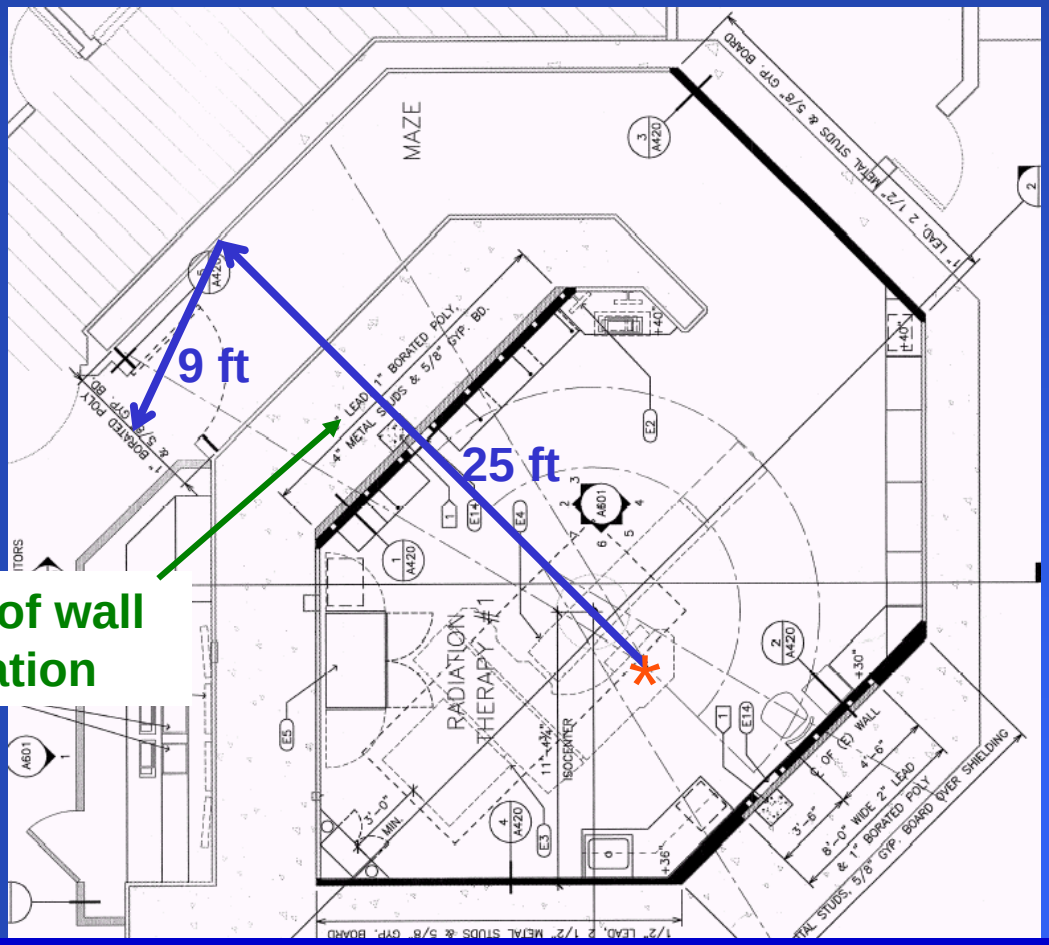
Capture Gamma Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Capture Gamma TVL1 (mm)	Capture Gamma TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Steel	95	95	8.57E-01
Layer #2	1	25	Borated Poly	817	817	9.31E-01
Layer #3	0.5	13	Lead	61	61	6.19E-01
Outside Layer	0.25	6	Steel	95	95	8.57E-01
Slant Angle:		0 deg		3.6 MV	Total:	4.24E-01

Example 4: Maze Door Shielded Dose Rate

Line	Parameter	Units	Patient Scatter	Wall Scatter	Leakage Scatter	Direct Leakage	Neutrons	Capture Gammas	Calculation
a	Calc. Unshield Dose Rate	mSv/wk	8.81E-03	2.31E-04	2.67E-02	4.76E-02	1.06E-01	8.77E-02	
b	Total / Calc. Dose Rate		2.64	2.64	1	1	1	1	NCRP 151 Eq. 2.14
c	Total Unshield Dose Rate	mSv/wk	2.33E-02	6.10E-04	2.67E-02	4.76E-02	1.06E-01	8.77E-02	a * b
d	Energy for TVL	MV	0.2	0.2	0.3	18.0	0.1	3.6	
e	Transmission		7.81E-04	7.81E-04	1.05E-02	4.28E-01	2.73E-01	4.24E-01	see above
f	Shielded Dose Rate	mSv/wk	0.0000	0.0000	0.0003	0.0204	0.0288	0.0372	c * e
g	Total Shielded Dose Rate	mSv/wk	0.0867						Sum Row f

Example 5: Maze with Axis of Rotation Perpendicular to Maze



Primary attenuation of wall included in calculation

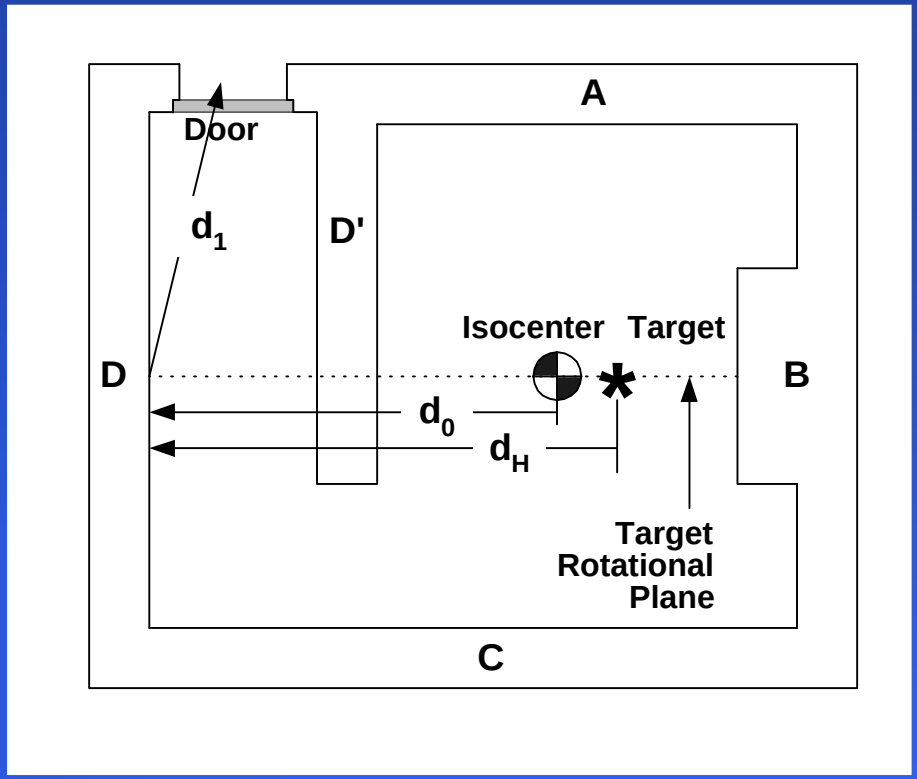
No shielding required for door (extremely long maze with extra bend)

Wall Scatter with Axis of Rotation Perpendicular to Maze

- Unshielded dose rate

$$f\,H_S = f\,\frac{W\,U\,\alpha_0\,A_0\,\,B}{d_H^{\,2}\,\,d_1^{\,2}}$$

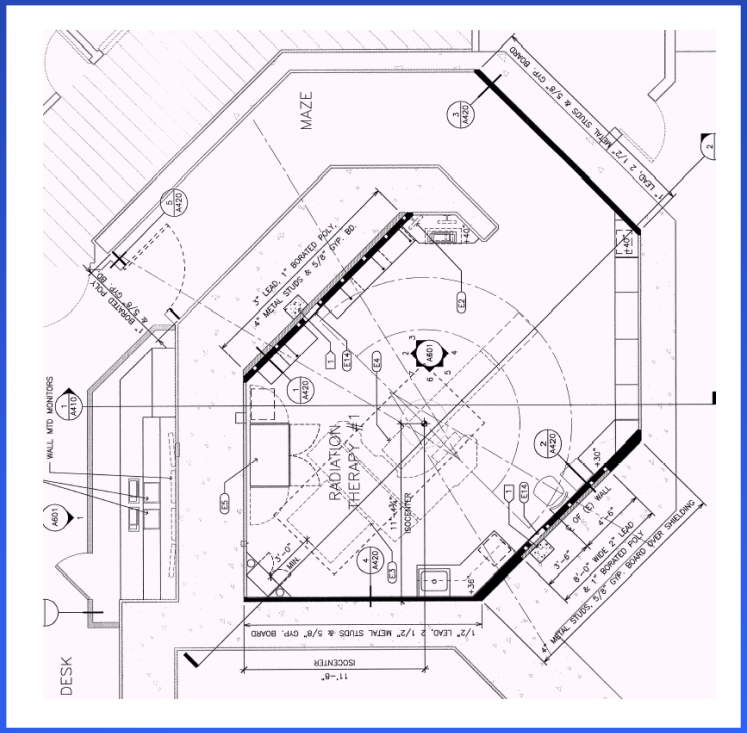
- where
  - *f* = patient transmission (0.25)
  - α_0 = reflection coefficient
    - » NCRP 151 Table B.8a vs. accelerator MV
    - » 75º angle of reflection typical
  - A_0 = beam area (m^2) at wall
  - B is primary beam transmission through maze wall



- NCRP 151 does not specifically address this situation
  - It is adapted based on the geometry
  - Lacking other guidance, the same use factor adjustment is maintained

Example 5: Long Maze with Axis of Rotation Perpendicular to Maze

- Length of maze makes patient and leakage scatter negligible
- Wall scatter calculation different
  - Calculated with beam toward maze
  - Single bounce instead of two bounce
  - Maze wall primary beam, mitigating the reduced number of bounces
- Direct leakage applicable, but with no door shielding
- Standard neutron and capture gamma calculation
  - Except factor of 3 reduction due to additional bend in maze

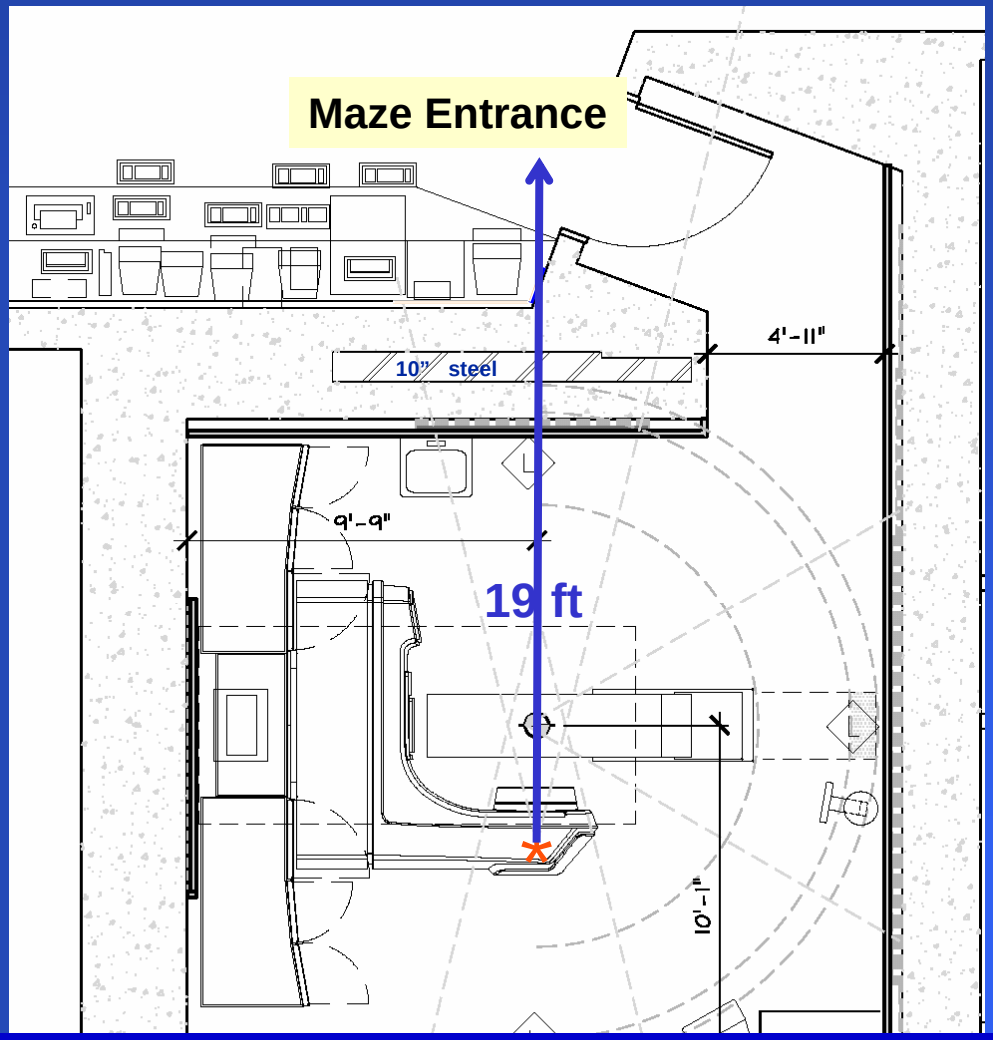


Example 5: Maze Door Shielded Dose Rate

Line	Parameter	Units	Patient Scatter	Wall Scatter	Leakage Scatter	Direct Secondary	Maze Neutrons	Capture Gammas	Calculation
a	Calc. Unshield Dose Rate	mSv/wk	0.00E+00	3.54E-04	0.00E+00	8.06E-03	2.26E-02	5.99E-03	
b	Total / Calc. Dose Rate		2.64	2.64	1	1	1	1	
c	Total Unshield Dose Rate	mSv/wk	0.00E+00	9.35E-04	0.00E+00	8.06E-03	2.26E-02	5.99E-03	a * b
d	Energy for TVL	MV	0.2	0.3	0.3	15.0	0.1	3.6	
e	Transmission		1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	see above
f	Shielded Dose Rate	mSv/wk	0.0000	0.0009	0.0000	0.0081	0.0226	0.0060	c * e
g	Total Shielded Dose Rate	mSv/wk	0.0376						Sum Row f

- No attenuation calculation since no door
- Maze wall scatter dominates the scatter mechanisms, and is different in form from typical maze
- No door required since relatively thick walls and long maze with additional bend

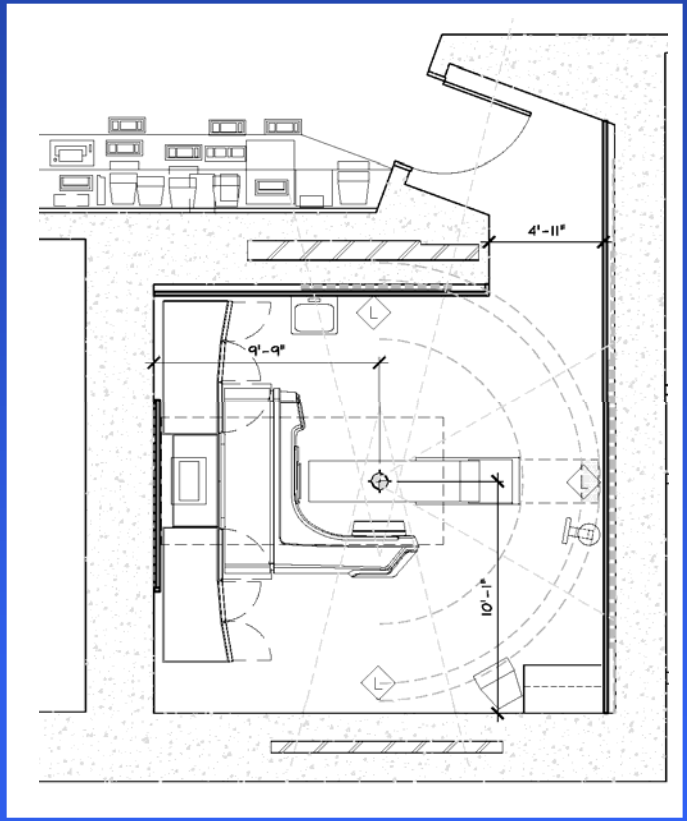
Example 6: Maze with Primary Barrier Contribution



Door for short maze does not provide shielding for primary barrier
Door: 3" lead, 6" borated polyethylene with 0.25" steel covers

Example 6: Maze with Primary Barrier Contribution

- Primary barrier calculation adds to maze calculations instead of direct leakage
  - Note also that the door does not shield primary radiation
- Maze orientation impacts wall scatter calculation
  - Beam toward maze for patient scatter
  - Beam away from maze for wall scatter
  - Leakage scatter unchanged



Example 6: Maze Door Transmission Calculation [1 of 3]

Maze Patient Scatter Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Steel	25	25	5.57E-01
Layer #2	1.5	38	Lead	5	5	2.40E-08
Layer #3	6	152	Borated Poly	322	322	3.36E-01
Layer #4	1.5	38	Lead	5	5	2.40E-08
Outside Layer	0.25	6	Steel	25	25	5.57E-01
Slant Angle:		0 deg		0.2 MV	Total:	6.01E-17

Maze Wall Scatter Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Wall Scatter TVL1 (mm)	Wall Scatter TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Steel	25	25	5.57E-01
Layer #2	1.5	76	Lead	5	5	5.75E-16
Layer #3	6	13	Borated Poly	322	322	9.13E-01
Layer #4	1.5	6	Lead	5	5	5.37E-02
Outside Layer	0.25	6	Steel	25	25	5.57E-01
Slant Angle:		0 deg		0.2 MV	Total:	8.76E-18

Example 6: Maze Door Transmission Calculation [2 of 3]

Maze Leakage Scatter Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Leakage Scatter TVL1 (mm)	Leakage Scatter TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Steel	39	39	6.87E-01
Layer #2	1.5	38	Lead	8	8	1.73E-05
Layer #3	6	152	Borated Poly	396	396	4.12E-01
Layer #4	1.5	38	Lead	8	8	1.73E-05
Outside Layer	0.25	6	Steel	39	39	6.87E-01
Slant Angle:		0 deg		0.3 MV	Total:	5.81E-11

