Shielding Design Methods for Radiation Oncology Departments

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Goals of Radiation Shielding Design

- To ensure that all exposure levels to the public and occupational personnel are maintained below the regulatory limits of 10 CFR Part 20, any special state regulatory requirements, and within ALARA limits established at the facility.

Required Information for Shielding Designs

- **Architectural drawings of equipment layout in room**
- **Architectural drawings of surrounding areas indicating usage of these areas - offices, restrooms, corridor, exterior, etc.**
- **Elevation view of room or construction of floor and ceiling and distance between floors**

Equipment to be included in departments typically consist of a CT Simulator and Linear Accelerator(s).

CT Simulator Shielding is covered by NCRP Report # 147

Linear Accelerator Shielding is covered by NCRP Report # 151

Nomenclature for Radiation Design Criteria

Required thickness = NT/Pd^2

where:

N = total no. of patients per week

T = Occupancy Factor

P = design goal (mGy/wk)

d = distance to occupied area (m)

Shielding Design Goal (Air Kerma):

Uncontrolled Areas

Annual: P = 1 mGy per year
Weekly: P = 0.02 mGy per week

Controlled Areas

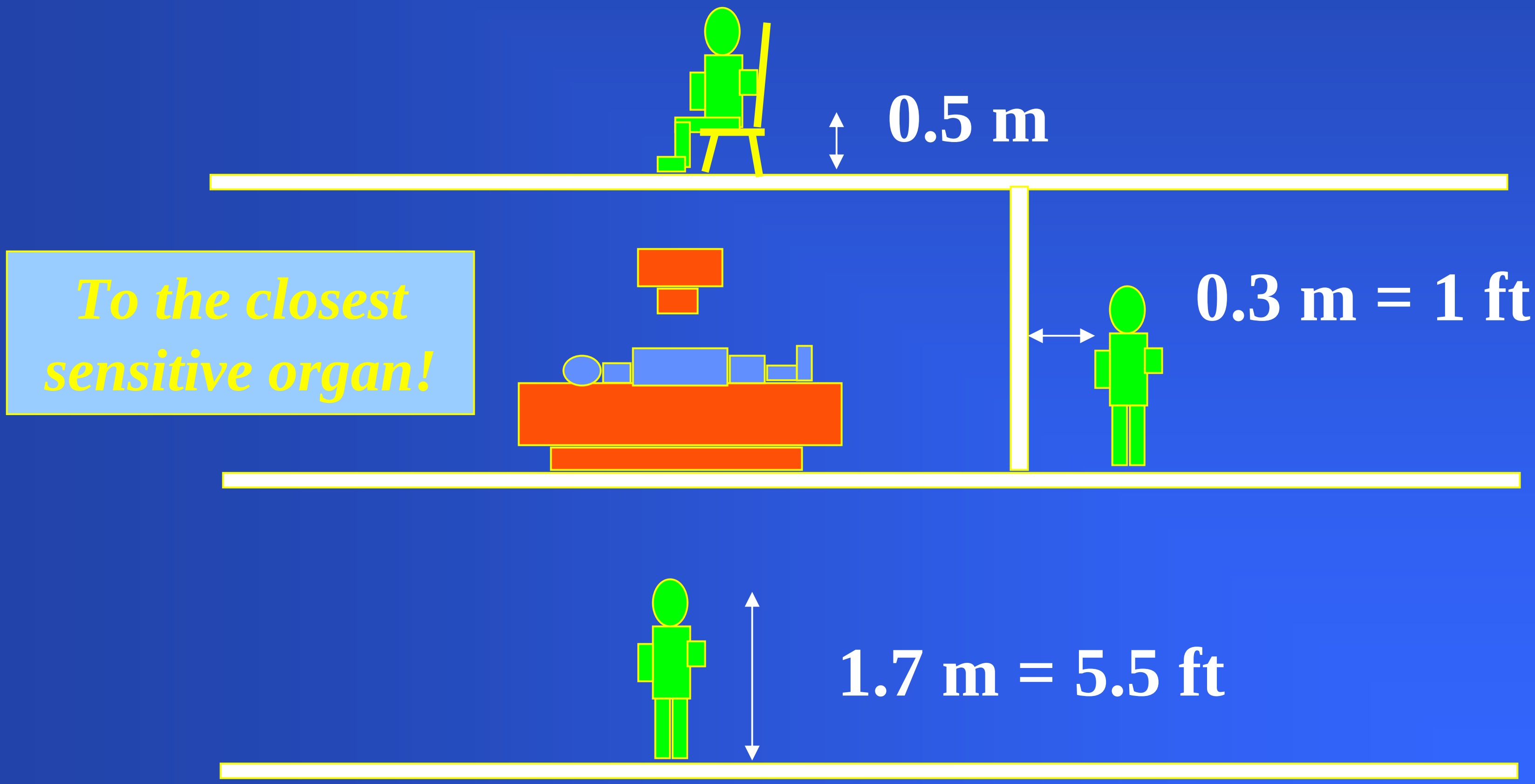
Annual: P = 5 mGy per year
Weekly: P = 0.1 mGy per week

Distance (d)

The distance in meters from either the primary or secondary radiation source to the occupied area.

Recommendations for distances to be used are in Report 147 and 151 for areas above and below source.

Where in the occupied area do you calculate the dose?



Recommended Occupancy Factors for Uncontrolled Areas:

<u>*T*=1</u> Clerical offices, labs, fully occupied work areas, kids' play areas, receptionist areas, film reading areas, attended waiting rooms, adjacent x-ray rooms, nurses' stations, x- ray control rooms

<u>*T*=1/2</u> Rooms used for patient examinations and treatments

<u>*T*=1/5</u> corridors, patient rooms, employee lounges, staff rest rooms

<u>*T*=1/8</u> corridor doors

Recommended Occupancy Factors for Uncontrolled Areas:

***T*=1/20** **public toilets, vending areas, storage rooms, outdoor area with seating, unattended waiting rooms, patient holding areas**

***T*=1/40** **minimal occupancy areas; transient traffic, attics, unattended parking lots, stairways, janitor's closets, unattended elevators**

Equivalency of Shielding Materials

Table 4.8 Page 67

Steel thickness requirement:

8 × Pb thickness requirement

Gypsum wallboard thickness requirement:

3.2 × concrete thickness requirement

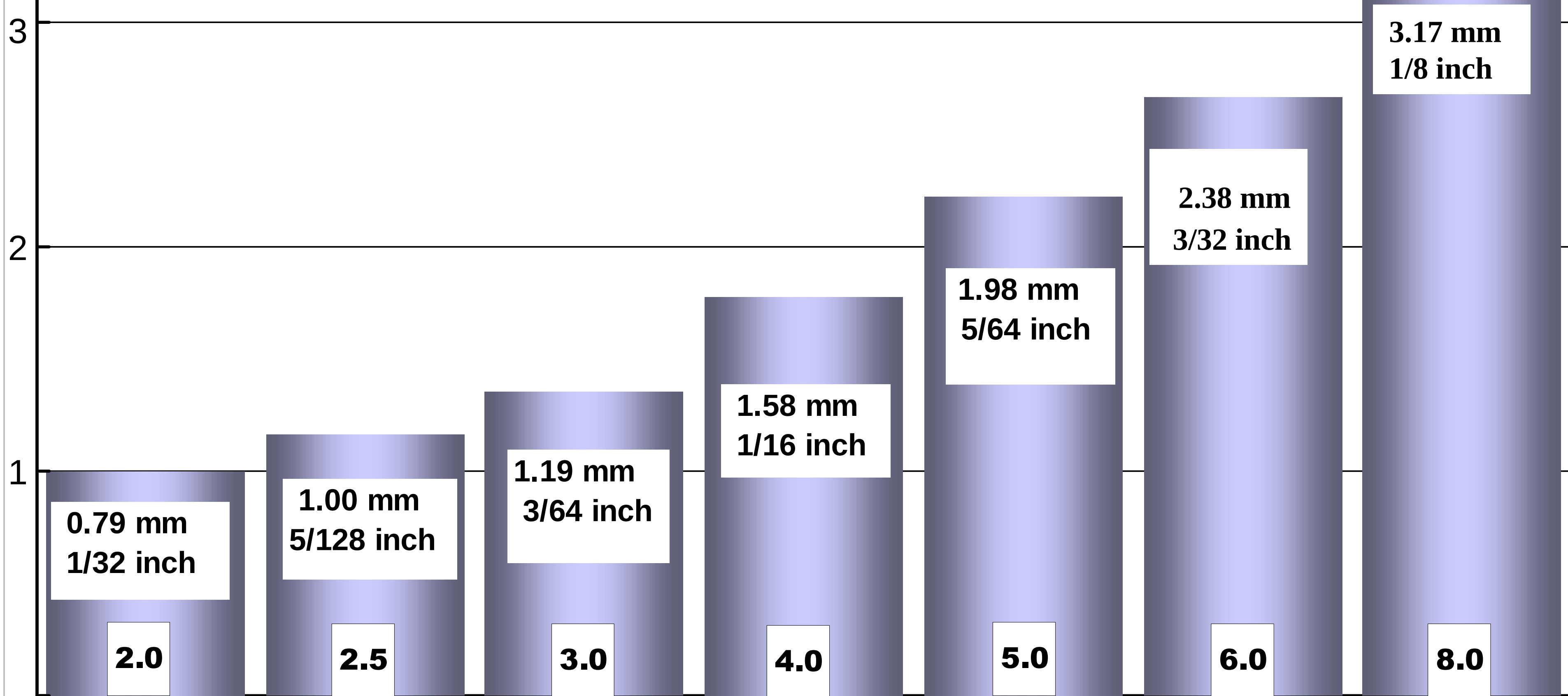
Plate Glass thickness requirement:

1.2 × concrete thickness requirement

Light-weight concrete thickness requirement:

1.3 × std-weight concrete thickness requirement

Nominal Lead Thicknesses



Nominal Thickness of Lead (mm and inches)
and Nominal Weight (lb ft^{-2}) at bottom of each bar

Multi-Slice Helical CT Shielding

- Larger collimator (slice thickness) settings generate more scatter
  - Offsets advantages of multiple slices per rotation
  - Environmental radiation levels typically increase
- Ceiling and floor deserve close scrutiny

Methodology

- Calculate the unshielded weekly exposure rate at area of interest
- Find the maximum weekly exposure at 1 m from isocenter and inverse-square this out to the occupied area beyond the barrier.
- Apply traditional barrier thickness calculations to arrive at an answer.
  - Occupancy, permissible dose, attenuation of concrete, etc.

NCRP 147 DLP Method

- **Weekly Air Kerma at 1m (K^1_{sec})**

K^1_{sec} (head) = κ_{head} * DLP
K^1_{sec} (body) = 1.2 * κ_{body} * DLP

$\kappa_{head} = 9 \times 10^{-5}\ {}^{1}/_{cm}$
$\kappa_{body} = 3 \times 10^{-4}\ {}^{1}/_{cm}$

Use inverse square to find unshielded weekly exposure at barrier from K^1_{sec}

NCRP 147 DLP Method

DLP (Dose-Length Product)

$= CTDI_{VOL} * L$

- **$CTDI_{VOL} = CTDI_W/Pitch$**
- **$CTDI_W = 1/3$ Center $CTDI_{100}$**
  $+ 2/3$ Surface $CTDI_{100}$ (mGy)
- **L = Scan length for average *series* in cm**
- **Units of mGy-cm**

$= [{}^{1}/_{3}\ CTDI_{100,\ Center} + {}^{2}/_{3}\ CTDI_{100,\ Surface}] * L/p$

NCRP 147 DLP Method

Procedure	$CTDI_{Vol}$ (mGy)	Scan Length (L) (cm)	DLP* (mGy-cm)
Head	60	20	1200
Body	15	35	525
Abdomen	25	25	625
Pelvis	25	20	500
Body (Chest, Abdomen, or Pelvis)			550

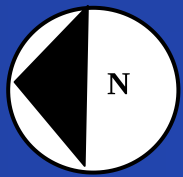
* Double the value shown for w/wo contrast

Example - Ceiling Calculation

- 180 Procedures/week
  - 150 Abdomen & Pelvis
  - 30 Head
- 40% w&w/o contrast
- 13’ (4.2 m) ceiling height (finished floor to finished floor)
- GE LightSpeed 16