Example 6: Maze Door Transmission Calculation [3 of 3]

Neutron Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Maze Neutrons TVL1 (mm)	Maze Neutrons TVLe (mm)	Neutron Trans.
Inside Layer	0.25	6	Steel	N/A	N/A	1.00E+00
Layer #2	1.5	38	Lead	N/A	N/A	1.00E+00
Layer #3	6	152	Borated Poly	45	45	4.11E-04
Layer #4	1.5	38	Lead	N/A	N/A	1.00E+00
Outside Layer	0.25	6	Steel	N/A	N/A	1.00E+00
Slant Angle:		0 deg		0.1 MV	Total:	4.11E-04

Capture Gamma Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Capture Gamma TVL1 (mm)	Capture Gamma TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Steel	110	110	8.76E-01
Layer #2	1.5	38	Lead	61	61	2.37E-01
Layer #3	6	152	Borated Poly	1015	916	7.08E-01
Layer #4	1.5	38	Lead	61	61	2.37E-01
Outside Layer	0.25	6	Steel	110	110	8.76E-01
Slant Angle:		0 deg		10 MV	Total:	3.06E-02

Example 6: Maze Door Shielded Dose Rate

Line	Parameter	Units	Patient Scatter	Wall Scatter	Leakage Scatter	Primary Barrier	Maze Neutrons	Capture Gammas	Calculation
a	Calc. Unshield Dose Rate	mSv/wk	3.74E-01	7.72E-04	1.02E+00	4.43E-02	3.04E+00	5.43E-01	
b	Total / Calc. Dose Rate		2.64	2.64	1	1	1	1	NCRP 151 Eq. 2.14
c	Total Unshield Dose Rate	mSv/wk	9.87E-01	2.04E-03	1.02E+00	4.43E-02	3.04E+00	5.43E-01	a * b
d	Energy for TVL	MV	0.2	0.2	0.3	15.0	0.1	10.0	
e	Transmission		6.01E-17	8.76E-18	5.81E-11	1.00E+00	4.11E-04	3.06E-02	see above
f	Shielded Dose Rate	mSv/wk	0.0000	0.0000	0.0000	0.0443	0.0012	0.0166	c * e
g	Total Shielded Dose Rate	mSv/wk	0.0621						Sum Row f

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Additional Information and Supporting Data

NCRP 151 Table B.7: Leakage TVLs (mm)

Linac MV	Lead		Concrete		Steel		Earth		Borated Poly	
	TVL1	TVLe	TVL1	TVLe	TVL1	TVLe	TVL1	TVLe	TVL1	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 ratio for steel leakage TVL relative concrete

Estimated 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]

borated poly = 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 (Primary TVL 100 mm at 6 MV, 110 mm at higher energy). NCRP 51 Figure E.13 implies leakage TVL should be less than primary. Constant steel TVL of 96 mm appears reasonable value based on ratio of concrete to steel leakage TVL in Varian document #12004.

Steel Leakage TVLs Rationale

Leakage TVLs in Varian Doc #12004

MV	TVL (mm)		Ratio
	Concrete	Steel	
4	250	83	3
6	280	88	3.2
10	320	91	3.5
15	330	89	3.7
18	330	89	3.7
25	360	90	4

Steel TVLs Calculated from NCRP 151 Table B.7 Concrete Leakage TVLs Using Varian Ratios

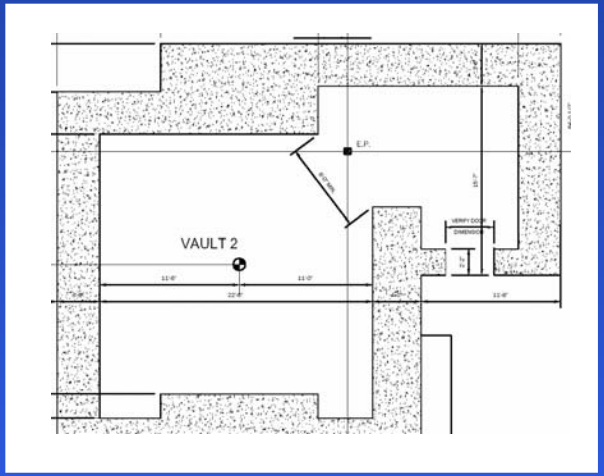
MV	Concrete		Steel Calculated			Varian Ratio
	TVL1	TVL eq	TVL 1	TVL eq	TVL Ave	
4	330	280	110	93	99	3
6	340	290	106	91	96	3.2
10	350	310	100	89	92	3.5
15	360	330	97	89	92	3.7
18	360	340	97	92	94	3.7
25	370	350	93	88	89	4

Average calculated assuming 3 TVLs with TVL ave = (TVL1 + 2* TVLeq) / 3

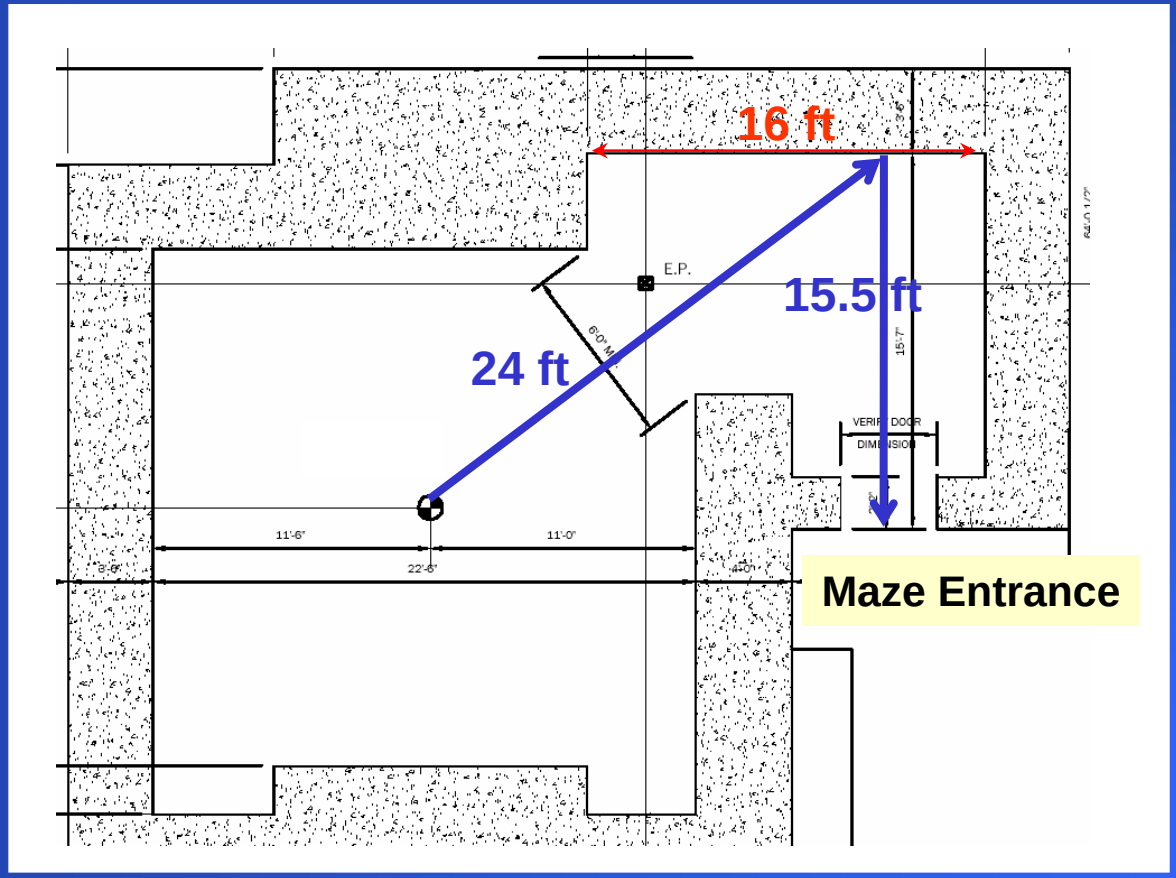
- Concrete Leakage TVLs reported in Varian Document # 12004 at slightly less than NCRP 151 Table B.7
- Applying Varian ratios to NCRP 151 concrete TVLs yields average steel TVLs ranging from 89 to 99 mm
  - TVL should monotonically decrease with MV (NCRP 51 Figure E.13)
  - 96 mm TVL appear reasonable upper bound for steel leakage

Example 3: Short Maze

- Shorter maze than illustrated in NCRP 151 example
  - Axis of rotation is parallel to maze
  - Maze extends only part of vault length
- Unshielded dose calculated the same as for conventional maze
  - 18 MV machine, so this includes neutrons and capture gammas
  - Distances are shorter so unshielded dose is higher
  - Higher capture gamma energy assumed
- Key difference is direct leakage
  - Door does not provide attenuation of direct leakage



Example 3a: Maze with Leakage Not Shielded by Door — Patient Scatter



Example 3 P/T and Average Field Size Calculation

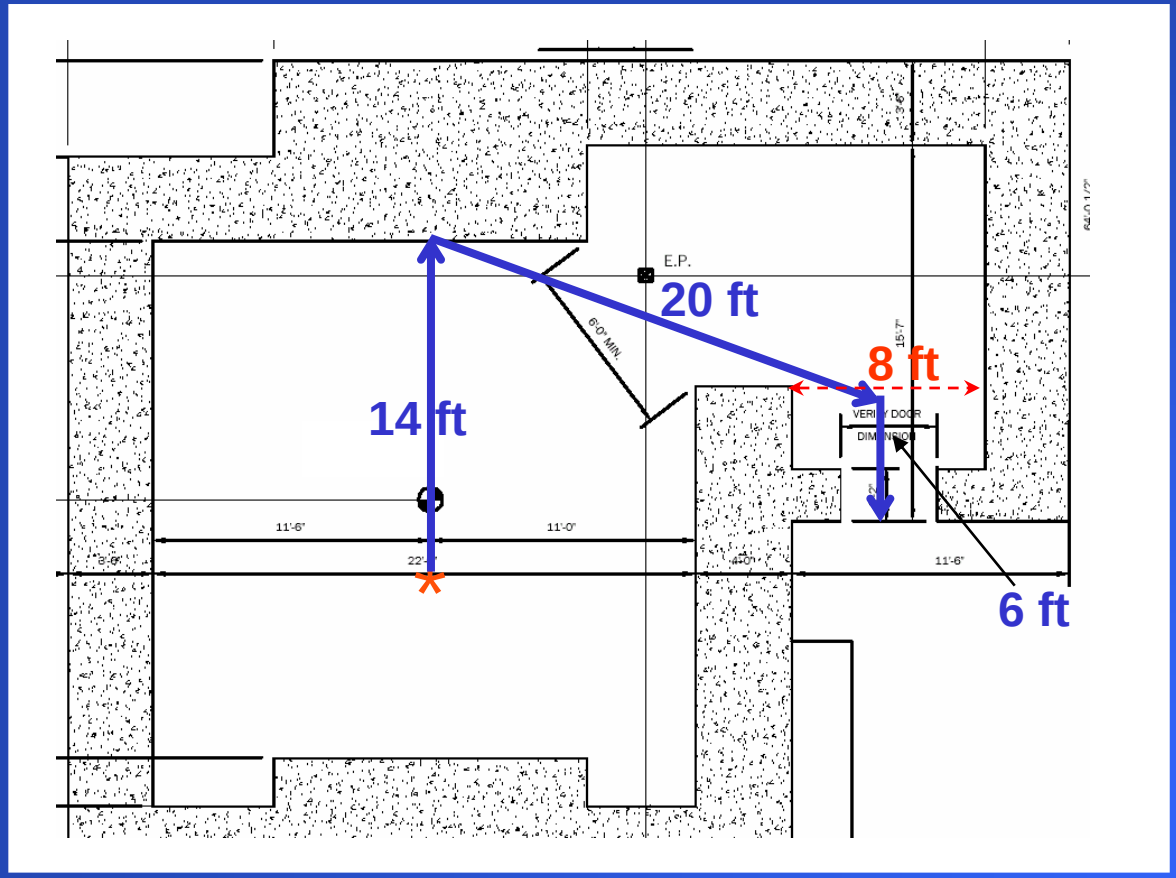
Line	Parameter	Units	Value	Calculation
a	Machine X-ray Energy	mSv/wk	18	
b	Workload/Patient /wk	Gy/patient	15	Table 3.1 Dual
c	Patients per Week	patient/wk	30	Table 3.2 Dual
d	Workload (W)	Gy/Wk	450	b * c
e	Design Dose Limit (P)	mSv/wk	0.1	
f	Occupancy Factor (T)		1	
g	P/T	mSv/wk	0.100	e / f

Line	Parameter	Units	Value		Calculation
			w/o IMRT	with IMRT	
a	Max Field Size	cm	40	15	
b	Fraction of Workload		50%	50%	
c	Effective Field Area	cm^2	912.5		$b_1 * a_1$^2 + $b_2 * a_2$^2
d	Effective Field Size	cm	30.2		sqrt (c)

Example 3a: Patient Scatter Unshielded Dose Rate Calculation

Line	Symbol	Parameter	Units	Value	Calculation
a	MV	Machine X-ray Energy	MV	18	
b	W	Workload	Gy/wk	450	
c	d_{sca}	Distance from target to isocenter	m	1.00	
d	d_{sec}	Distance from isocenter to wall at maze end	ft	24	measured
e			m	7.32	d * 0.3048
f	d_{zz}	Distance from wall at maze end to door	ft	15.5	measured
g			m	4.72	f * 0.3048
h	w_1	Wall width seen from door	ft	16	measured
i			m	4.88	h * 0.3048
j	h	Room height	ft	10	measured
k			m	3.05	j * 0.3048
L	A_1	Scatter area	m^2	14.9	i * k
m	a	Patient scatter fraction ($400\ cm^2$ field)		8.64E-04	NCRP 151 Table B.4 (45º) Function of MV
n	α_1	2nd bounce scatter fraction / m^2		2.20E-02	Table B.8b, 0.5 MV, 0º
o	F	Average field area	cm^2	912.5	See above
p	U	Use Factor		0.25	Orientation with highest dose rate
q	H_{PS}	Patient scatter unshielded dose rate	mSv/wk	6.07E-02	1000*m*b*p*(o/400)*L / (c^2 * e^2 * g^2)

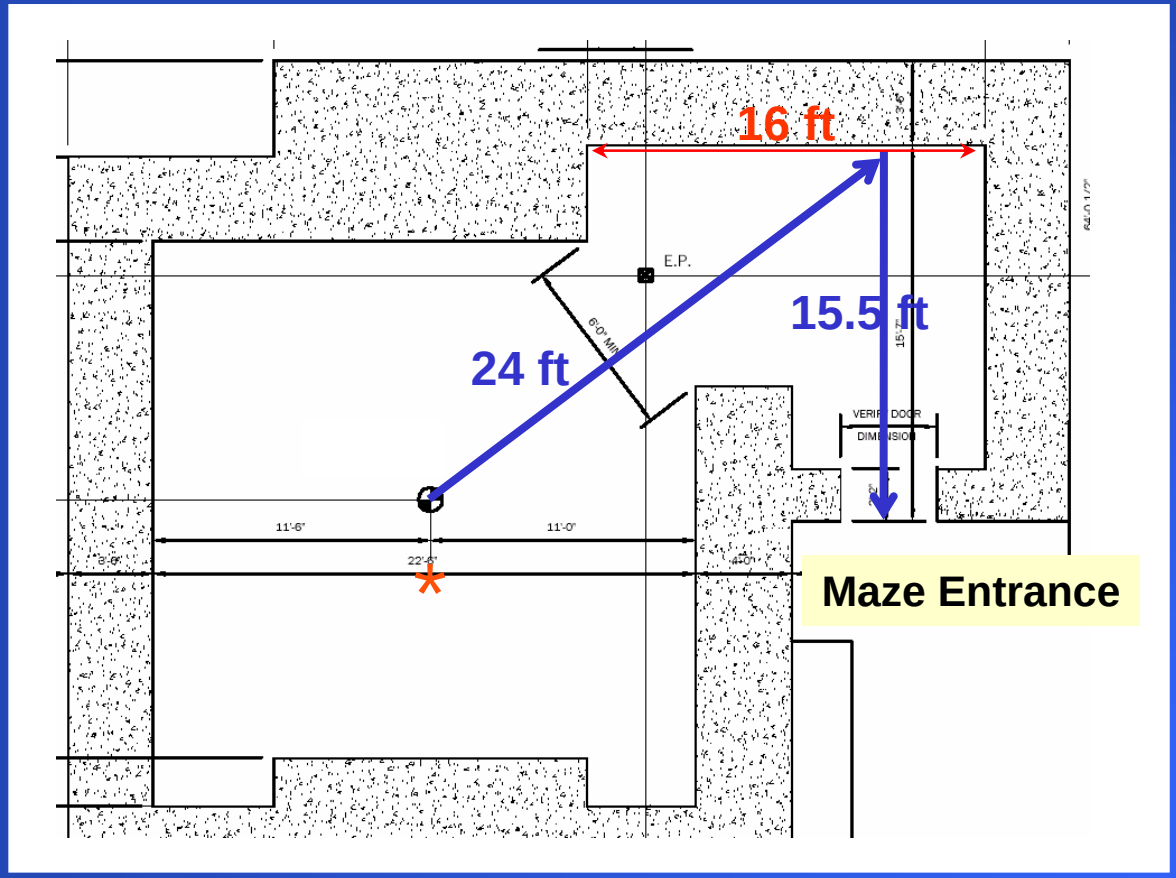
Example 3b: Maze with Leakage Not Shielded by Door — Wall Scatter