Preliminary Information

- **Architectural drawings (Plan view) of exam room, floor above, and floor below**
  - Elevation sections through scanner location for floor and ceiling
  - Occupancy factors for floors above and below
  - Two rooms away for possibility that remote areas may be more sensitive than adjacent areas
- **Composition of walls, ceilings and floors**
  - Materials and thickness
- **Scanner placement from vendor**
  - Distance from scanner to protected areas beyond barriers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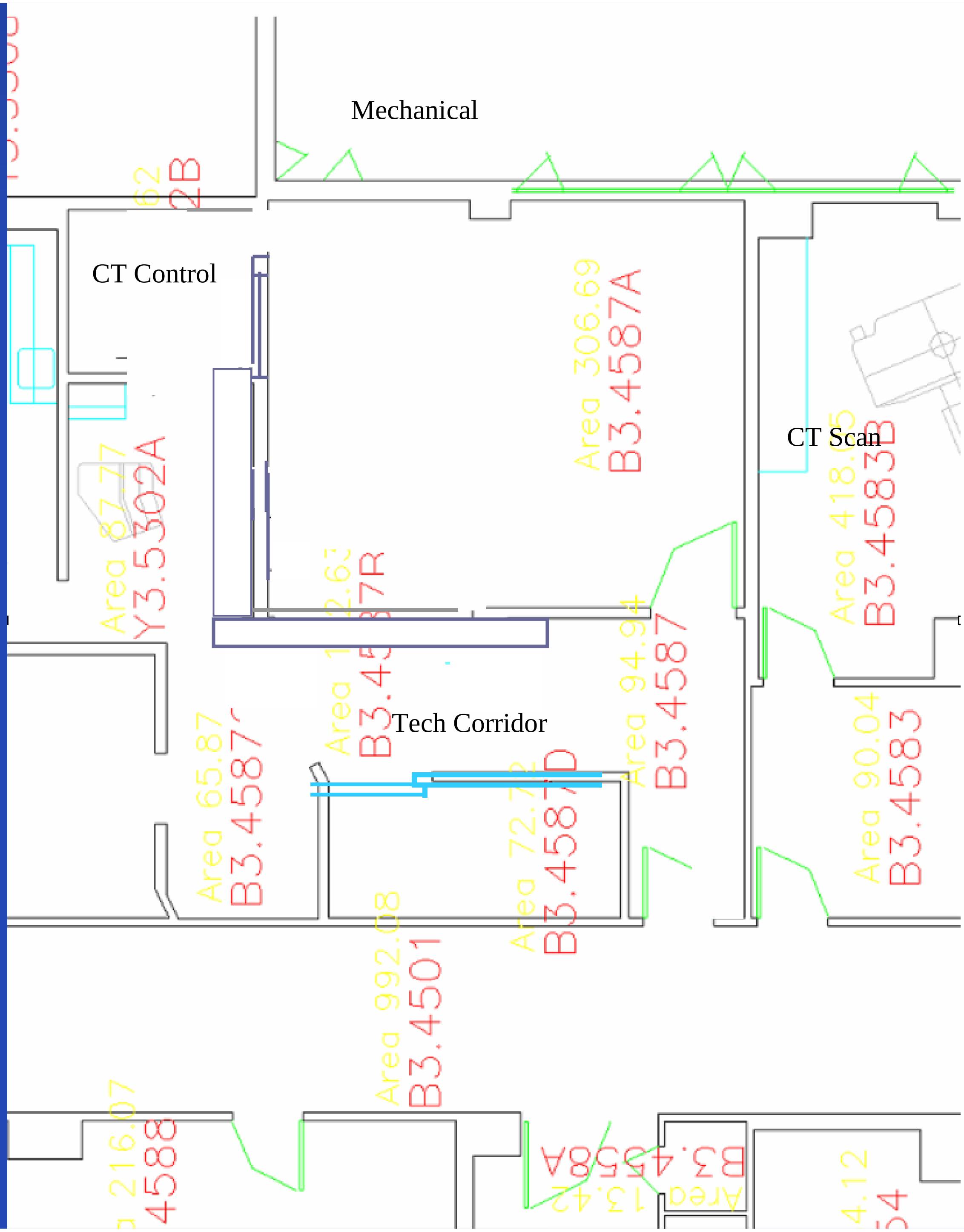
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CT Control
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Area 418.05
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Area 72.72
Area 992.08
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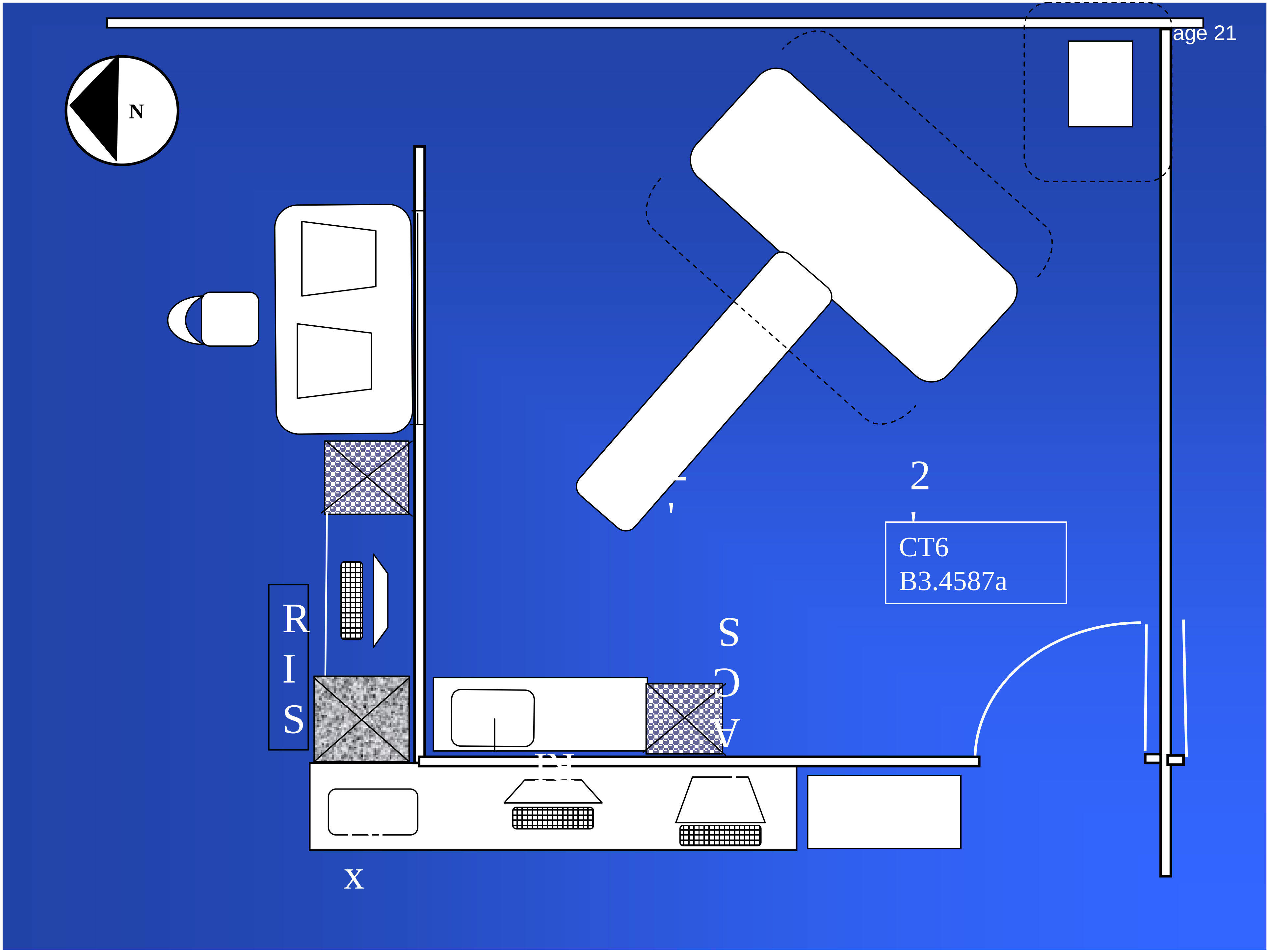
B3.4558A
Area 13.42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Unshielded Weekly Exposure at Barrier

- **Air Kerma/procedure at 1m (K^1_{sec})**
  - **40% w&w/o contrast**

$$K^1_{sec}\ (\text{head}) = \kappa_{head} * \text{DLP}$$
$$= 1.4 * 9\text{x}10^{-5}\ \text{cm}^{-1} * 1200\ \text{mGy-cm}$$
$$= 4.9\ \text{mGy}$$

$$K^1_{sec}\ (\text{body}) = \kappa_{body} * \text{DLP}$$
$$= 1.4 * 1.2 * 3\text{x}10^{-4}\ \text{cm}^{-1} * 550\ \text{mGy-cm}$$
$$= 41.6\ \text{mGy}$$

Unshielded Weekly Exposure at Barrier

- Weekly Air Kerma (K_{sec}) at Ceiling:
  - 30 head procedures/wk
  - 150 body procedures/wk
  - D_{sec}= 4.2 m + 0.5 m – 1 m = 3.7 m

K_{sec} (head) = 30 * 4.9 mGy * $(1m/3.7m)^2$
= 0.36 mGy

K_{sec} (body) = 150 * 41.6 mGy * $(1m/3.7m)^2$
= 3.04 mGy

Unshielded Weekly Exposure at Barrier

- **Weekly Air Kerma (K_{sec}) at Ceiling:**

K_{sec} (Total) = K_{sec} (head) + K_{sec} (body)

K_{sec} (Total) = 0.36 mGy + 3.04 mGy

K_{sec} (Total) = 3.40 mGy

Required Transmission (B)

$$B = \frac{P}{K_{sec} * T}$$

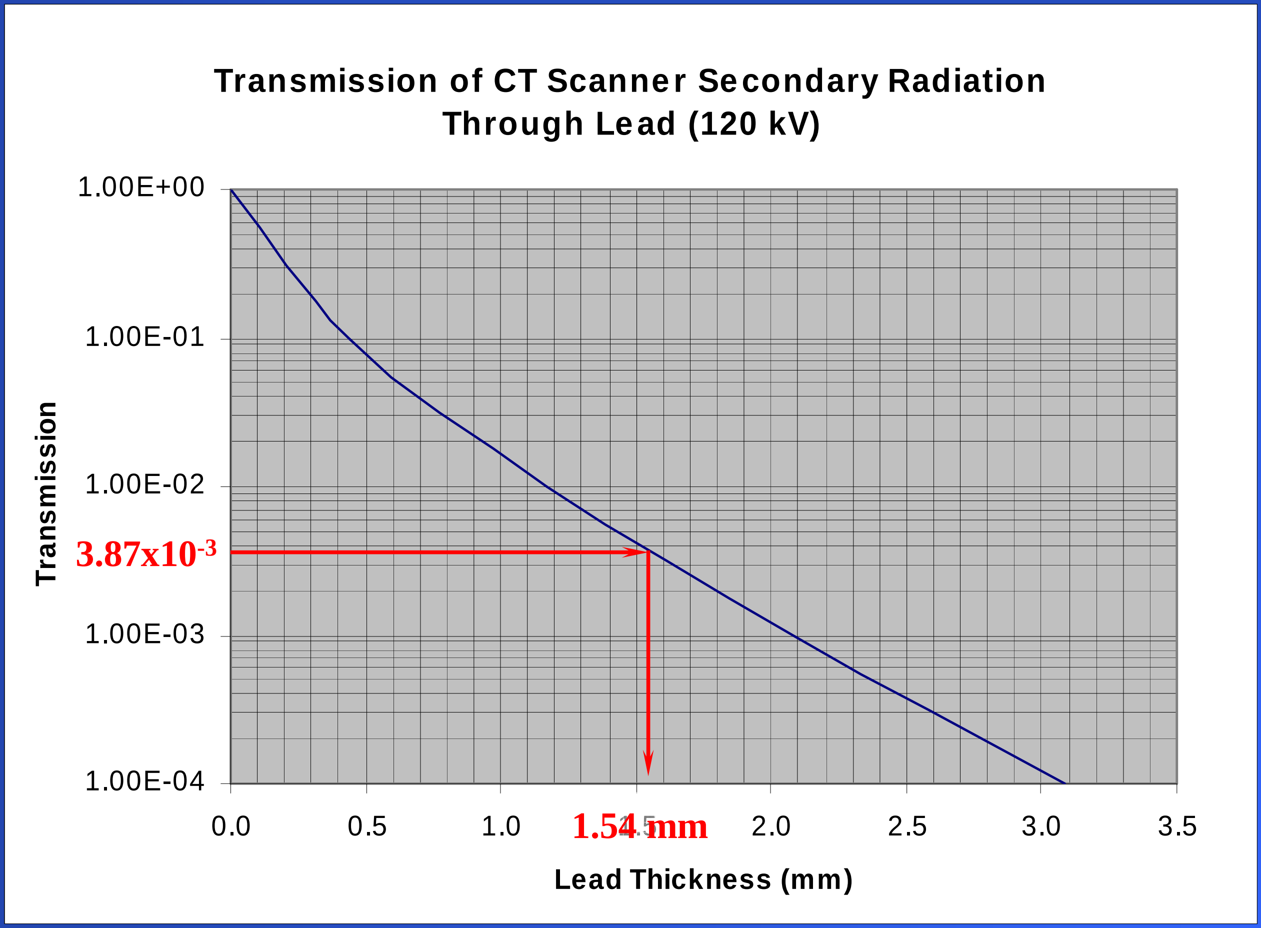
P = Maximum permissible weekly exposure

T = Occupancy Factor

$$= \frac{0.02 \text{ mGy}}{3.40 \text{ mGy} * 1} = 3.87\text{x}10^{-3}$$

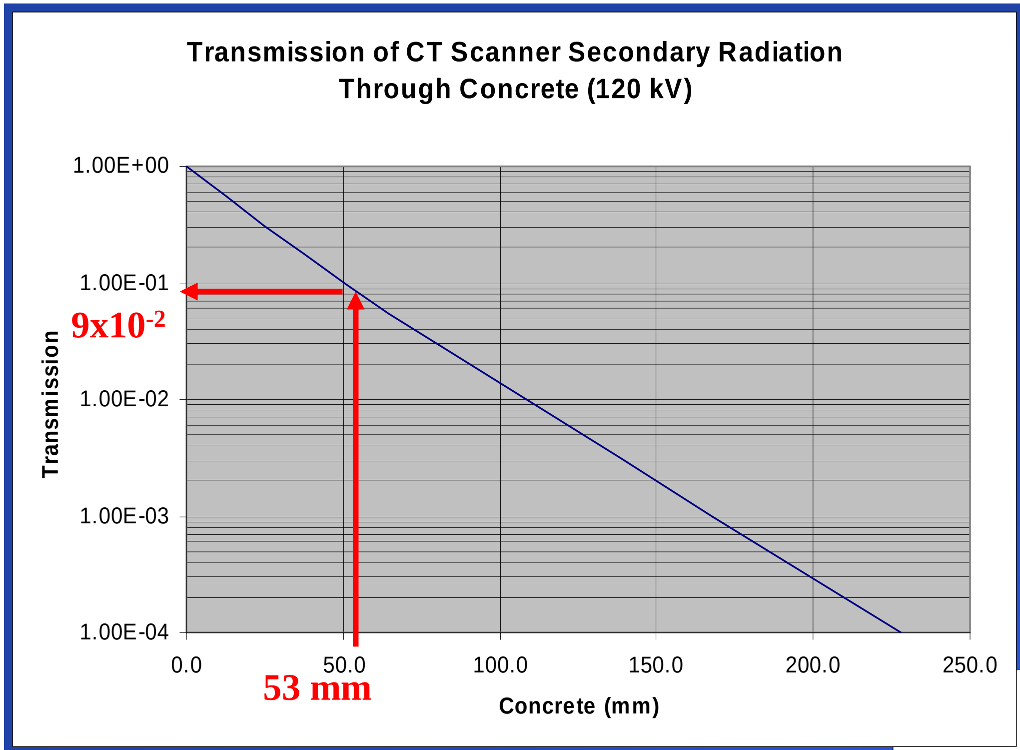
Total Shielding Required

Use Simpkin curve fit equations or look up on published attenuation diagrams (NCRP 147 Fig. A-2)



Existing Shielding

- Floors and ceilings
  - Find lead equivalence from documentation of concrete thickness.
  - Find thickness by drilling a test hole and measuring.
  - Always assume light weight concrete, unless proven otherwise (30% less dense than standard density, coefficients used in NCRP 147)