Example 3b: Wall Scatter Unshielded Dose Rate

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	14	measured
e			m	4.27	d * 0.3048
f	d_r	Distance from primary barrier wall to maze inside opening	ft	20	measured
g			m	6.10	f * 0.3048
h	d_z	Distance from maze inside opening to door	ft	6	measured
i			m	1.83	h * 0.3048
j	d_m	Maze width	ft	8	measured
k			m	2.44	j * 0.3048
L	h	Room height	ft	10	measured
m			m	3.05	L * 0.3048
n	α_0	1sr reflection coefficient	$1 / m^2$	0.0016	Table B.8a with 18 MV 75º scatter angle
o		Effective field size	cm	30.2	see above
p	A_0	Beam area at first reflection	m^2	1.66	(e * o/100)^2
q	α_z	2nd bounce scatter fraction / m^2		0.0080	Table B.8a with 0.5 MV 75º scatter angle
r	A_z	Maze cross section	m^2	7.4	j * L
s	U	Use Factor		0.25	Orientation with highest dose rate
t	f H_S	Wall scatter unshielded dose	mSv/wk	2.12E-03	1000*m*b*s*(o/400)* L / (e^2 * g^2 * i^2)

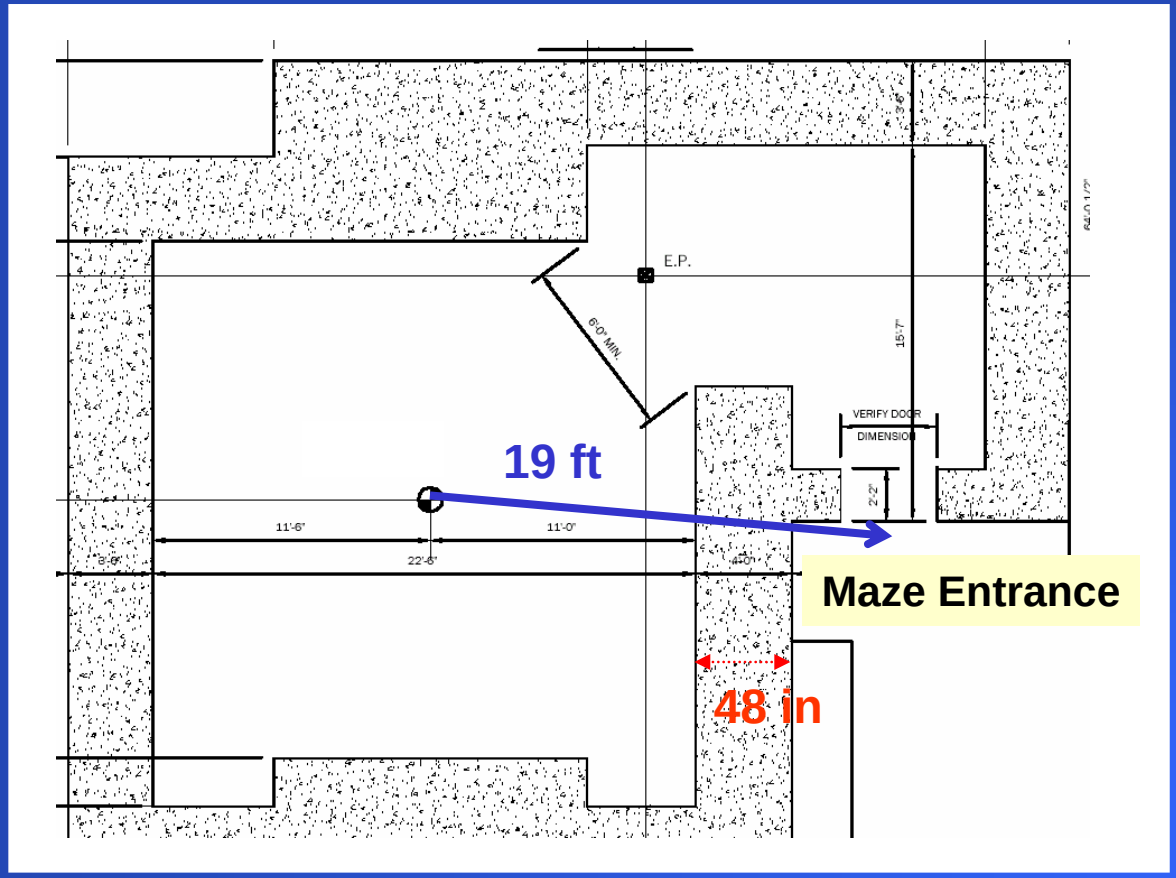
Example 3c: Maze with Leakage Not Shielded by Door — Leakage Scatter



Example 3c: Leakage Scatter Unshielded Dose Rate Calculation

Line	Symbol	Parameter	Units	Value	Calculation
a	MV	Machine X-ray Energy	MV	18	
b	W	Workload	Gy/wk	450	
c		Leakage Fraction	%	0.10%	
d		IMRT Factor		2	
e	d_{sec}	Distance from target to wall at maze end	ft	24	measured
f			m	7.32	d * 0.3048
g	d_{zz}	Distance from wall at maze end to door	ft	15.5	measured
h			m	4.72	f * 0.3048
i	w_1	Wall width seen from door	ft	16	measured
j			m	4.88	h * 0.3048
k	h	Room height	ft	10	measured
L			m	3.05	j * 0.3048
m	α_1	1sr reflection coefficient	$1 / m^2$	0.0179	Table B.8b with 1.5 MV 0º Reflection angle
n	A_1	Scatter area	m^2	14.9	i * k
o	U	Use Factor		1	Calculation does not depend on orientation
p	H_{LS}	Leakage scatter unshielded dose rate	mSv/wk	2.00E-01	1000 * b * o * c * d * m * n / (f^2 * h^2)

Example 3d: Maze with Leakage Not Shielded by Door — Direct Leakage



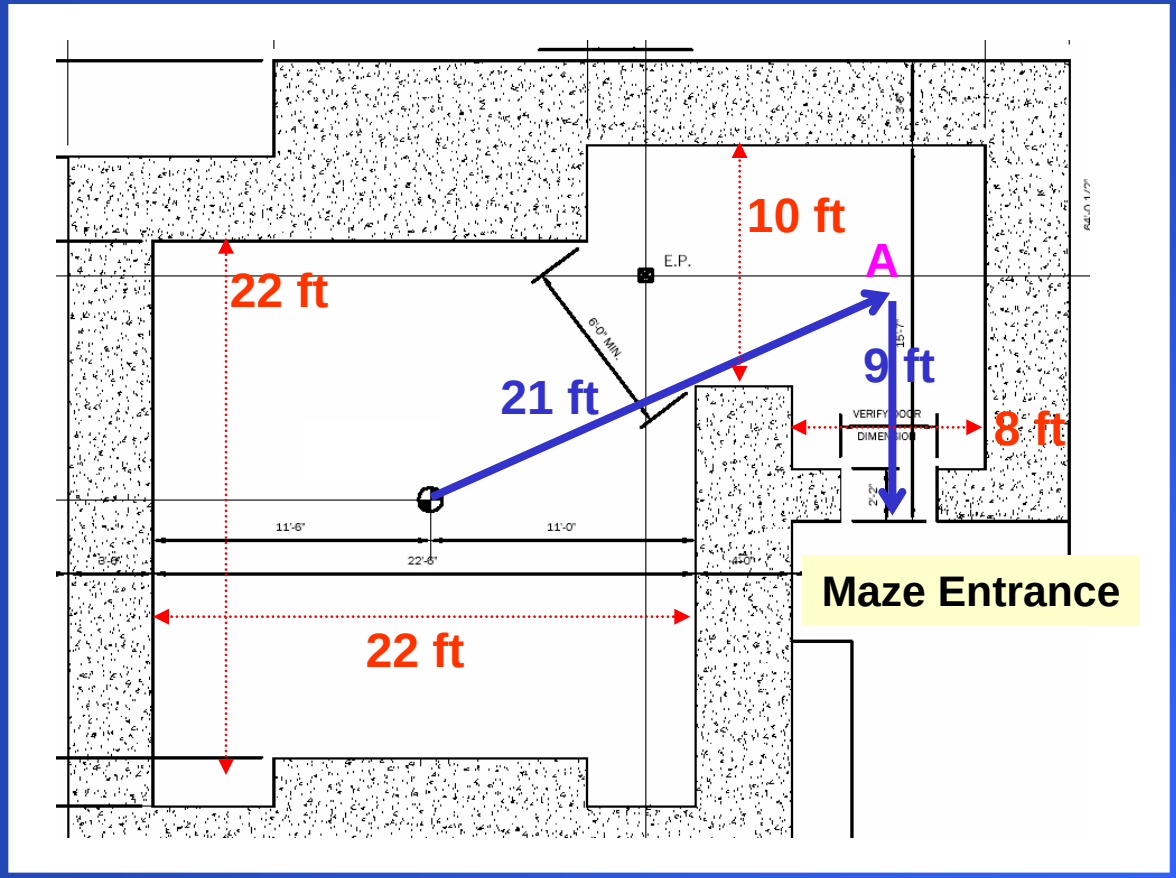
Door for short maze does not provide shielding for direct leakage

Example 3d: Direct Leakage Unshielded Dose Rate Calculation

Line	Parameter	Units	Value	Calculation
a	Machine X-ray Energy	MV	18	
b	Workload (W)	Gy/Wk	450	
c	Use Factor	Ratio	1	
d	Leakage Fraction	%	0.10%	
e	IMRT Factor		2	
f	Isocenter to Protected Point Distance	ft	19.0	
g		m	5.8	f * 0.3048
h	Unshielded Dose	mSv/wk	2.68E+01	1000*b*c*d*e / g^2
i	Wall Transmission		2.97E-04	see below
j	Shielded Dose	mSv/wk	7.97E-03	h * i

Barrier	Material Thickness inches	Slant Thickness mm	Material	Direct Leakage TVL1 (mm)	Direct Leakage TVLe (mm)	Photon Trans.
Inside Layer	48	1219	Concrete	360	340	2.97E-04
Layer #2						1.00E+00
Outside Layer						1.00E+00
Slant Angle: 0 deg				18 MV	Total:	2.97E-04

Example 3e: Maze with Leakage Not Shielded by Door — Maze Neutrons



Capture gamma Energy for short maze 10 MV vs 7.2 MV long maze

Example 3e: 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	21	measured
f			m	6.40	e * 0.3048
g	d_L	Vault Average Length	ft	22	measured
h			m	6.71	g * 0.3048
i	d_W	Vault Average Width	ft	22	measured
j			m	6.71	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	171.7	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	7.83E+09	c*n* [d/(4*π* f^2) + (5.4*d+1.3)/(2*π*m)]

Example 3e: 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	7.83E+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	1.68E-06	g * c * 10^(-e / f)
i		Capture Gamma Unshielded Dose Rate	mSv/wk	7.55E-01	1000 * a * h

Example 3e: Maze Neutron Unshielded Dose Rate Calculation

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	7.83E+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	10	measured
f			m	3.05	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	9.29	f * h
j	d_m	Maze Width	ft	8	measured
k			m	2.44	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	7.43	i * m
o	TVD_n	Maze Neutron Tenth-Value Distance	m	5.62	2.06 * sqrt(n)
p	$H_{n,D}$	Neutron Unshielded Dose-Equivalent at Door per Dose at Isocenter	Sv/Gy	8.06E-06	2.4E-15 * b * sqrt(i / n) * [1.64*10^(-d/1.9)+10^(-d/o)]
q		Neutron Unshielded Dose-Equivalent Rate at Door	Sv/wk	3.63E+00	1000 * a * p

Example 3: Maze Door Transmission Calculation [1 of 2]

Maze Patient Scatter Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Steel	25	25	5.57E-01
Layer #2	1.5	38	Lead	5	5	2.40E-08
Layer #3	6	152	Borated Poly	322	322	3.36E-01
Layer #4	1.5	38	Lead	5	5	2.40E-08
Outside Layer	0.25	6	Steel	25	25	5.57E-01
Slant Angle:		0 deg		0.2 MV	Total:	6.01E-17

Maze Wall Scatter Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Wall Scatter TVL1 (mm)	Wall Scatter TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Steel	25	25	5.57E-01
Layer #2	1.5	76	Lead	5	5	5.75E-16
Layer #3	6	13	Borated Poly	322	322	9.13E-01
Layer #4	1.5	6	Lead	5	5	5.37E-02
Outside Layer	0.25	6	Steel	25	25	5.57E-01
Slant Angle:		0 deg		0.2 MV	Total:	8.76E-18

Maze Leakage Scatter Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Leakage Scatter TVL1 (mm)	Leakage Scatter TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Steel	39	39	6.87E-01
Layer #2	1.5	38	Lead	8	8	1.73E-05
Layer #3	6	152	Borated Poly	396	396	4.12E-01
Layer #4	1.5	38	Lead	8	8	1.73E-05
Outside Layer	0.25	6	Steel	39	39	6.87E-01
Slant Angle:		0 deg		0.3 MV	Total:	5.81E-11

Example 3: Maze Door Transmission Calculation [2 of 2]

Maze Direct Leakage Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Direct Leakage TVL1 (mm)	Direct Leakage TVLe (mm)	Photon Trans.
Inside Layer			Steel	110	110	1.00E+00
Layer #2			Lead	57	57	1.00E+00
Layer #3			Borated Poly	842	842	1.00E+00
Layer #4			Lead	57	57	1.00E+00
Outside Layer			Steel	110	110	1.00E+00
Slant Angle:		0 deg		18 MV	Total	1.00E+00

Neutron Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Maze Neutrons TVL1 (mm)	Maze Neutrons TVLe (mm)	Neutron Trans.
Inside Layer	0.25	6	Steel	N/A	N/A	1.00E+00
Layer #2	1.5	38	Lead	N/A	N/A	1.00E+00
Layer #3	6	152	Borated Poly	45	45	4.11E-04
Layer #4	1.5	38	Lead	N/A	N/A	1.00E+00
Outside Layer	0.25	6	Steel	N/A	N/A	1.00E+00
Slant Angle:		0 deg		0.1 MV	Total:	4.11E-04

Capture Gamma Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Capture Gamma TVL1 (mm)	Capture Gamma TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Steel	110	110	8.76E-01
Layer #2	1.5	38	Lead	61	61	2.37E-01
Layer #3	6	152	Borated Poly	1015	916	7.08E-01
Layer #4	1.5	38	Lead	61	61	2.37E-01
Outside Layer	0.25	6	Steel	110	110	8.76E-01
Slant Angle:		0 deg		10 MV	Total:	3.06E-02

No shielding by door

Example 3: Maze Door Shielded Dose Rate

Line	Parameter	Units	Patient Scatter	Wall Scatter	Leakage Scatter	Direct Leakage	Neutrons	Capture Gammas	Calculation
a	Calc. Unshield Dose Rate	mSv/wk	6.07E-02	2.12E-03	2.00E-01	7.97E-03	3.63E+00	7.55E-01	
b	Total / Calc. Dose Rate		2.64	2.64	1	1	1	1	NCRP 151 Eq. 2.14
c	Total Unshield Dose Rate	mSv/wk	1.60E-01	5.60E-03	2.00E-01	7.97E-03	3.63E+00	7.55E-01	a * b
d	Energy for TVL	MV	0.2	0.2	0.3	18.0	0.1	10.0	
e	Transmission		6.28E-17	9.16E-18	5.81E-11	1.00E+00	4.11E-04	3.06E-02	see above
f	Shielded Dose Rate	mSv/wk	0.0000	0.0000	0.0000	0.0080	0.0015	0.0231	c * e
g	Total Shielded Dose Rate	mSv/wk	0.0325						Sum Row f

- Scatter negligible for high energy machine
- Usually dominated by fast neutrons and capture gammas
- Direct leakage may be significant or not, depending on maze wall width (not very large in this case)

Example 3: Wall Adj. to Maze Door Transmission Calc. [1 of 2]

Maze Patient Scatter Transmission for Wall Adjacent to Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Photon Trans.
Inside Layer	24	610	Concrete	130	130	2.05E-05
Layer #2						1.00E+00
Layer #3						1.00E+00
Outside Layer						1.00E+00
Slant Angle:		0 deg		0.2 MV	Total:	2.05E-05

Maze Wall Scatter Transmission for Wall Adjacent to Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Photon Trans.
Inside Layer	24	610	Concrete	130	130	2.05E-05
Layer #2						1.00E+00
Layer #3						1.00E+00
Outside Layer						1.00E+00
Slant Angle:		0 deg		0.2 MV	Total:	2.05E-05

Maze Leakage Scatter Transmission for Wall Adjacent to Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Photon Trans.
Inside Layer	24	610	Concrete	160	160	1.55E-04
Layer #2						1.00E+00
Layer #3						1.00E+00
Outside Layer						1.00E+00
Slant Angle:		0 deg		0.3 MV	Total:	1.55E-04

Example 3: Wall Adj. to Maze Door Transmission Calc. [2 of 2]

Maze Direct Leakage Transmission for Wall Adjacent to Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Photon Trans.
Inside Layer			Concrete	360	340	1.00E+00
Layer #2						1.00E+00
Layer #3						1.00E+00
Outside Layer						1.00E+00
Slant Angle:		0 deg		18 MV	Total:	1.00E+00

Neutron Transmission for Wall Adjacent to Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Neutron Trans.
Inside Layer	24	610	Concrete	161	161	1.64E-04
Layer #2						1.00E+00
Layer #3						1.00E+00
Outside Layer						1.00E+00
Slant Angle:		0 deg		0.1 MV	Total:	1.64E-04

Capture Gamma Transmission for Wall Adjacent to Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Photon Trans.
Inside Layer	24	610	Concrete	410	370	2.89E-02
Layer #2						1.00E+00
Layer #3						1.00E+00
Outside Layer						1.00E+00
Slant Angle:		0 deg		10 MV	Total:	2.89E-02

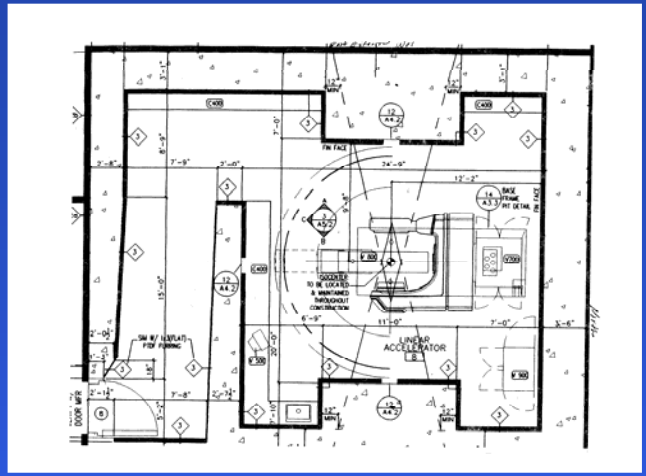
Example 3: Wall Adjacent to Maze Door Shielded Dose Rate