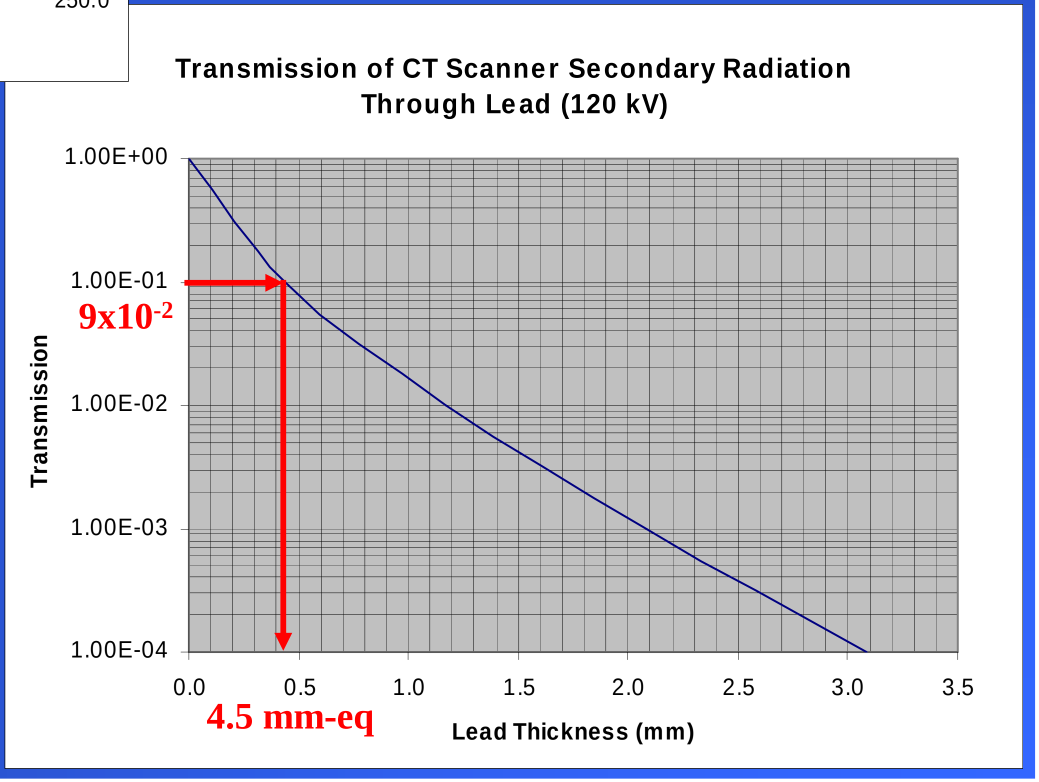


3" light concrete = 2.1" std concrete

= 53 mm std concrete

B = 9×10^{-2}

= 0.45 mm Pb-eqiv



Existing Shielding

- Subtract existing lead-equivalence from total required
- Convert to 1/32 inch multiples (round up)

Total lead to add = (Total required) – (Existing)

= 1.54 mm – 0.45 mm

= 1.1 mm

Round up to 1/16” Pb Additional Lead required

While the average $CTDI_{vol}$ for Head CT Scans is 60 mGy with an average scan length of 20 cm resulting in a DLP (dose length product) of 1200 mGy cm, the recommended DLP for average Body scans (chest, abdomen or pelvis) to be used in CT Scanner Shielding Calculations is:

0%	1.	250 mGy cm
0%	2.	350 mGy cm
100%	3.	550 mGy cm
0%	4.	750 mGy cm
0%	5.	1500 mGy cm

10

Answer: # 3 - 550 mGy cm

- **Ref: "Structural Shielding Design for Medical X-Ray Imaging Facilities," NCRP Report # 147 (2004), p. 99**

For a facility with an average workload of 30 head scans and 150 body scans per week, the required lead shielding typically needed for a public (non-controlled) area with an occupancy of 1 at a distance of 3 meters would be expected to be:

0%	1.	2.5 mm lead
0%	2.	1.0 mm lead
100%	3.	0.5 mm lead
0%	4.	5.0 mm lead
0%	5.	1.5 mm lead

10

Answer: # 5 - 1.5 mm lead

- Ref: "Structural Shielding Design for Medical X-Ray Imaging Facilities," NCRP Report # 147 (2004), p. 100

The suggested occupancy factor for doors leading into radiographic/therapeutic exam rooms from the corridor is:

67%	1.	0.125
10%	2.	0.200
19%	3.	0.250
5%	4.	0.500
0%	5.	1.000

10

Answer: # 1 - 0.025 mm lead

- Ref: "Structural Shielding Design for Medical X-Ray Imaging Facilities," NCRP Report # 147 (2004), p. 31

The weekly shielding design goal for a controlled area is an air-kerma value of:

4%	1.	0.001 mGy per week
16%	2.	0.010 mGy per week
32%	3.	0.020 mGy per week
40%	4.	0.100 mGy per week
8%	5.	0.500 mGy per week

10

Answer: # 4 - 0.10 mGy per week

- Ref: "Structural Shielding Design for Medical X-Ray Imaging Facilities," NCRP Report # 147 (2004), p. 29

The minimum distance to the occupied area from a shielded wall is assumed to be:

13%	1.	1.0 meter
0%	2.	0.1 meter
3%	3.	0.5 meter
0%	4.	1.5 meter
83%	5.	0.3 meter

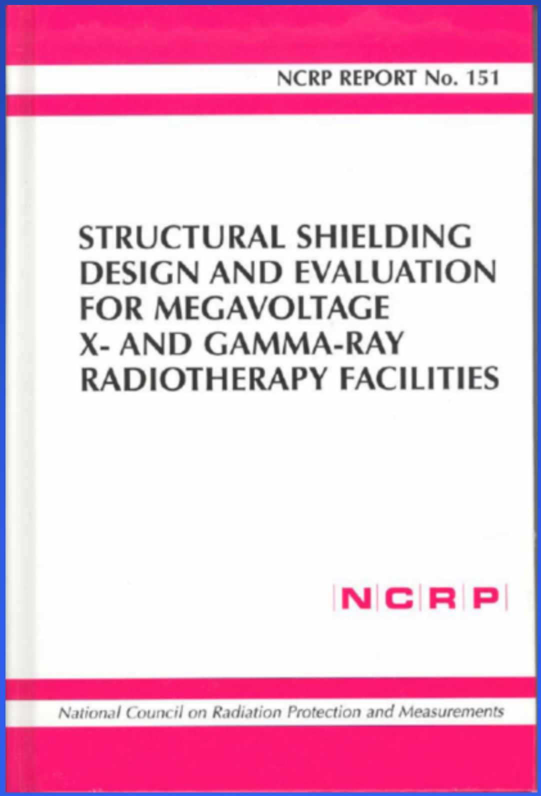
10

Answer: # 5 - 0.3 meter

- Ref: "Structural Shielding Design for Medical X-Ray Imaging Facilities," NCRP Report # 147 (2004), p. 7.

Therapy Shielding Calculations Are Primarily Based on NCRP Report No. 151

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



NCRP 151 recommendations are addressed throughout this presentation

Topics

- Primary and Secondary Barriers
  - Simple primary barrier calculations, including required width
  - Secondary barrier calculations
    - » Photon leakage, neutron leakage, scatter, and IMRT impact
  - Laminated primary barrier calculations (i.e., barrier with metal)
  - Tapered ceilings
  - Lightly shielded wall for vault below ground level
- Vault entrances
  - Mazes (five examples with five different layouts)
  - Direct-shielded doors
- Skyshine
  - Photon and neutron skyshine for lightly-shielded ceiling
  - Generally not recommended for new construction
  - May be appropriate for cost-effective retrofit to existing vault

Primary and Secondary Barrier Examples

1. Basic primary barrier photon shielded dose rate
2. Minimum width of primary barrier
3. Secondary barrier photon leakage
4. Secondary barrier photon leakage with IMRT
5. Secondary barrier photon & neutron leakage with IMRT
6. Secondary barrier photon & neutron leakage plus patient scatter with IMRT

7,8. Secondary barrier calculation including slant factor

Maze and Direct Shielded Door Calculation Examples

9. Maze with secondary leakage through door, 6 MV
10. Maze with secondary leakage through door, 18 MV

11. Direct shielded door in secondary barrier

Key Messages in This Presentation

- Each linear accelerator vault is unique
- Challenges in generating a shielding report
  - Identifying the locations around the vault that require a calculation
  - Appropriately calculating the shielded dose rate for these locations
  - Communicating the calculation implications to the architect and contractor
- Do not expect to generate a report simply by filling numbers in a spreadsheet
  - Assumptions implicit in spreadsheet may not match vault
  - Especially true if you do not understand the calculations in the spreadsheet
    - » Including how to adapt the calculations to the vault

Linear Accelerator Energy

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

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

NCRP 151 Recommended Workload [1 of 2]

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

450 Gy / wk absorbed dose is the default weekly workload

NCRP 151 Recommended Workload [2 of 2]

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

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

Workload Assumptions for Dual Energy Linear Accelerators

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

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

At least 250 Gy/wk at high MV mode

Radiation Protection Limits

- Shielding Design Goal (P)
  - Level of dose equivalent (H) used in the design calculations
  - Applies to barriers designed to limit exposure to people
    - » Limiting exposure to unoccupied locations is not the goal
  - Stated in terms of mSv at the point of nearest occupancy
- Recommended values for shielding design goal
  - 0.10 mSv/week for controlled areas
  - 0.02 mSv/week for uncontrolled areas
- Typical international shielding design goals
  - 0.12 mSv/week for controlled areas
  - 0.004 mSv/week for uncontrolled areas

Controlled Areas

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

Uncontrolled Areas

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

Radiation Protection Limits for Locations

- Protected location
  - Walls: 1 ft beyond the barrier
  - Ceilings: 1.5 ft above the floor of the room above the vault
  - Floors: 5.5 ft above the floor of the room below
- Permissible dose at protected location depends on occupancy
- *Occupancy factor (T):*

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

Max shielded dose rate traditionally referred to as P/T

NCRP 151 Recommended Occupancy

- T=1: Areas occupied full-time by an individual) e.g. administrative or clerical offices; treatment planning areas, treatment control rooms, nurse stations, receptionist areas, attended waiting rooms, occupied space in nearby building
- T= 0.5: Adjacent treatment room, patient examination room adjacent to shielded vault
- T = 0.2: Corridors, employee lounges, staff rest rooms
- T = 0.125: Treatment vault doors
- T = 0.05: Public toilets, unattended vending rooms, storage areas, outdoor areas with seating, unattended waiting rooms, patient holding areas, attics, janitor’s closets
- T = 0.025: Outdoor areas with only transient pedestrian or vehicular traffic, unattended parking

Occupancy Factor Selection

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

Use Factor

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

90º gantry angle intervals

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

45º gantry angle intervals

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

Hourly Limit for Uncontrolled Areas

- Recommendation is based on maximum Time-Averaged Dose Equivalent Rate (TADR) per hour (NCRP 151, 3.3.2)
  - TADR synonymous with shielded dose rate in this presentation
- Calculation adjusts weekly TADR (R_w) to hourly TADR (R_h)

$$R_h = (M / 40)\, R_w$$

  - where M = ratio of maximum to average patient treatments per hour
  - Shielding must be sufficient so that $R_h \leq 0.02$ mSv/wk NRC limit
- More realistic than traditional U=1 recommendation
  - Several beam orientations are almost always used for each patient
  - Exception: 35 Gy/hr with U=1 for a lateral barrier used for TBI

NCRP 151 eliminates traditional U=1 assumption

Hourly Limit for Uncontrolled Areas: Recommended Approach

- **Max patients / hour at highest energy: Six**
  - Maximum in any one hour estimated as one each 10 minutes
  - Max workload per hour (W_h) is 6 patients x 3 Gy/patient = 18 Gy

- **Max weekly P/T (mSv/wk) = 0.02 (mSv/hr) W (Gy/wk) / W_h (Gy/hr)**
  - where W = 450 Gy/wk (single/dual) or W=255 Gy/wk (at high MV)

Mode	Patients per day	W (Gy/wk)	Max Patients per hour	Gy per Patient Treatment	Max Gy/hr (W_h)	Weekly Max P/T (mSv/wk)	Equiv. Min T
Single MV mode	30	450	6	3	18	0.500	0.040
Dual MV mode	30	450	6	3	18	0.500	0.040
High MV mode	17	255	6 (High MV)	3	18	0.283	0.071
Low MV mode	13	195		3			

Max P/T applies to both primary & secondary barriers

- **Minimum occupancy (T) = W_h (Gy/hr) / W (Gy/wk)**
  - Hourly NCR limit and weekly NCRP 151 limit are both 0.02 mSv
  - Implies full benefit of T=0.025 applies only to restricted locations

Primary Barrier Photon Shielded Dose Rate

- **Photon unshielded dose rate**

$$H_{pri} = \frac{WU}{d_{pri}^2}$$

where distance is in meters

- **Transmission by shielding material thickness t**

$$Trans. = 0.1 \times 10^{[-(t - TVL_1)/TVL_e]}$$

  - **Where TVL_1 and TVL_e are the values for the first and subsequent tenth-value layers, respectively**
    - **Assumes t > TVL_1**

- **Shielded dose rate is unshielded dose rate times transmission**
  - **Must be less than P/T**

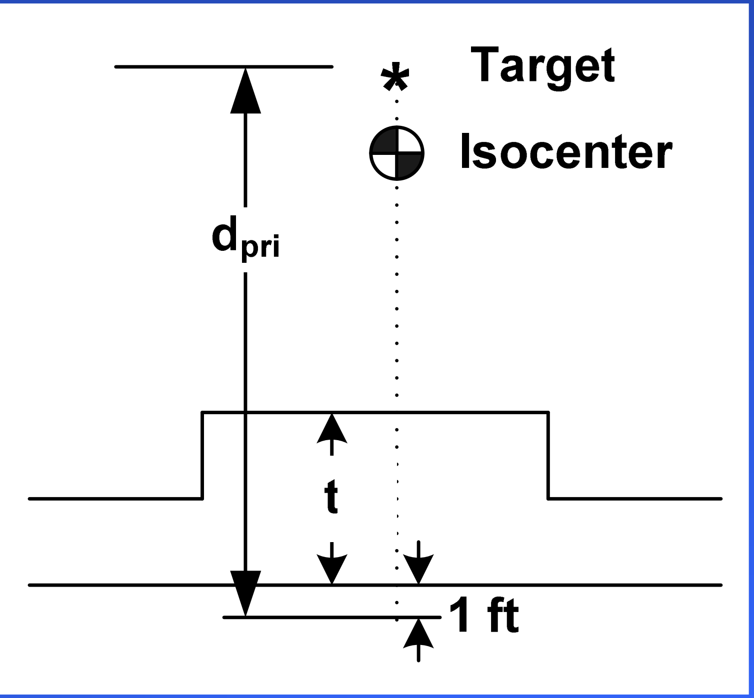


Table 1: NCRP 151 Table B.2
Primary Barrier Photon TVLs (mm)

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

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]