Maze Shielded Dose at Wall Adjacent to Door

Line	Parameter	Units	Patient Scatter	Wall Scatter	Leakage Scatter	Direct Leakage	Neutrons	Capture Gammas	Calculation
a	Calc. Unshield Dose Rate	mSv/wk	6.07E-02	2.12E-03	1.71E-01	7.97E-03	3.63E+00	7.55E-01	
b	Total / Calc. Dose Rate		2.64	2.64	1	1	1	1	McGinley
c	Total Unshield Dose Rate	mSv/wk	1.60E-01	5.60E-03	1.71E-01	7.97E-03	3.63E+00	7.55E-01	a * b
d	Energy for TVL	MV	0.2	0.2	0.3	18.0	0.1	10.0	
e	Transmission		2.05E-05	2.05E-05	1.55E-04	1.00E+00	1.64E-04	2.89E-02	see above
f	Shielded Dose Rate	mSv/wk	0.0000	0.0000	0.0000	0.0080	0.0006	0.0218	c * e
g	Total Shielded Dose Rate	mSv/wk	0.0304						Sum Row f

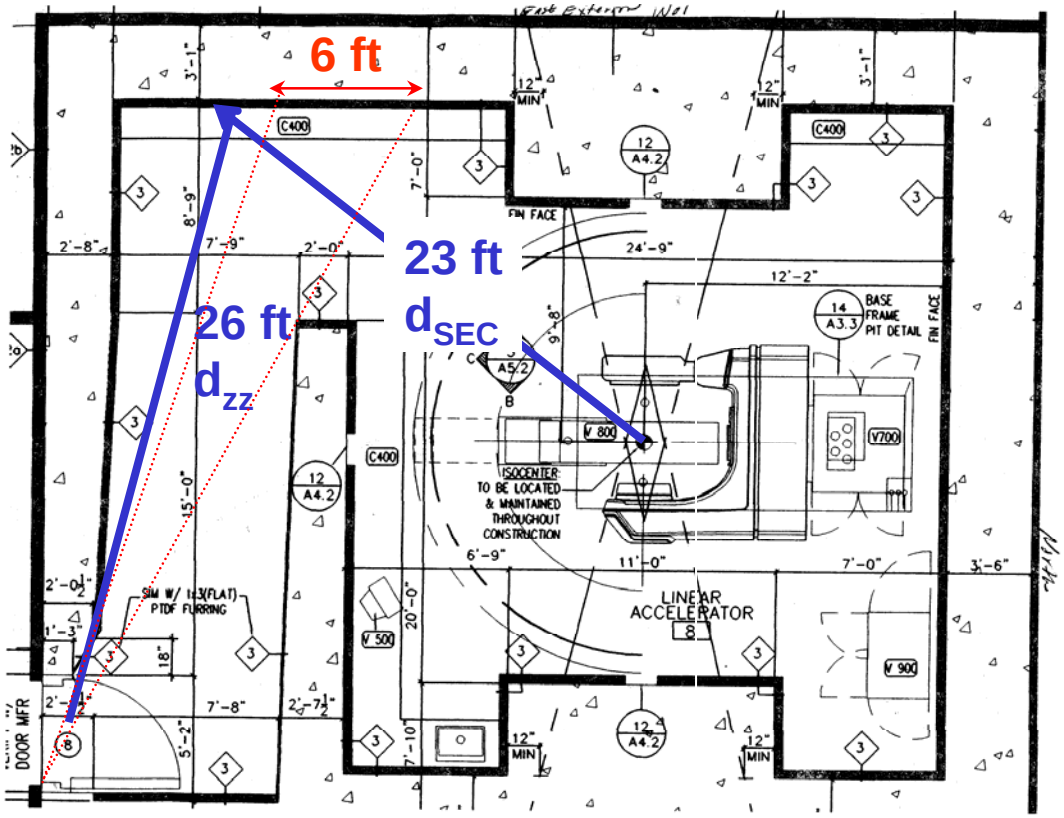
Example 4: Maze with Additional Bend

- Conventional maze similar to examples in NCRP 151
- Maze includes additional bend
  - Less scatter since walls barely visible from door
  - Neutron distance d_2 measured along center line to door
  - Factor of three reduction in neutron dose rate with extra bend
    - » NCRP 151 wording is ambiguous about Kersey vs. Modified Kersey
  - No comparable reduction for capture gammas identified



- 18 MV machine energy
  - Scatter calculations included to illustrate 6 MV calculations

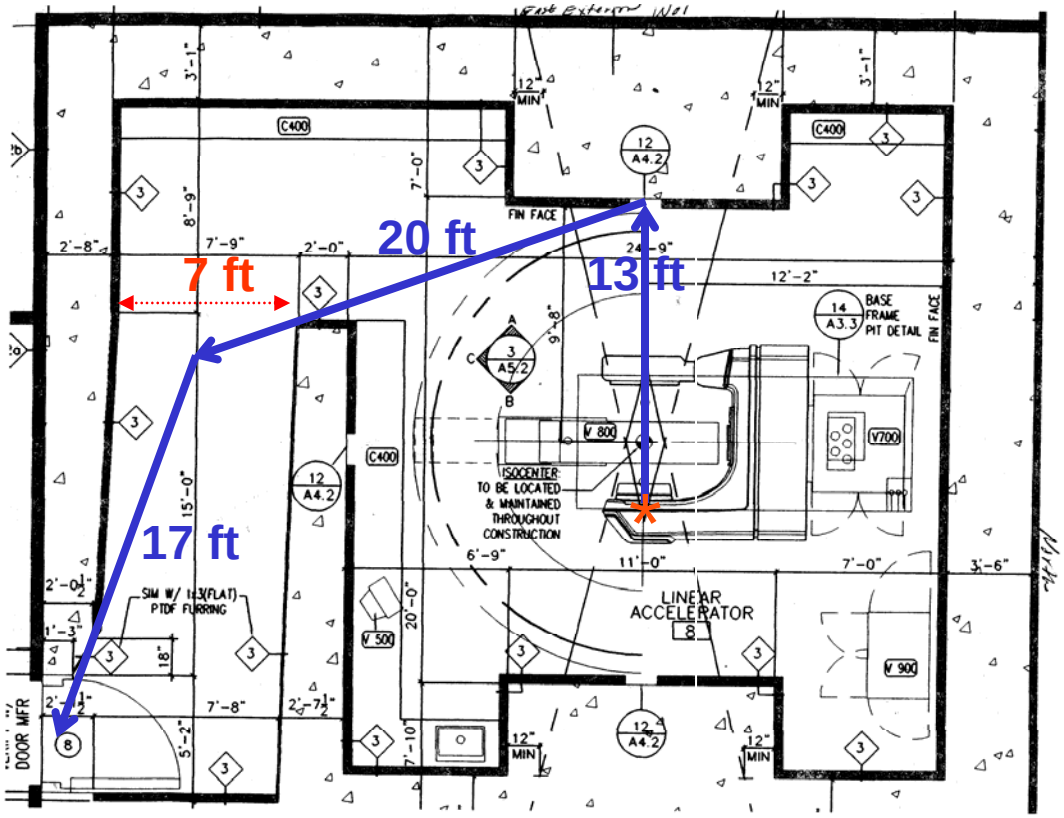
Example 4a: Maze with Second Bend — Patient Scatter



Example 4a: Patient Scatter Unshielded Dose Rate Calculation

Line	Symbol	Parameter	Units	Value	Calculation
a	MV	Machine X-ray Energy	MV	18	
b	W	Workload	Gy/wk	450	
c	d_{sca}	Distance from target to isocenter	m	1.00	
d	d_{sec}	Distance from isocenter to wall at maze end	ft	23	measured
e			m	7.01	d * 0.3048
f	d_{zz}	Distance from wall at maze end to door	ft	26	measured
g			m	7.92	f * 0.3048
h	w_1	Wall width seen from door	ft	6	measured
i			m	1.83	h * 0.3048
j	h	Room height	ft	10	measured
k			m	3.05	j * 0.3048
L	A_1	Scatter area	m^2	5.6	i * k
m	a	Patient scatter fraction ($400\ cm^2$ field)		8.64E-04	NCRP 151 Table B.4 (45º) Function of MV
n	α_1	2nd bounce scatter fraction / m^2		2.20E-02	Table B.8b, 0.5 MV, 0º
o	F	Average field area	cm^2	912.5	See above
p	U	Use Factor		0.25	Orientation with highest dose rate
q	H_{PS}	Patient scatter unshielded dose rate	mSv/wk	8.81E-03	1000*m*b*p*(o/400)*L / (c^2 * e^2 * g^2)

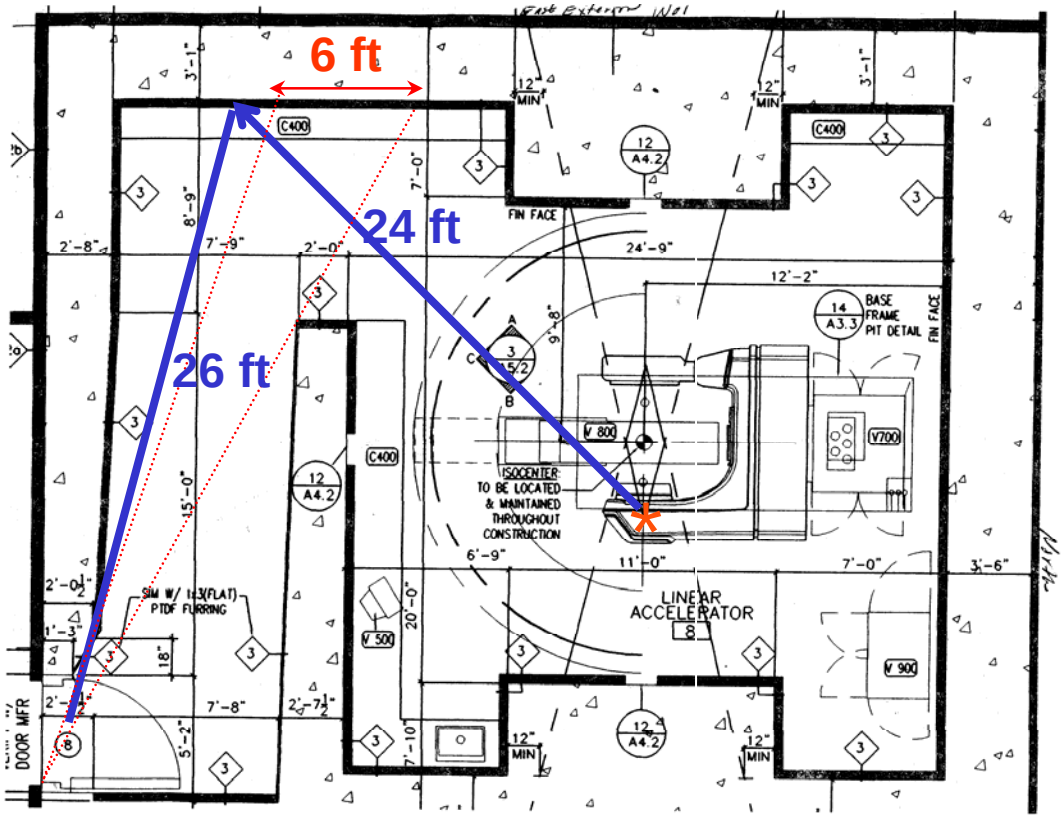
Example 4b: Maze with Second Bend — Wall Scatter



Example 4b: Wall Scatter Unshielded Dose Rate Calculation

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	13	measured
e			m	3.96	d * 0.3048
f	d_r	Distance from primary barrier wall to maze inside opening	ft	20	measured
g			m	6.10	f * 0.3048
h	d_z	Distance from maze inside opening to door	ft	17	measured
i			m	5.18	h * 0.3048
j	d_m	Maze width	ft	7	measured
k			m	2.13	j * 0.3048
L	h	Room height	ft	10	measured
m			m	3.05	L * 0.3048
n	α_0	1sr reflection coefficient	$1 / m^2$	0.0016	Table B.8a with 18 MV 75º scatter angle
o		Effective field size	cm	30.2	see above
p	A_0	Beam area at first reflection	m^2	1.43	(e * o/100)^2
q	α_z	2nd bounce scatter fraction / m^2		0.0080	Table B.8a with 0.5 MV 75º scatter angle
r	A_z	Maze cross section	m^2	6.5	j * L
s	U	Use Factor		0.25	Orientation with highest dose rate
t	f H_S	Wall scatter unshielded dose	mSv/wk	2.31E-04	1000*m*b*s*(o/400)* L / (e^2 * g^2 * i^2)

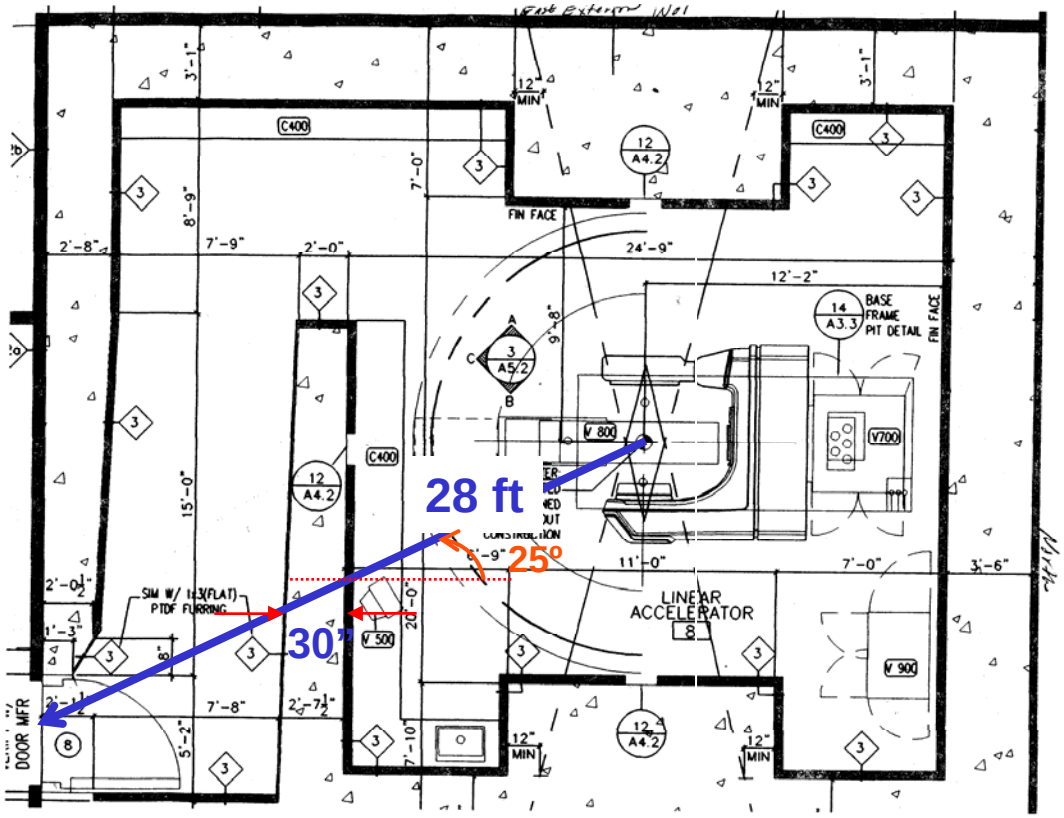
Example 4c: Maze with Second Bend — Leakage Scatter



Example 4c: Leakage Scatter Unshielded Dose Rate Calculation

Line	Symbol	Parameter	Units	Value	Calculation
a	MV	Machine X-ray Energy	MV	18	
b	W	Workload	Gy/wk	450	
c		Leakage Fraction	%	0.10%	
d		IMRT Factor		2	
e	d_{sec}	Distance from target to wall at maze end	ft	24	measured
f			m	7.32	d * 0.3048
g	d_{zz}	Distance from wall at maze end to door	ft	26	measured
h			m	7.92	f * 0.3048
i	w_1	Wall width seen from door	ft	6	measured
j			m	1.83	h * 0.3048
k	h	Room height	ft	10	measured
L			m	3.05	j * 0.3048
m	α_1	1sr reflection coefficient	$1 / m^2$	0.0179	Table 8b with 1.4 MV 0º Reflection angle
n	A_1	Scatter area	m^2	5.6	i * k
o	U	Use Factor		1	Calculation does not depend on orientation
p	H_{LS}	Leakage scatter unshielded dose rate	mSv/wk	2.67E-02	1000 * b * o * c * d * m * n / (f^2 * h^2)