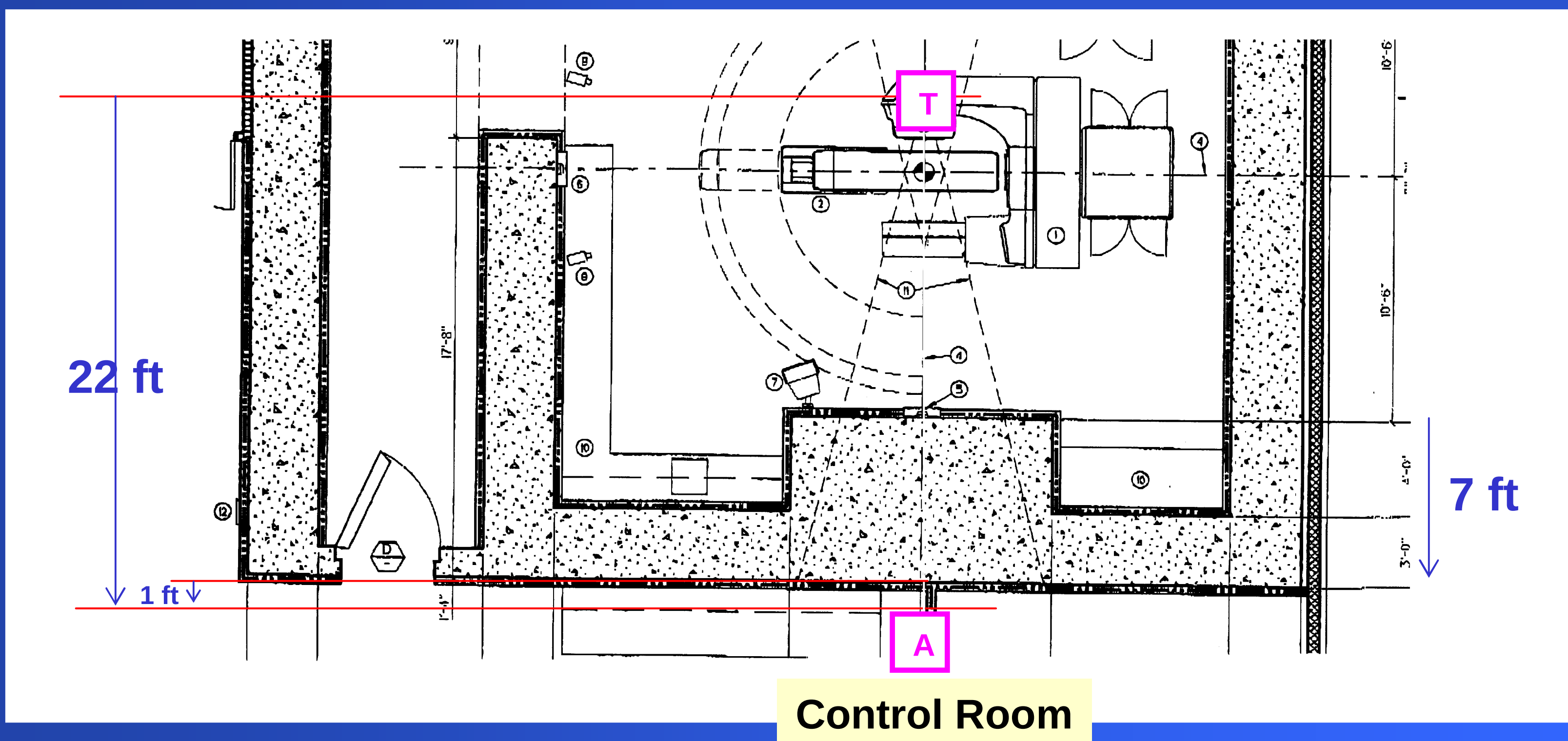
Include density in the shielding report and recommend that construction contracts specify the density

TVLs for Other Material

- High density concrete
  - Alternative to lead / steel if wall must have limited thickness
  - Generally construction uses blocks instead of poured concrete
    - Mixers not designed for use with high density aggregates
  - Photon TVL based on density relative normal concrete 147 lb/ft^3
    - Typically 288 lb/ft^3 for primary barriers, 240 lb/ft^3 secondary
  - Neutron TVL considered to be the same as normal concrete
    - With boron added to compensate for lower hydrogen content
- Conventional concrete block
  - Generally less than 147 lb/ft^3 density, so adjust TVLs accordingly
- Asphalt may provide ceiling shielding
  - Parking lot placed over top of vault
  - Typical density is 2.0 g/cm^3
  - Resulting in TVL 1.18 times concrete TVL

Example 1: 18 MV Primary Concrete Barrier

1. Establish P/T for protected location A: P/T = 0.1 mSv/wk (P = 0.1 mSv/wk, T = 1)
2. Measure distance from target to protected location (22 ft from target)
3. Measure (or read from annotations) the barrier material thickness (7 ft)
4. Determine TVLs based on MV (18) and material type (concrete)
5. Calculate unshielded dose rate, transmission, and shielded dose rate
   (add or increase material until shielded dose rate < P/T)



Example 1: P/T Calculation for Primary Barrier

Line	Parameter	Units	Value	Calculation
a	Design Dose Limit (P)	mSv/wk	0.1	
b	Occupancy Factor (T)		1	
c	Weekly Protect P/T Limit	mSv/wk	0.100	a / b
d	Dose Limit Per Hour	mSv/hr	0.02	
e	Dose per Patient Treatment	Gy/pt	3	Default value
f	Patients per Day	pt/day	30	Default value
g	Workload (W) per Week	Gy/wk	450	5 * e * f
h	Max patient / hr	patient	6	
i	Max Workload / Hour (W_h)	Gy/hr	3.6	h * e / 5
j	Hourly Protect P/T Limit	mSv/wk	2.500	0.02 * g / i
k	P/T	mSv/wk	0.100	min{ c, j }

Weekly P/T Limit (lines a–c)

Hourly limit converted to equivalent weekly P/T limit (lines d–j)

P/T = 0.1 mSv/wk

Cells with inputs are shaded green

- Hourly protection limit does not impact P/T for high occupancy location
- Hourly protection limit may impact P/T for low occupancy locations in uncontrolled areas

Example 1: Shielded Photon Dose Calculation

Line	Parameter	Units	Value	Calculation
a	Machine X-ray Energy	MV	18	
b	Workload (W)	Gy/Wk	450	
c	Use Factor		0.25	
d	Target to Protected Point Distance	ft	22	
e		m	6.71	d * 0.3048
f	Unshielded Dose	mSv/wk	2.50E+03	1000 * b * c / e^2
g	Total Photon Transmission		1.22E-05	see below
h	Shielded Photon Dose	mSv/wk	0.030	f * g

0.030 mSv is less than P/T = 0.1 mSv/wk

Key inputs to the calculation

	Material Thickness			X-Ray Primary		
Barrier	inches	mm	Material	TVL1 (mm)	TVLe (mm)	Photon Trans.
Inside Layer	84	2134	Concrete	450	430	1.22E-05
Layer #2						1.00E+00
Outside Layer						1.00E+00
				18 MV	Total:	1.22E-05

Photon transmission through concrete
= 0.1 * 10^[-(2134 - 450)/ 430)] = 1.22E-5

TVLs are function of MV and Concrete

Typical Primary Concrete Barrier

- **Primary barrier calculation tends to be relatively accurate**
  - **Unlike secondary barrier calculation, which tends to be conservative**
- **Desirable to have factor of 2 or 3 margin for shielded dose rate to account for variation in concrete density**
  - **NCRP 151 factor of 2.7 for primary barriers with metal above 10 MV is reasonable goal for all primary barriers**
- **Typical concrete primary barrier thickness (ft)**