Example 4d: Maze with Second Bend — Direct Leakage

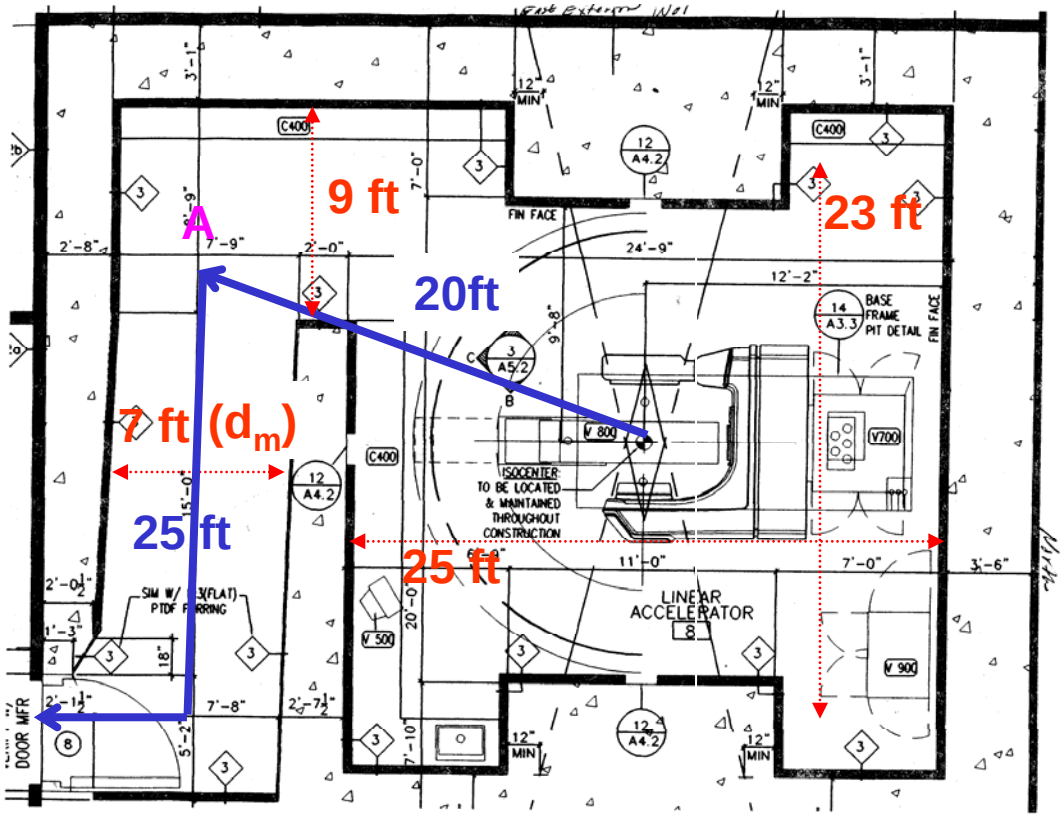


Example 4d: Direct Leakage Unshielded Dose Rate Calculation

Line	Parameter	Units	Value	Calculation
a	Machine X-ray Energy	MV	18	
b	Workload (W)	Gy/Wk	450	
c	Use Factor	Ratio	1	
d	Leakage Fraction	%	0.10%	
e	IMRT Factor		2	
f	Isocenter to Protected Point Distance	ft	28.0	
g		m	8.5	f * 0.3048
h	Unshielded Dose	mSv/wk	1.24E+01	1000*b*c*d*e / g^2
i	Wall Transmission		3.85E-03	see below
j	Dose at Inside of Door	mSv/wk	4.76E-02	h * i

Barrier	Material Thickness inches	Slant Thickness mm	Material	Direct Leakage TVL1 (mm)	Direct Leakage TVLe (mm)	Photon Trans.
Inside Layer	30	841	Concrete	360	340	3.85E-03
Layer #2						1.00E+00
Outside Layer						1.00E+00
Slant Angle: 25 deg				18 MV	Total:	3.85E-03

Example 4e: Maze with Second Bend — Maze Neutrons



Neutrons attenuated by factor of 3 due to extra bend in maze

Example 4e: 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	20	measured
f			m	6.10	e * 0.3048
g	d_L	Vault Average Length	ft	25	measured
h			m	7.62	g * 0.3048
i	d_W	Vault Average Width	ft	23	measured
j			m	7.01	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	196.0	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	$n/m^2/Gy$	7.28E+09	c*n* [d/(4*π* f^2) + (5.4*d+1.3)/(2*π*m)]

Example 4e: 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	7.28E+09	see above
d	d_2	Distance from maze opening (Point A) to door	ft	25	measured
e			m	7.62	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		6.9E-16	Constant
h	h_φ	Capture Gamma Unshielded Dose at Door per Dose at Isocenter	Sv/Gy	1.95E-07	g * c * 10^(-e / f)
i		Capture Gamma Unshielded Dose Rate	mSv/wk	8.77E-02	1000 * a * h

Example 4e: Maze Neutron Unshielded Dose Rate Calculation

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	7.28E+09	See above
c	d_2	Distance from maze opening (Point A) to door	ft	25	measured
d			m	7.62	c * 0.3048
e	d_0	Inner Maze Entrance Width	ft	9	measured
f			m	2.74	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	8.36	f * h
j	d_m	Maze Width	ft	7	measured
k			m	2.13	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	6.50	i * m
o	TVD_n	Maze Neutron Tenth-Value Distance	m	5.25	2.06 * sqrt(n)
p		Reduction due to added bend in maze		3	
q	$H_{n,D}$	Neutron Unshielded Dose-Equivalent at Door per Dose at Isocenter	Sv/Gy	2.35E-07	2.4E-15 * b * sqrt(i / n) /p * [1.64*10^(-d/1.9)+10^(-d/o)]
r		Neutron Unshielded Dose-Equivalent Rate at Door	Sv/wk	1.06E-01	1000 * a * q

Factor of 3 reduction due to additional bend in maze

Example 4: Maze Door Transmission Calculation [1 of 2]

Maze Patient Scatter Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Steel	25	25	5.57E-01
Layer #2	1	25	Borated Poly	322	322	8.34E-01
Layer #3	0.5	13	Lead	5	5	2.88E-03
Outside Layer	0.25	6	Steel	25	25	5.57E-01
Slant Angle:		0 deg		0.2 MV	Total:	7.47E-04

Maze Wall Scatter Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Wall Scatter TVL1 (mm)	Wall Scatter TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Steel	25	25	5.57E-01
Layer #2	1	25	Borated Poly	322	322	8.34E-01
Layer #3	0.5	13	Lead	5	5	2.88E-03
Outside Layer	0.25	6	Steel	25	25	5.57E-01
Slant Angle:		0 deg		0.2 MV	Total:	7.47E-04

Maze Leakage Scatter Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Leakage Scatter TVL1 (mm)	Leakage Scatter TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Steel	39	39	6.87E-01
Layer #2	1	25	Borated Poly	396	396	8.63E-01
Layer #3	0.5	13	Lead	8	8	2.59E-02
Outside Layer	0.25	6	Steel	39	39	6.87E-01
Slant Angle:		0 deg		0.3 MV	Total:	1.05E-02

Example 4: Maze Door Transmission Calculation [2 of 2]

Maze Direct Leakage Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Direct Leakage TVL1 (mm)	Direct Leakage TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Steel	110	110	8.76E-01
Layer #2	1	25	Borated Poly	842	842	9.33E-01
Layer #3	0.5	13	Lead	57	57	5.99E-01
Outside Layer	0.25	6	Steel	110	110	8.76E-01
Slant Angle:		0 deg		18 MV	Total:	4.28E-01

Neutron Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Maze Neutrons TVL1 (mm)	Maze Neutrons TVLe (mm)	Neutron Trans.
Inside Layer	0.25	6	Steel	N/A	N/A	1.00E+00
Layer #2	1	25	Borated Poly	45	45	2.73E-01
Layer #3	0.5	13	Lead	N/A	N/A	1.00E+00
Outside Layer	0.25	6	Steel	N/A	N/A	1.00E+00
Slant Angle:		0 deg		0.1 MV	Total:	2.73E-01

Capture Gamma Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Capture Gamma TVL1 (mm)	Capture Gamma TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Steel	95	95	8.57E-01
Layer #2	1	25	Borated Poly	817	817	9.31E-01
Layer #3	0.5	13	Lead	61	61	6.19E-01
Outside Layer	0.25	6	Steel	95	95	8.57E-01
Slant Angle:		0 deg		3.6 MV	Total:	4.24E-01

Example 4: Maze Door Shielded Dose Rate

Line	Parameter	Units	Patient Scatter	Wall Scatter	Leakage Scatter	Direct Leakage	Neutrons	Capture Gammas	Calculation
a	Calc. Unshield Dose Rate	mSv/wk	8.81E-03	2.31E-04	2.67E-02	4.76E-02	1.06E-01	8.77E-02	
b	Total / Calc. Dose Rate		2.64	2.64	1	1	1	1	NCRP 151 Eq. 2.14
c	Total Unshield Dose Rate	mSv/wk	2.33E-02	6.10E-04	2.67E-02	4.76E-02	1.06E-01	8.77E-02	a * b
d	Energy for TVL	MV	0.2	0.2	0.3	18.0	0.1	3.6	
e	Transmission		7.81E-04	7.81E-04	1.05E-02	4.28E-01	2.73E-01	4.24E-01	see above
f	Shielded Dose Rate	mSv/wk	0.0000	0.0000	0.0003	0.0204	0.0288	0.0372	c * e
g	Total Shielded Dose Rate	mSv/wk	0.0867						Sum Row f

Example 4: Wall Adj. to Maze Door Transmission Calc. [1 of 2]

Maze Patient Scatter Transmission for Wall Adjacent to Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Photon Trans.
Inside Layer	6	152	Concrete	130	130	6.73E-02
Layer #2						1.00E+00
Layer #3						1.00E+00
Outside Layer						1.00E+00
Slant Angle:		0 deg		0.2 MV	Total:	6.73E-02

Maze Wall Scatter Transmission for Wall Adjacent to Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Photon Trans.
Inside Layer	6	152	Concrete	130	130	6.73E-02
Layer #2						1.00E+00
Layer #3						1.00E+00
Outside Layer						1.00E+00
Slant Angle:		0 deg		0.2 MV	Total:	6.73E-02

Maze Leakage Scatter Transmission for Wall Adjacent to Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Photon Trans.
Inside Layer	6	152	Concrete	160	160	1.12E-01
Layer #2						1.00E+00
Layer #3						1.00E+00
Outside Layer						1.00E+00
Slant Angle:		0 deg		0.3 MV	Total:	1.12E-01

Example 4: Wall Adj. to Maze Door Transmission Calc. [2 of 2]

Maze Direct Leakage Transmission for Wall Adjacent to Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Photon Trans.
Inside Layer	6	152	Concrete	360	340	3.56E-01
Layer #2						1.00E+00
Layer #3						1.00E+00
Outside Layer						1.00E+00
Slant Angle:		0 deg		18 MV	Total:	3.56E-01

Neutron Transmission for Wall Adjacent to Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Neutron Trans.
Inside Layer	6	152	Concrete	161	161	1.13E-01
Layer #2						1.00E+00
Layer #3						1.00E+00
Outside Layer						1.00E+00
Slant Angle:		0 deg		0.1 MV	Total:	1.13E-01

Capture Gamma Transmission for Wall Adjacent to Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Photon Trans.
Inside Layer	6	152	Concrete	330	330	3.45E-01
Layer #2						1.00E+00
Layer #3						1.00E+00
Outside Layer						1.00E+00
Slant Angle:		0 deg		3.6 MV	Total:	3.45E-01

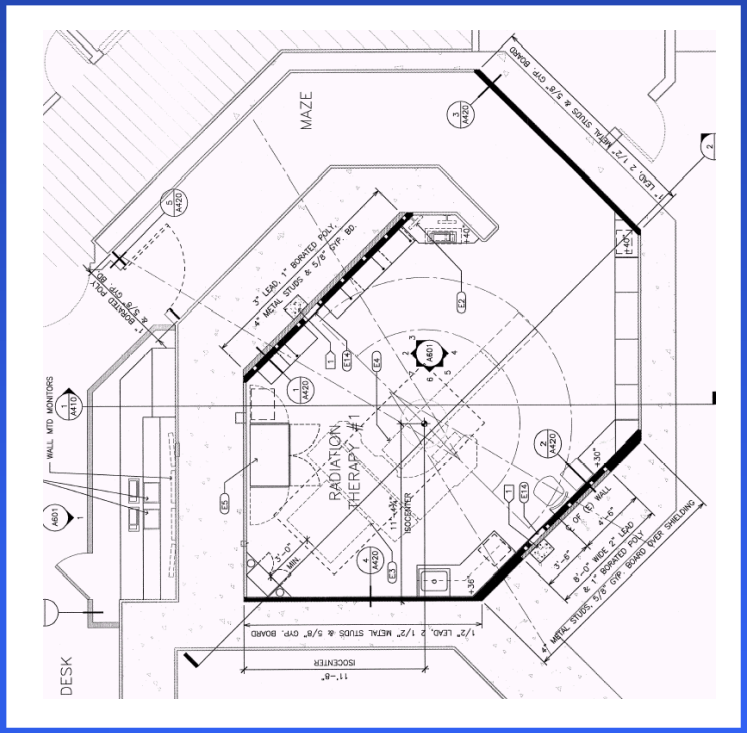
Example 4: Wall Adjacent to Maze Door Shielded Dose Rate

Maze Shielded Dose at Wall Adjacent to Door

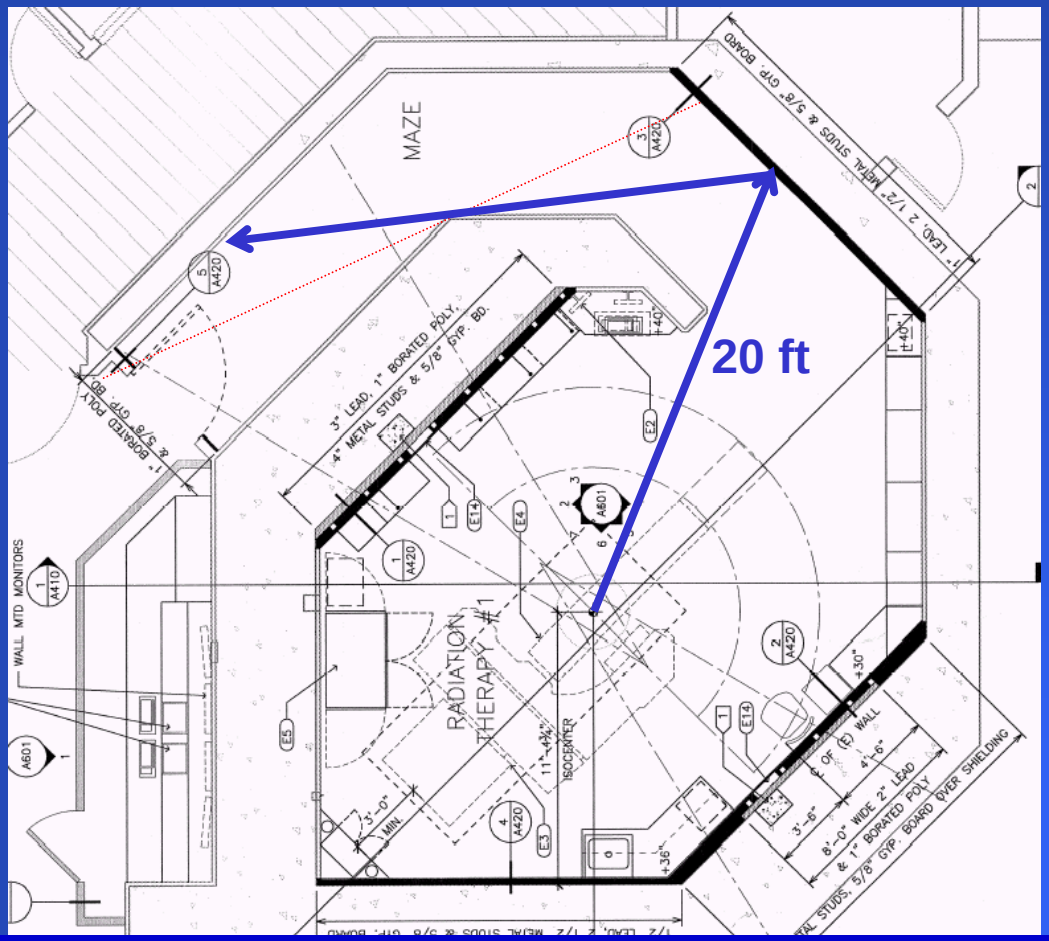
Line	Parameter	Units	Patient Scatter	Wall Scatter	Leakage Scatter	Direct Leakage	Neutrons	Capture Gammas	Calculation
a	Calc. Unshield Dose Rate	mSv/wk	8.81E-03	2.31E-04	2.67E-02	4.76E-02	1.06E-01	8.77E-02	
b	Total / Calc. Dose Rate		2.64	2.64	1	1	1	1	NCRP 151 Eq. 2.14
c	Total Unshield Dose Rate	mSv/wk	2.33E-02	6.10E-04	2.67E-02	4.76E-02	1.06E-01	8.77E-02	a * b
d	Energy for TVL	MV	0.2	0.2	0.3	18.0	0.1	3.6	
e	Transmission		6.73E-02	6.73E-02	1.12E-01	3.56E-01	1.13E-01	3.45E-01	see above
f	Shielded Dose Rate	mSv/wk	0.0016	0.0000	0.0030	0.0170	0.0120	0.0303	c * e
g	Total Shielded Dose Rate	mSv/wk	0.0638						Sum Row f

Example 5: Long Maze with Axis of Rotation Perpendicular to Maze

- Length of maze makes patient and leakage scatter negligible
- Wall scatter calculation different
  - Calculated with beam toward maze
  - Single bounce instead of two bounce
  - Maze wall primary beam, mitigating the reduced number of bounces
- Direct leakage applicable, but with no door shielding
- Standard neutron and capture gamma calculation
  - Except factor of 3 reduction due to additional bend in maze

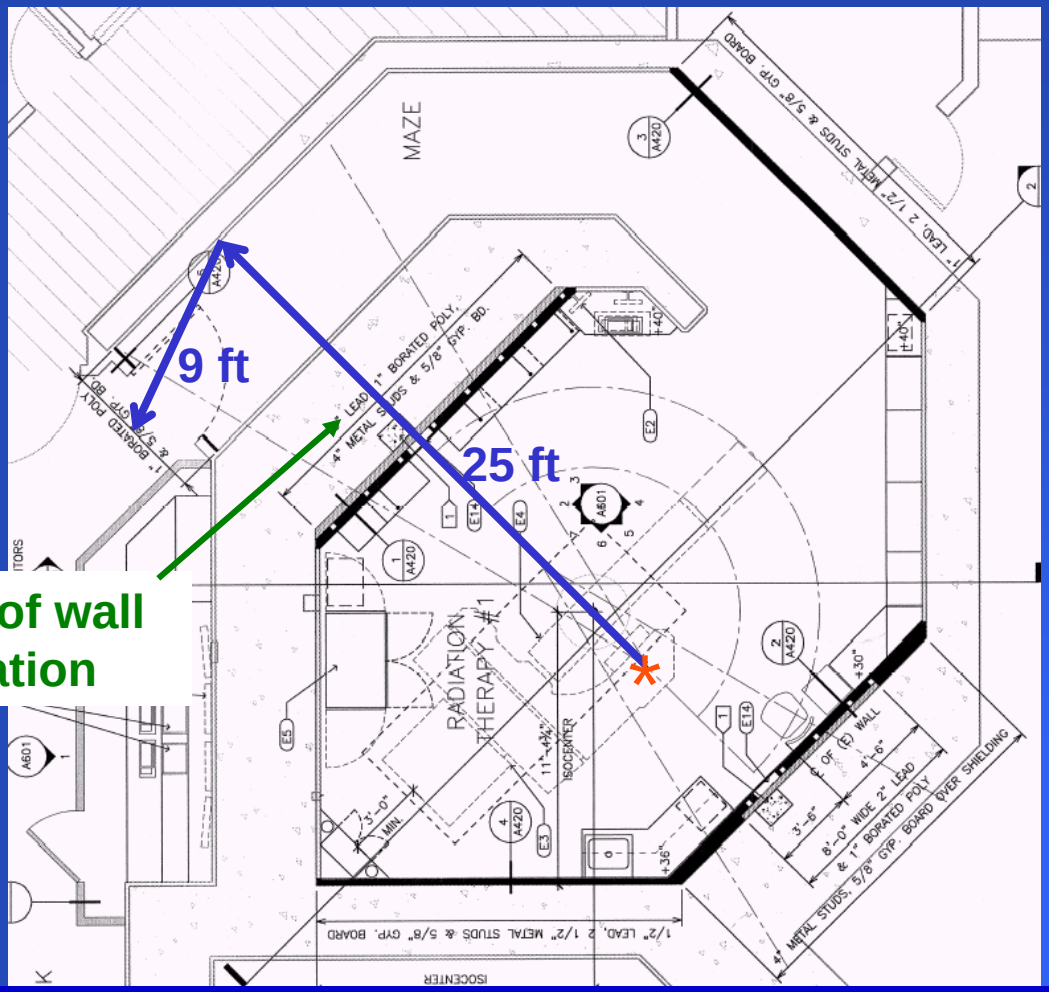


Example 5a: Maze with Axis of Rotation Perpendicular to Maze — Patient Scatter



Two bounce (patient, wall) scatter not directly visible from door
⇨ No Contribution

Example 5b: Maze with Axis of Rotation Perpendicular to Maze — Wall Scatter



Primary attenuation of wall included in calculation

Maze wall attenuation added to wall scatter calculation

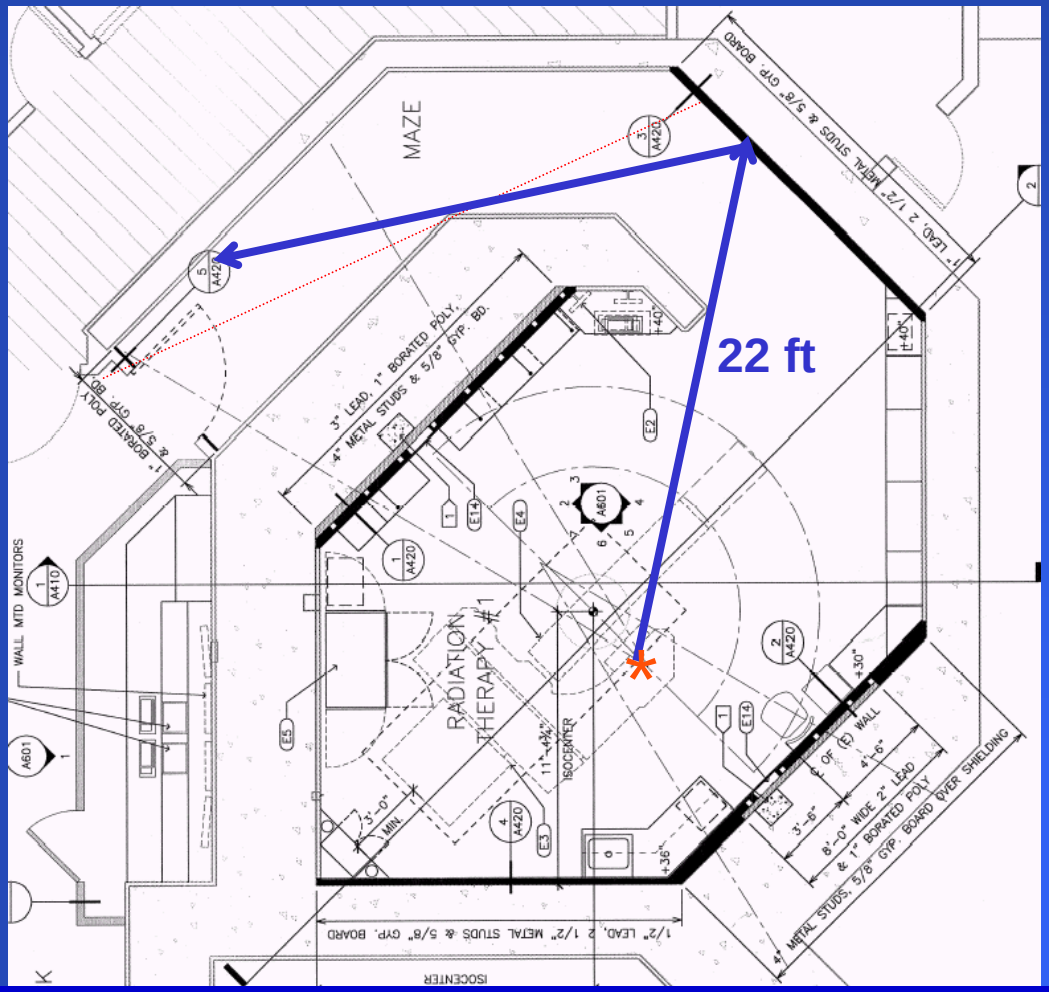
Example 5b: Wall Scatter Unshielded Dose Rate Calculation

Line	Symbol	Parameter	Units	Value	Calculation
a	MV	Machine X-ray Energy	MV	15	
b	W	Workload	Gy/wk	450	
c	f	Patient transmission		0.27	0.27 if MV > 10
d	d_0	Distance from target to far side of maze wall	ft	25	measured
e			m	7.62	d * 0.3048
f	d_1	Distance from far side of maze wall to door	ft	9	measured
g			m	2.74	f * 0.3048
h	α_0	Reflection coefficient	$1 / m^2$	0.0018	Table 8a with 15 MV 75º scatter angle
i		Effective field size	cm	30.2	see above
j	A_0	Beam area at far maze wall	m^2	5.30	(e * i/100)^2
k	B	Maze Wall Transmission		5.34E-04	see below
L	U	Use Factor		0.25	Orientation with highest dose rate
m	f H_S	Wall scatter unshielded dose	mSv/wk	3.54E-04	1000 * b * c * L * h * j / (e^2 * g^2)

Example 5b: Wall Scatter — Maze Wall Transmission

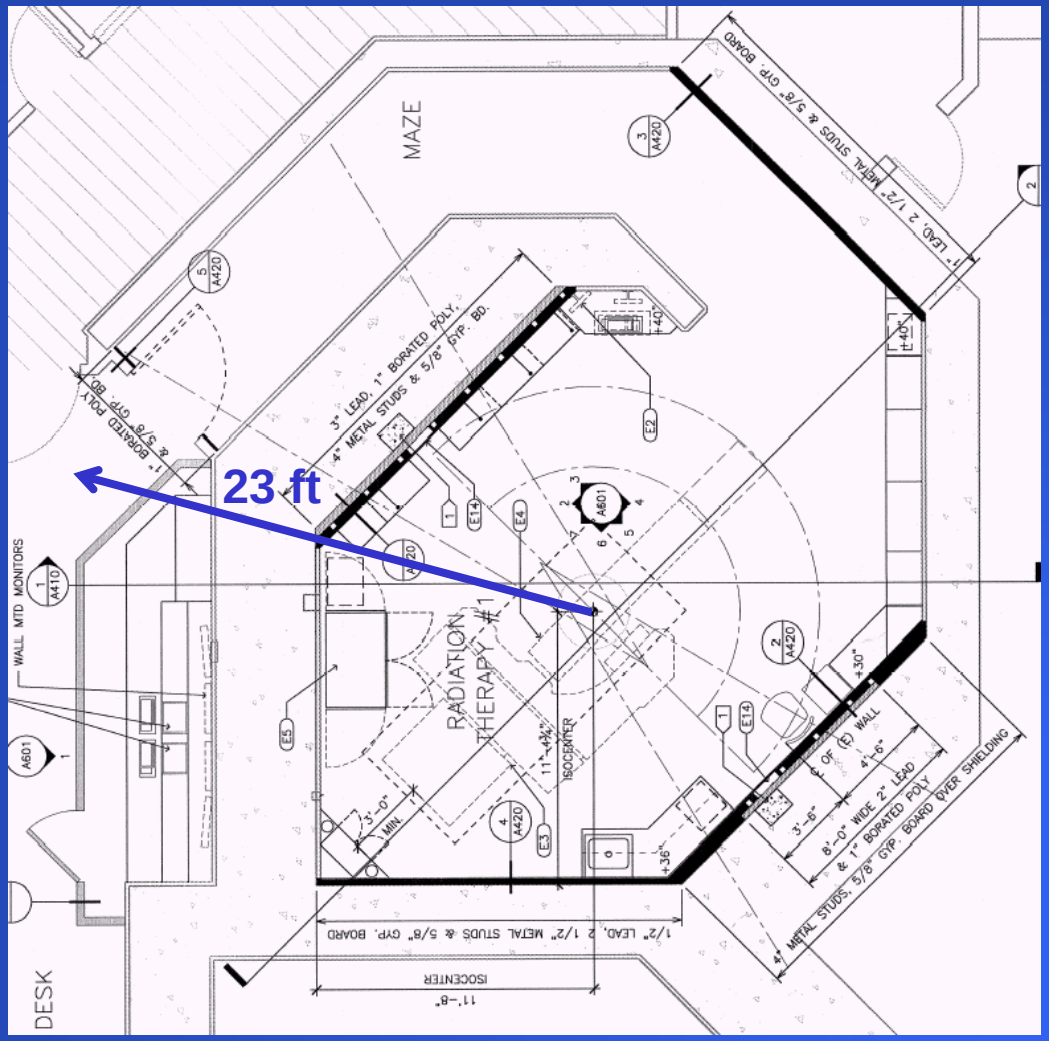
Barrier	Material Thickness inches	Slant Thickness mm	Material	X-Ray Primary TVL1 (mm)	X-Ray Primary TVLe (mm)	Photon Trans.
Inside Layer	54	1372	Concrete	440	410	5.34E-04
Layer #2						1.00E+00
Layer #3						1.00E+00
Outside Layer						1.00E+00
Slant Angle:		0 deg		15 MV	Total:	5.34E-04

Example 5c: Maze with Axis of Rotation Perpendicular to Maze — Leakage Scatter



Leakage scatter not directly visible from door ⇨ No Contribution

Example 5d: Maze with Axis of Rotation Perpendicular to Maze — Direct Secondary



Example 5d: Direct Secondary Path - Scatter Fraction Calculation

Line	Parameter	Units	Value		Calculation
			w/o IMRT	with IMRT	
a	Max Field Size	cm	40	15	
b	Fraction of Workload		50%	50%	
c	Effective Field Area	cm^2	912.5		$b_1*a_1\text{^}2 + b_2*a_2\text{^}2$
d	Effective Field Size	cm	30.2		sqrt (c)
e	Scatter Angle	deg	30		
f	Machine X-ray Energy	MV	15		
g	Scatter / 400 cm^2		2.77E-03		Function of e & f
h	Scatter Fraction		0.00632		g * c / 400

- Don't normally include scatter
  - Negligible compared to direct leakage for most maze layouts

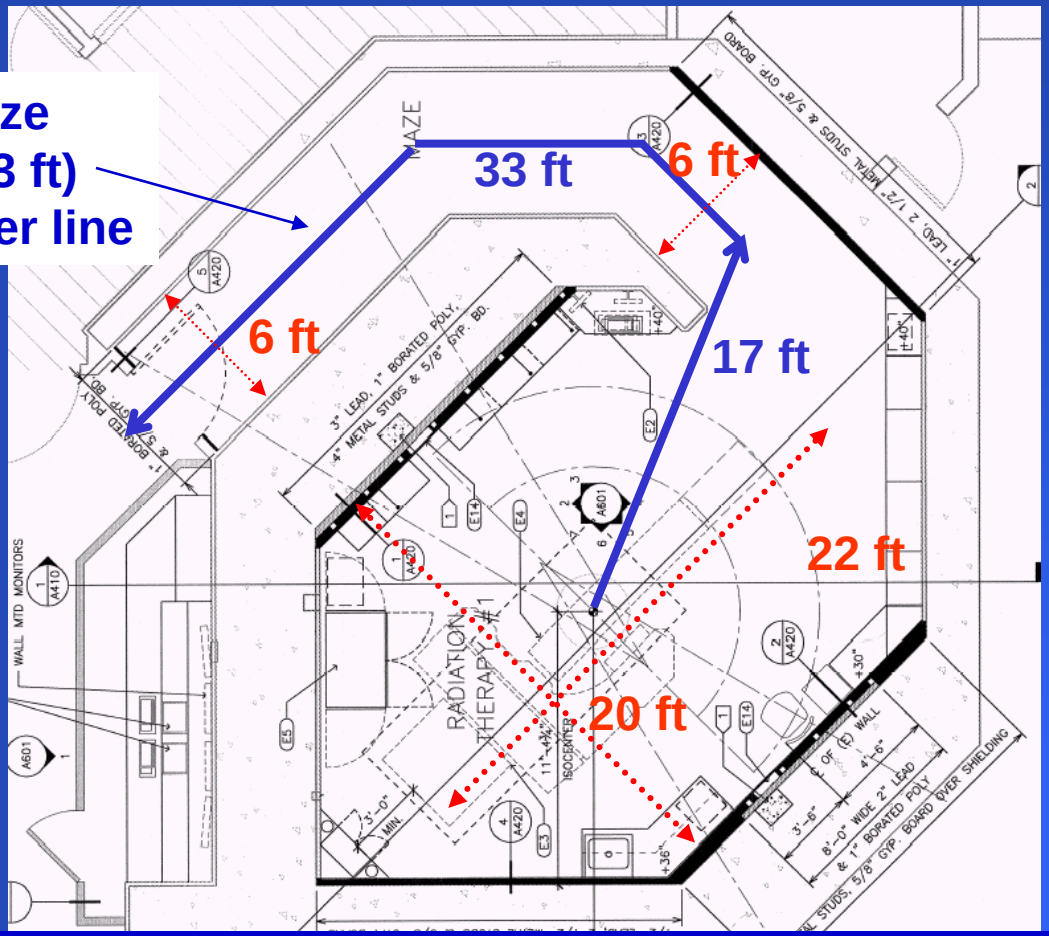
Example 5d: Direct Secondary Path

Line	Parameter	Units	Photon Leakage	Photon Scatter	Calculation
a	Workload/Patient /wk	Gy/patient	15	15	Table 3.1 Dual
b	Patients per Week	patient/wk	30	30	Table 3.2 Dual
c	Workload (W)	Gy/Wk	450	450	a * b
d	Use Factor	Ratio	1	0.25	
e	Fraction	Ratio	1.0E-03	6.3E-03	Varian at 18 MV
f	IMRT Factor		2	1	
g	Isocenter to Protected Point Distance	ft	23.0	23.0	
h		m	7.0	7.0	g * 0.3048
i	Unshielded Dose Rate	mSv/wk	1.83E+01	1.45E+01	1000*c*d*e*f/h^2
j	Transmission		3.20E-04	1.52E-04	see below
k	Shielded Dose Rate	mSv/wk	0.006	0.002	i * j
L	Total Shielded Dose Rate	mSv/wk	0.008		Sum row k

Barrier	Material Thickness inches	Slant Thickness mm	Material	Photon Leakage TVL1 (mm)	Photon Leakage TVLe (mm)	Photon Leakage Trans.	Scatter TVL1 (mm)	Scatter TVLe (mm)	Scatter Trans.
Inside Layer	45	1183	Concrete	360	330	3.20E-04	310	310	1.52E-04
Layer #2						1.00E+00			1.00E+00
Layer #3						1.00E+00			1.00E+00
Outside Layer						1.00E+00			1.00E+00
Slant Angle:	15 deg			15 MV	Total:	3.20E-04		Total:	1.52E-04

Example 5e: Maze with Axis of Rotation Perpendicular to Maze — Maze Neutrons

Distance from maze opening to door (33 ft) measured along center line



Neutrons / capture gammas attenuated by additional factor of 3 since more than one bend in maze

Example 5e: Maze Neutron Fluence Calculation

Line	Symbol	Parameter	Units	Value	Calculation
a	MV	Machine X-ray Energy	MV	15	
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	20	measured
h			m	6.10	g * 0.3048
i	d_W	Vault Average Width	ft	22	measured
j			m	6.71	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	159.8	2 * (h*j + h*L + j*L)
n	Q_n	Neutron Source Strenth	n / Gy	7.60E+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 5e: Capture Gamma Unshielded Dose Rate Calculation

Line	Symbol	Parameter	Units	Value	Calculation
a	MV	Machine X-ray Energy	MV	15	
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	33	measured
e			m	10.06	d * 0.3048
f	TVD	Tenth-Value Distance	m	3.9	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	1.33E-08	g * c * 10^(-e / f)
i		Capture Gamma Unshielded Dose Rate	mSv/wk	5.99E-03	1000 * a * h

Example 5e: Maze Neutron Unshielded Dose Rate Calculation

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	33	measured
d			m	10.06	c * 0.3048
e	d_0	Inner Maze Entrance Width	ft	6	measured
f			m	1.83	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	5.57	f * h
j	d_m	Maze Width	ft	6	measured
k			m	1.83	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	5.57	i * m
o	TVD_n	Maze Neutron Tenth-Value Distance	m	4.86	2.06 * sqrt(n)
p		Reduction due to 2nd bend in maze		3	
q	$H_{n,D}$	Neutron Unshielded Dose-Equivalent at Door per Dose at Isocenter	Sv/Gy	5.01E-08	2.4E-15 * b * sqrt(i / n)/p * [1.64*10^(-d/1.9)+10^(-d/o)]
r		Neutron Unshielded Dose-Equivalent Rate at Door	Sv/wk	2.26E-02	1000 * a * p

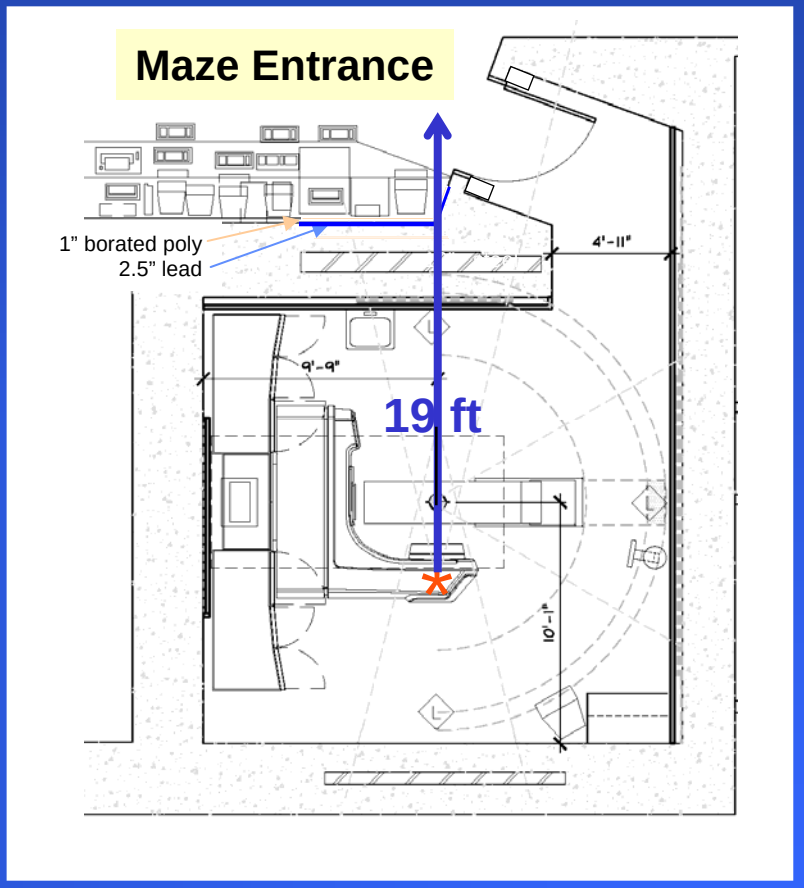
Example 5: Maze Door Shielded Dose Rate

Line	Parameter	Units	Patient Scatter	Wall Scatter	Leakage Scatter	Direct Secondary	Maze Neutrons	Capture Gammas	Calculation
a	Calc. Unshield Dose Rate	mSv/wk	0.00E+00	3.54E-04	0.00E+00	8.06E-03	2.26E-02	5.99E-03	
b	Total / Calc. Dose Rate		2.64	2.64	1	1	1	1	
c	Total Unshield Dose Rate	mSv/wk	0.00E+00	9.35E-04	0.00E+00	8.06E-03	2.26E-02	5.99E-03	a * b
d	Energy for TVL	MV	0.2	0.3	0.3	15.0	0.1	3.6	
e	Transmission		1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	1.00E+00	see above
f	Shielded Dose Rate	mSv/wk	0.0000	0.0009	0.0000	0.0081	0.0226	0.0060	c * e
g	Total Shielded Dose Rate	mSv/wk	0.0376						Sum Row f

- No attenuation calculation since no door
- Maze wall scatter dominates the scatter mechanisms, and is different in form from typical maze
- No door required since relatively thick walls and long maze with additional bend

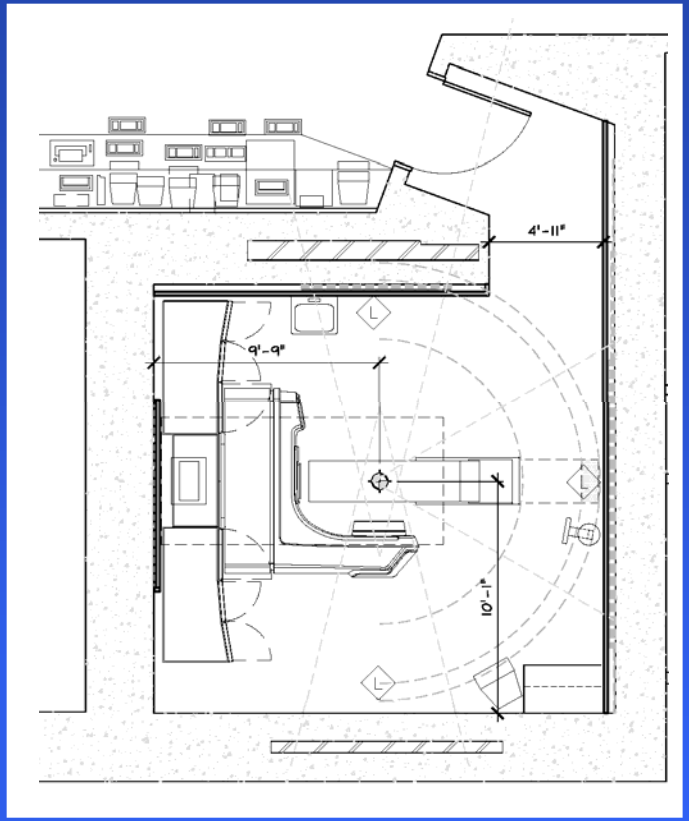
Example 6d: Maze with Primary Barrier Contribution — Primary Barrier

- Primary barrier calculation applicable instead of direct leakage
- Primary barrier photoneutrons add to shielded maze neutrons
- Note of entrance to control area makes use of 0.125 occupancy for door inappropriate
  - Although calculation possibly made where technologists are seated vs. directly in front of door

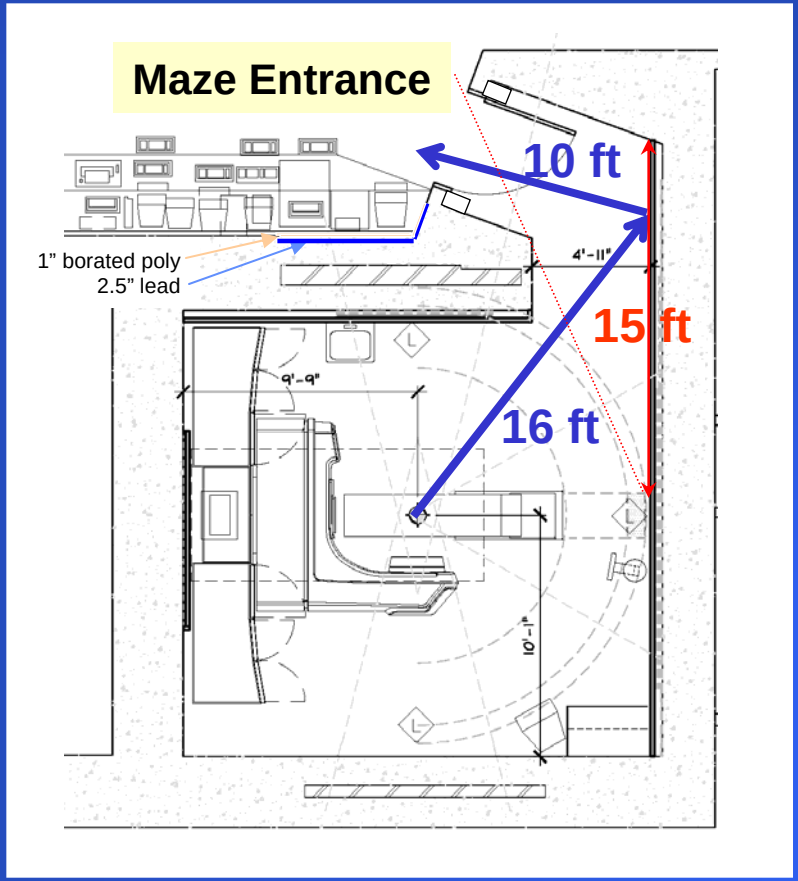


Example 6: Short Maze with Axis of Rotation Perpendicular to Maze

- Orientation of maze relative axis of rotation impacts scatter calculations
  - Beam toward maze for patient scatter
  - Beam away from maze for wall scatter
  - Leakage scatter unchanged
  - 15 MV so scatter is negligible, but included to illustrate calculations
- Other key difference is direct leakage is not applicable
  - Entrance is beyond primary barrier, so primary barrier calculation instead of direct leakage
  - Door does not shield primary radiation



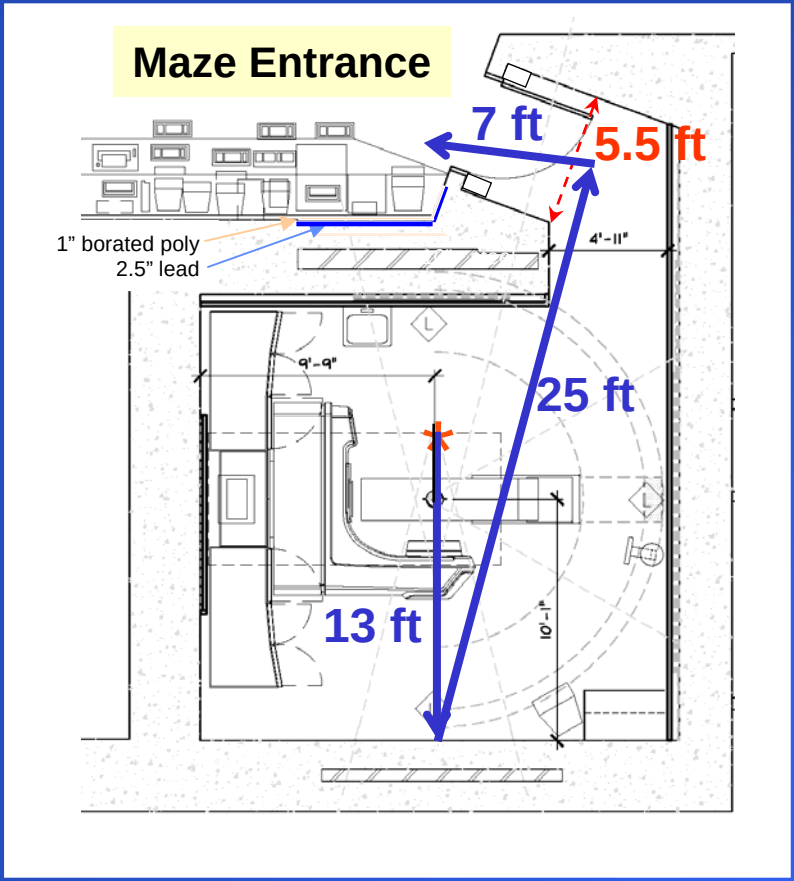
Example 6a: Maze with Primary Barrier Contribution — Patient Scatter



Example 6a: Patient Scatter Unshielded Dose Rate Calculation

Line	Symbol	Parameter	Units	Value	Calculation
a	MV	Machine X-ray Energy	MV	15	
b	W	Workload	Gy/wk	450	
c	d_{sca}	Distance from target to isocenter	m	1.00	
d	d_{sec}	Distance from isocenter to wall at maze end	ft	16	measured
e			m	4.88	d * 0.3048
f	d_{zz}	Distance from wall at maze end to door	ft	10	measured
g			m	3.05	f * 0.3048
h	w_1	Wall width seen from door	ft	15	measured
i			m	4.57	h * 0.3048
j	h	Room height	ft	10	measured
k			m	3.05	j * 0.3048
L	A_1	Scatter area	m^2	13.9	i * k
m	a	Patient scatter fraction ($400\ cm^2$ field)		1.05E-03	NCRP 151 Table B.4 (45º) Function of MV
n	α_1	2nd bounce scatter fraction / m^2		2.20E-02	Table B.8b, 0.5 MV, 0º
o	F	Average field area	cm^2	912.5	See above
p	U	Use Factor		0.25	Orientation with highest dose rate
q	H_{PS}	Patient scatter unshielded dose rate	mSv/wk	3.74E-01	1000*m*b*p*(o/400)*L / (c^2 * e^2 * g^2)

Example 6b: Maze with Primary Barrier Contribution — Wall Scatter



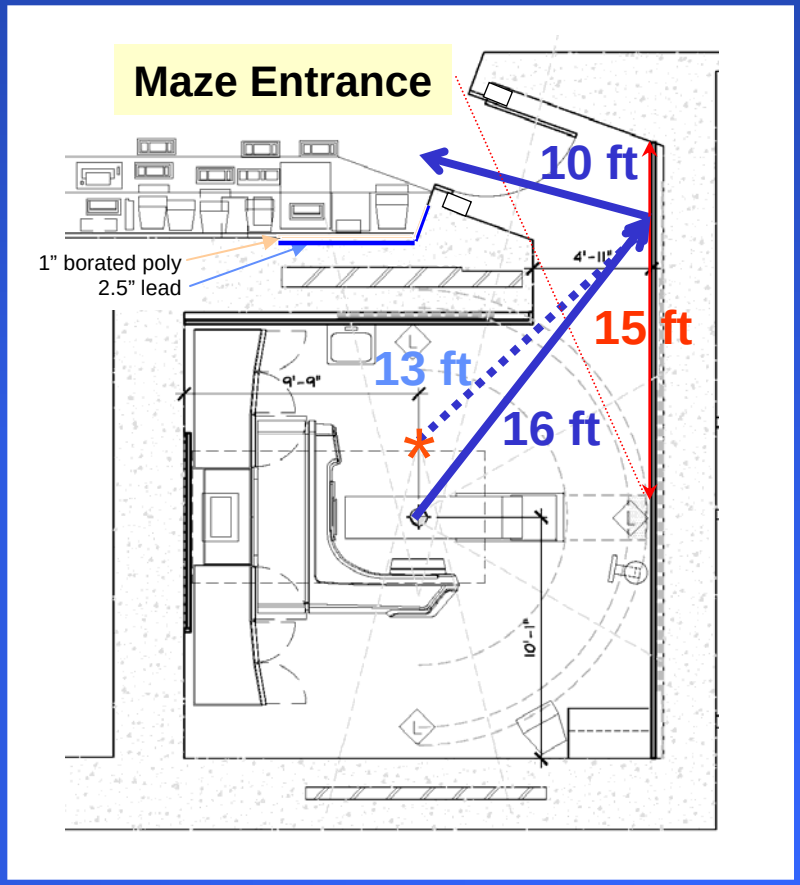
Have to target this direction orient it this way because doesn't make sense the other way

Example 6b: Wall Scatter Unshielded Dose Rate Calculation

Line	Symbol	Parameter	Units	Value	Calculation
a	MV	Machine X-ray Energy	MV	15	
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	13	measured
e			m	3.96	d * 0.3048
f	d_r	Distance from primary barrier wall to maze inside opening	ft	25	measured
g			m	7.62	f * 0.3048
h	d_z	Distance from maze inside opening to door	ft	7	measured
i			m	2.13	h * 0.3048
j	d_m	Maze width	ft	5.5	measured
k			m	1.68	j * 0.3048
L	h	Room height	ft	10	measured
m			m	3.05	L * 0.3048
n	α_0	1sr reflection coefficient	$1 / m^2$	0.0018	Table B.8a with 15 MV 75º scatter angle
o		Effective field size	cm	30.2	see above
p	A_0	Beam area at first reflection	m^2	1.43	(e * o/100)^2
q	α_z	2nd bounce scatter fraction / m^2		0.0080	Table B.8a with 0.5 MV 75º scatter angle
r	A_z	Maze cross section	m^2	5.1	j * L
s	U	Use Factor		0.25	Orientation with highest dose rate
t	f H_S	Wall scatter unshielded dose	mSv/wk	7.72E-04	1000*m*b*s*(o/400)* L / (e^2 * g^2 * i^2)

Example 6c: Maze with Primary Barrier Contribution — Leakage Scatter

- Target to wall distance
  - Example in NCRP 151 shows it measured from closest target location
    - » With factor of 2.64 / 4 applied
  - Leakage scatter explanation in body of NCRP 151 shows it measured from isocenter
- Reasonable to measure from isocenter and not apply 2.64/4
- Also reasonable to measure from closest location and then apply the 2.64/4 factor

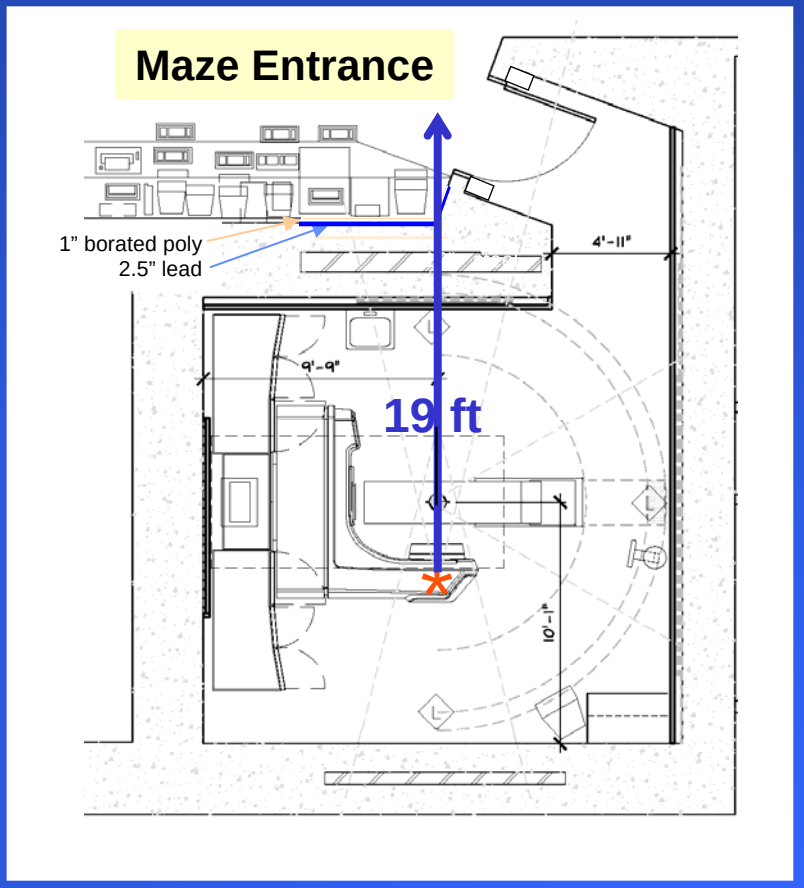


Example 6c: Leakage Scatter Unshielded Dose Rate Calculation

Line	Symbol	Parameter	Units	Value	Calculation
a	MV	Machine X-ray Energy	MV	15	
b	W	Workload	Gy/wk	450	
c		Leakage Fraction	%	0.10%	
d		IMRT Factor		2	
e	d_{sec}	Distance from target to wall at maze end	ft	16	measured
f			m	4.88	d * 0.3048
g	d_{zz}	Distance from wall at maze end to door	ft	10	measured
h			m	3.05	f * 0.3048
i	w_1	Wall width seen from door	ft	15	measured
j			m	4.57	h * 0.3048
k	h	Room height	ft	10	measured
L			m	3.05	j * 0.3048
m	α_1	1sr reflection coefficient	$1 / m^2$	0.0179	Table B.8b with 1.5 MV 0º Reflection angle
n	A_1	Scatter area	m^2	13.9	i * k
o	U	Use Factor		1	Calculation does not depend on orientation
p	H_{LS}	Leakage scatter unshielded dose rate	mSv/wk	1.02E+00	1000 * b * o * c * d * m * n / (f^2 * h^2)

Example 6d: Maze with Primary Barrier Contribution — Primary Barrier

- Primary barrier calculation applicable instead of direct leakage
- Primary barrier photoneutrons add to shielded maze neutrons
- Note of entrance to control area makes use of 0.125 occupancy for door inappropriate
  - Although calculation possibly made where technologists are seated vs. directly in front of door



NCRP 151 Table B.2
Primary Barrier Photon TVLs (mm)

Linac MV	Lead		Concrete		Steel		Earth		Borated Poly	
	TVL1	TVLe	TVL1	TVLe	TVL1	TVLe	TVL1	TVLe	TVL1	TVLe
4	57	57	350	300	99	99	549	470	866	743
6	57	57	370	330	100	100	580	517	916	817
10	57	57	410	370	110	110	643	580	1015	916
15	57	57	440	410	110	110	690	643	1089	1015
18	57	57	450	430	110	110	705	674	1114	1064
20	57	57	460	440	110	110	721	690	1138	1089
25	57	57	490	460	110	110	768	721	1213	1138

NCRP 151
Table B.2

Est. by density vs. concrete

earth density =1.5 g / cm^3 [Section 4.3.7]
concrete = 2.35 g / cm^3 [Section 4.3.1]
borated poly = 0.95 g / cm^3 [Table B.3]

Example 6d: Primary Barrier Contribution Calculation

Line	Parameter	Units	Value	Calculation
a	Machine X-ray Energy	MV	15	
b	Workload (W)	Gy/Wk	450	
c	Use Factor		0.25	
d	Target to Protected Point Distance	ft	19	
e		m	5.79	d * 0.3048
f	Unshielded Dose	mSv/wk	3.35E+03	1000 * b * c / e^2
g	Photon Transmission		9.91E-06	see below
h	Shielded Photon Dose Rate	mSv/wk	0.033	f * g
i	Photoneutron Dose Rate	mSv/wk	0.011	see next charts
j	Total Shielded Dose Rate	mSv/wk	0.044	h + i

Barrier	Material Thickness		Material	X-Ray Primary		Photon Trans.
	inches	mm		TVL1 (mm)	TVLe (mm)	
Inside Layer	13	330	Concrete	440	410	1.78E-01
Layer #2	10	254	Steel	110	110	4.91E-03
Layer #3	13	330	Concrete	440	410	1.57E-01
Layer #4	2.5	64	Lead	57	57	7.69E-02
Outside Layer	1	25	Borated Poly	1089	1015	9.44E-01
				15 MV	Total:	9.91E-06

Example 6d: Primary Barrier Contribution Calculation — First Metal Layer Photoneutrons

Barrier	Material Thickness		Material	Photon			Neutron	
	inches	mm		TVL1 (mm)	TVLe (mm)	Trans.	TVL (mm)	Trans.
Inside Layer #1	13	330	Concrete	440	410	1.78E-01		
Inside Layer #2						1.00E+00		
Inside Layer #3						1.00E+00		
Metal Layer	10	254	Steel					
Outside Layer #1	13	330	Concrete				239	4.15E-02
Outside Layer #2	2.5	64	Lead				N/A	1.00E+00
Outside Layer #3	1	25	Borated Poly				113	5.96E-01
			15 MV		Total (X):	1.78E-01	Total (Y):	2.48E-02

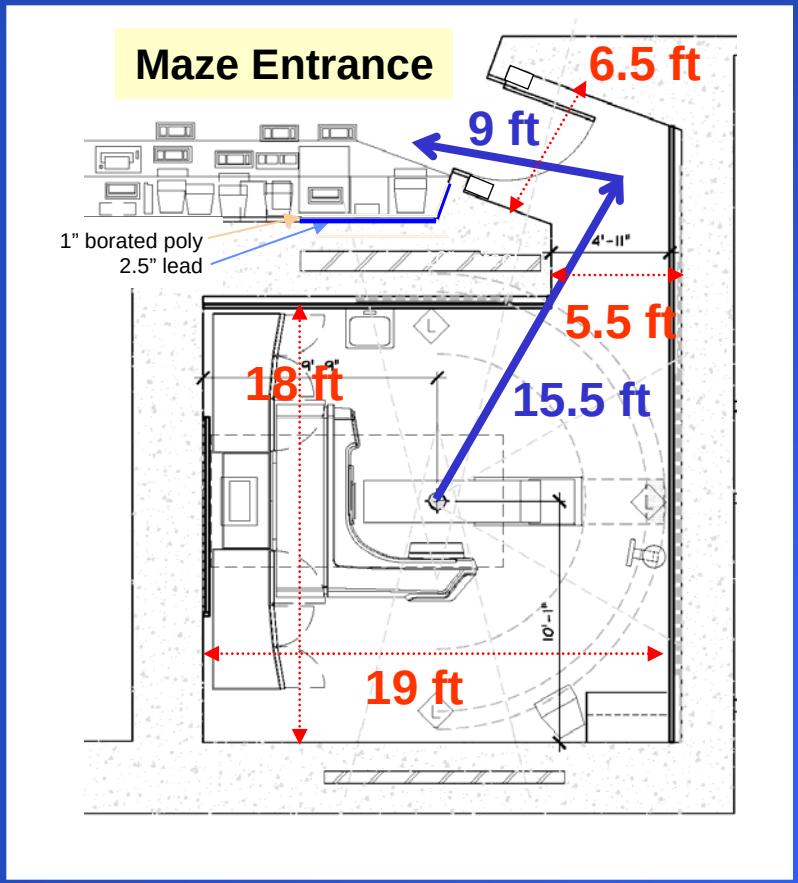
Line	Parameter	Units	Value	Calculation
a	Machine X-ray Energy	MV	15	
b	Workload (W)	Gy/Wk	450	
c	Use Factor		0.25	
d	Neutron Prod. Constant (R)	Sv/Gy/m^2	7.90E-05	Function of a & metal
e	Max Field Size (F_{max})	m^2	0.16	40 cm x 40 cm
f	U W R F_{max}		1.42E-03	b * c * d * e
g	tm / 2	m	0.127	Metal layer / 2
h	t2	m	0.419	Total outside layers
i	Photoneutron Dose	mSv/wk	0.007	1000*f *X*Y / (g+h+0.3)

Example 6d: Primary Barrier Contribution Calculation — Second Metal Layer Photoneutrons

Barrier	Material Thickness		Material	Photon			Neutron	
	inches	mm		TVL1 (mm)	TVLe (mm)	Trans.	TVL (mm)	Trans.
Inside Layer #1	13	330	Concrete	440	410	1.78E-01		
Inside Layer #2	10	254	Steel	110	110	4.91E-03		
Inside Layer #3	13	330	Concrete	440	410	1.57E-01		
Metal Layer	2.5	64	Lead					
Outside Layer #1	1	25	Borated Poly				113	5.96E-01
Outside Layer #2								1.00E+00
Outside Layer #3								1.00E+00
			15 MV	Total (X):		1.36E-04	Total (Y):	5.96E-01

Line	Parameter	Units	Value	Calculation
a	Machine X-ray Energy	MV	15	
b	Workload (W)	Gy/Wk	450	
c	Use Factor		0.25	
d	Neutron Prod. Constant (R)	Sv/Gy/m^2	8.87E-04	Function of a & metal
e	Max Field Size (F_{max})	m^2	0.16	40 cm x 40 cm
f	U W R F_{max}		1.60E-02	b * c * d * e
g	tm / 2	m	0.032	Metal layer / 2
h	t2	m	0.025	Total outside layers
i	Photoneutron Dose	mSv/wk	0.004	1000*f *X*Y / (g+h+0.3)

Example 6e: Maze with Primary Barrier Contribution — Maze Neutrons



Example 6e: Maze Neutron Fluence Calculation

Line	Symbol	Parameter	Units	Value	Calculation
a	MV	Machine X-ray Energy	MV	15	
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	15.5	measured
f			m	4.72	e * 0.3048
g	d_L	Vault Average Length	ft	18	measured
h			m	5.49	g * 0.3048
i	d_W	Vault Average Width	ft	19	measured
j			m	5.79	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	132.3	2 * (h*j + h*L + j*L)
n	Q_n	Neutron Source Strenth	n / Gy	7.60E+11	Function of a & b
o	φ_A	Neutron Fluence at Point A per Gy	n /m^2/Gy	8.84E+09	c*n* [d/(4*π* f^2) + (5.4*d+1.3)/(2*π*m)]

Example 6e: Capture Gamma Unshielded Dose Rate Calculation

Line	Symbol	Parameter	Units	Value	Calculation
a	MV	Machine X-ray Energy	MV	15	
a	W	Workload	Gy/wk	450	
c	φ_A	Neutron Fluence at Point A per Gy	n /m^2/Gy	8.84E+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	3.9	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	1.21E-06	g * c * 10^(-e / f)
i		Capture Gamma Unshielded Dose Rate	mSv/wk	5.43E-01	1000 * a * h

Example 6e: Maze Neutron Unshielded Dose Rate Calculation

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	8.84E+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	5.5	measured
f			m	1.68	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	5.11	f * h
j	d_m	Maze Width	ft	6.5	measured
k			m	1.98	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	6.04	i * m
o	TVD_n	Maze Neutron Tenth-Value Distance	m	5.06	2.06 * sqrt(n)
p	$H_{n,D}$	Neutron Unshielded Dose-Equivalent at Door per Dose at Isocenter	Sv/Gy	6.75E-06	2.4E-15 * b * sqrt(i / n) * [1.64*10^(-d/1.9)+10^(-d/o)]
q		Neutron Unshielded Dose-Equivalent Rate at Door	Sv/wk	3.04E+00	1000 * a * p

Example 6: Maze Door Transmission Calculation [1 of 3]

Maze Patient Scatter Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Steel	25	25	5.57E-01
Layer #2	1.5	38	Lead	5	5	2.40E-08
Layer #3	6	152	Borated Poly	322	322	3.36E-01
Layer #4	1.5	38	Lead	5	5	2.40E-08
Outside Layer	0.25	6	Steel	25	25	5.57E-01
Slant Angle:		0 deg		0.2 MV	Total:	6.01E-17

Maze Wall Scatter Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Wall Scatter TVL1 (mm)	Wall Scatter TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Steel	25	25	5.57E-01
Layer #2	1.5	76	Lead	5	5	5.75E-16
Layer #3	6	13	Borated Poly	322	322	9.13E-01
Layer #4	1.5	6	Lead	5	5	5.37E-02
Outside Layer	0.25	6	Steel	25	25	5.57E-01
Slant Angle:		0 deg		0.2 MV	Total:	8.76E-18

Example 6: Maze Door Transmission Calculation [2 of 3]

Maze Leakage Scatter Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Leakage Scatter TVL1 (mm)	Leakage Scatter TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Steel	39	39	6.87E-01
Layer #2	1.5	38	Lead	8	8	1.73E-05
Layer #3	6	152	Borated Poly	396	396	4.12E-01
Layer #4	1.5	38	Lead	8	8	1.73E-05
Outside Layer	0.25	6	Steel	39	39	6.87E-01
Slant Angle:		0 deg		0.3 MV	Total:	5.81E-11

Example 6: Maze Door Transmission Calculation [3 of 3]

Neutron Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Maze Neutrons TVL1 (mm)	Maze Neutrons TVLe (mm)	Neutron Trans.
Inside Layer	0.25	6	Steel	N/A	N/A	1.00E+00
Layer #2	1.5	38	Lead	N/A	N/A	1.00E+00
Layer #3	6	152	Borated Poly	45	45	4.11E-04
Layer #4	1.5	38	Lead	N/A	N/A	1.00E+00
Outside Layer	0.25	6	Steel	N/A	N/A	1.00E+00
Slant Angle:		0 deg		0.1 MV	Total:	4.11E-04

Capture Gamma Transmission for Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Capture Gamma TVL1 (mm)	Capture Gamma TVLe (mm)	Photon Trans.
Inside Layer	0.25	6	Steel	110	110	8.76E-01
Layer #2	1.5	38	Lead	61	61	2.37E-01
Layer #3	6	152	Borated Poly	1015	916	7.08E-01
Layer #4	1.5	38	Lead	61	61	2.37E-01
Outside Layer	0.25	6	Steel	110	110	8.76E-01
Slant Angle:		0 deg		10 MV	Total:	3.06E-02

Example 6: Maze Door Shielded Dose Rate

Line	Parameter	Units	Patient Scatter	Wall Scatter	Leakage Scatter	Primary Barrier	Maze Neutrons	Capture Gammas	Calculation
a	Calc. Unshield Dose Rate	mSv/wk	3.74E-01	7.72E-04	1.02E+00	4.43E-02	3.04E+00	5.43E-01	
b	Total / Calc. Dose Rate		2.64	2.64	1	1	1	1	NCRP 151 Eq. 2.14
c	Total Unshield Dose Rate	mSv/wk	9.87E-01	2.04E-03	1.02E+00	4.43E-02	3.04E+00	5.43E-01	a * b
d	Energy for TVL	MV	0.2	0.2	0.3	15.0	0.1	10.0	
e	Transmission		6.01E-17	8.76E-18	5.81E-11	1.00E+00	4.11E-04	3.06E-02	see above
f	Shielded Dose Rate	mSv/wk	0.0000	0.0000	0.0000	0.0443	0.0012	0.0166	c * e
g	Total Shielded Dose Rate	mSv/wk	0.0621						Sum Row f

Example 6: Wall Adj. to Maze Door Transmission Calc. [1 of 3]

Maze Patient Scatter Transmission for Wall Adjacent to Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Photon Trans.
Inside Layer	14	356	Concrete	130	130	1.84E-03
Layer #2						1.00E+00
Layer #3						1.00E+00
Layer #4						1.00E+00
Outside Layer	12	305	Concrete	130	130	4.52E-03
Slant Angle:		0 deg		0.2 MV	Total:	8.32E-06

Maze Wall Scatter Transmission for Wall Adjacent to Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Photon Trans.
Inside Layer	14	356	Concrete	130	130	1.84E-03
Layer #2						1.00E+00
Layer #3						1.00E+00
Layer #4						1.00E+00
Outside Layer	12	305	Concrete	130	130	4.52E-03
Slant Angle:		0 deg		0.2 MV	Total:	8.32E-06

Example 6: Wall Adj. to Maze Door Transmission Calc. [2 of 3]

Maze Leakage Scatter Transmission for Wall Adjacent to Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Photon Trans.
Inside Layer	14	356	Concrete	160	160	5.99E-03
Layer #2						1.00E+00
Layer #3						1.00E+00
Layer #4						1.00E+00
Outside Layer	12	305	Concrete	160	160	1.24E-02
	Slant Angle:	0 deg		0.3 MV	Total:	7.46E-05

Example 6: Wall Adj. to Maze Door Transmission Calc. [3 of 3]

Neutron Transmission for Wall Adjacent to Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Patient Scatter TVL1 (mm)	Patient Scatter TVLe (mm)	Neutron Trans.
Inside Layer	14	356	Concrete	161	161	6.18E-03
Layer #2						1.00E+00
Layer #3						1.00E+00
Layer #4						1.00E+00
Outside Layer	12	305	Concrete	161	161	1.28E-02
Slant Angle:		0 deg		0.1 MV	Total:	7.91E-05

Capture Gamma Transmission for Wall Adjacent to Door

Barrier	Material Thickness inches	Slant Thickness mm	Material	Capture Gamma TVL1 (mm)	Capture Gamma TVLe (mm)	Photon Trans.
Inside Layer	14	356	Concrete	410	370	1.36E-01
Layer #2						1.00E+00
Layer #3						1.00E+00
Layer #4						1.00E+00
Outside Layer	12	305	Concrete	410	370	1.55E-01
Slant Angle:		0 deg		10 MV	Total:	2.10E-02

Example 6: Wall Adjacent to Maze Door Shielded Dose Rate

Maze Shielded Dose at Wall Adjacent to Door

Line	Parameter	Units	Patient Scatter	Wall Scatter	Leakage Scatter	Primary Barrier	Neutrons	Capture Gammas	Calculation
a	Calc. Unshielded Dose	mSv/wk	3.74E-01	7.72E-04	1.02E+00	4.43E-02	3.04E+00	5.43E-01	
b	Average / Calculated Dose		2.64	2.64	1	1	1	1	NCRP 151 Eq. 2.14
c	Average Unshielded Dose	mSv/wk	9.87E-01	2.04E-03	1.02E+00	4.43E-02	3.04E+00	5.43E-01	a * b
d	Energy for TVL	MV	0.2	0.2	0.3	15.0	0.1	10.0	
e	Transmission		8.32E-06	8.32E-06	7.46E-05	1.00E+00	7.91E-05	2.10E-02	see above
f	Shielded Dose	mSv/wk	0.0000	0.0000	0.0001	0.0443	0.0002	0.0114	c * e
g	Total Shielded Dose	mSv/wk	0.0560						Sum Row f