P/T	6 MV	18 MV
0.02	6.5	8
0.1	6	7.5
0.2	5.5	7
0.4	5	6.5 to 7
0.8	4.5 to 5	6

- **Shielding report should emphasize that construction contracts specify 147 lb/ft^3 concrete density**

Factor of 2 to 3 Margin Recommended for Primary Shielded Dose Rate Calculation

- 2.7 margin recommended for laminated barriers by NCRP 151
  - Based McGinley & Butker (1994)
  - Attributed to capture gammas
- Safety survey vs. calculated dose rate indicates factor 2 to 3 appropriate for all primary barriers
  - Likely due to variation in concrete density, not capture gammas
  - 2.7 recommended by NCRP 151 for laminated barriers is appropriate goal for all barriers

McGinley & Butker (1994) Data			
	Photon Dose Equivalent Rate (nSv/s)		
Line	Calculated	Measured	Meas / Calc
a	27.5	55.6	2.0
b	3.3	3.3	1.0
c	11.6	31.1	2.7
d	1.9	1.9	1.0
e	108.3	244.0	2.3
f	5.9	6.7	1.1

Barriers with concrete only			Shielded Dose (mSv/wk)		
Line	Protected Location	P/T	Calc	Meas	Ratio
a	Toilet	0.080	0.042	0.009	0.2
b	Toilet	0.080	0.037	0.069	1.9
c	Adjacent Vault	0.100	0.031	0.024	0.8
d	Adjacent Vault	0.100	0.034	0.031	0.9
e	Adjacent Vault	0.100	0.031	0.031	1.0
f	Adjacent Vault	0.100	0.022	0.042	1.9
g	Adjacent Vault	0.100	0.039	0.100	2.6
h	Exterior Wall	0.165	0.115	0.115	1.0
i	Exterior Wall	0.165	0.034	0.069	2.1
j	Exterior Wall	0.165	0.031	0.076	2.5
k	Ceiling	0.320	0.136	0.122	0.9

Laminated Barriers			Shielded Dose (mSv/wk)		
Line	Protected Location	P/T	Calc	Meas	Ratio
a	Office	0.020	0.006	0.003	0.5
b	Ceiling	0.320	0.008	0.005	0.7
c	Ceiling	0.320	0.118	0.139	1.2

Directly Solving for Barrier Thickness

- NCRP 151 typically illustrates calculations by solving for the required thickness instead of directly calculating time-average dose rate
- Transmission factor B_{pri}
  - Reciprocal of required attenuation

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

- Number of tenth-value layers (TVLs): $n = -\log_{10}(B_{pri})$
- Required barrier thickness

$$t_c = TVL_1 + (n-1)\, TVL_e$$

“Two Source Rule”

- Applicable when required thickness is calculated for more than one type of radiation
- If thickness required is comparable for two type of radiation, add 1 HVL to the larger thickness
- If the two thicknesses differ by a tenth-value-layer (TVL) or more, the larger barrier thickness is used
- Also sometimes called the “Add HVL Rule”

Examples Use Time Averaged Dose Rate Instead of Calculating Thickness

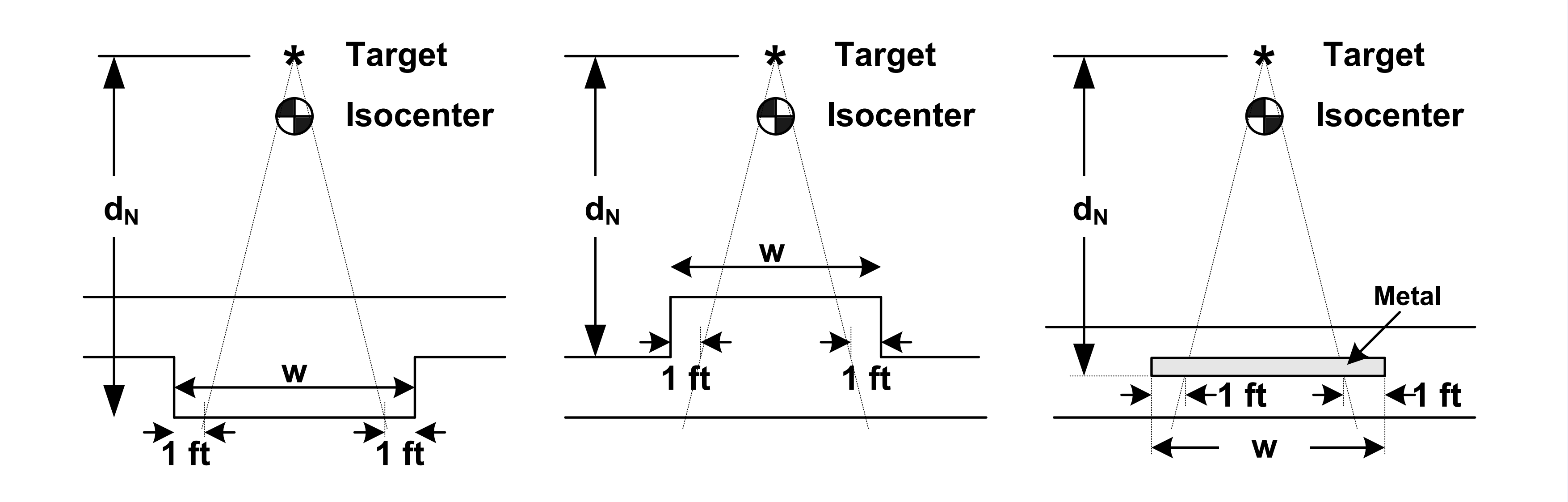
- **Two Source Rule either over-estimates or under-estimates required shielding for two or more sources of radiation**
- **Up to three types of radiation for secondary calculations**
- **TADR must be calculated anyway for primary barriers**
  - **To determine factor of 2.7 margin**
  - **TADR needed for hourly limit**
- **Potentially multiple layers of dissimilar material in barrier**
- **No direct way to calculate required thickness for photoneutron generation**

Primary Barrier Width

- 1 foot margin on each side of beam rotated 45 degrees
  - Barrier width required assuming 40 cm x 40 cm field size

$$w = 0.4\sqrt{2}\, d_N + 0.6 \ \ m \qquad \text{(where } d_N \text{ is in meters)}$$

- Field typically not perfectly square (corners are clipped)
  - 35 cm x 35 cm field size used to account for this



Primary Barrier Width Typically Calculated Assuming 35 cm x 35 cm Field Size

- **Field typically not perfectly square (corners are clipped)**
  - **35 cm x 35 cm field size used to account for this**

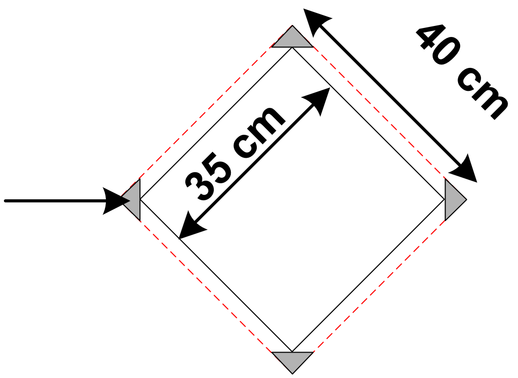
$$W = 0.35\sqrt{2}\,d_N + 0.6 \;\; m$$

(where d_N is in meters)

40 cm x 40 cm field

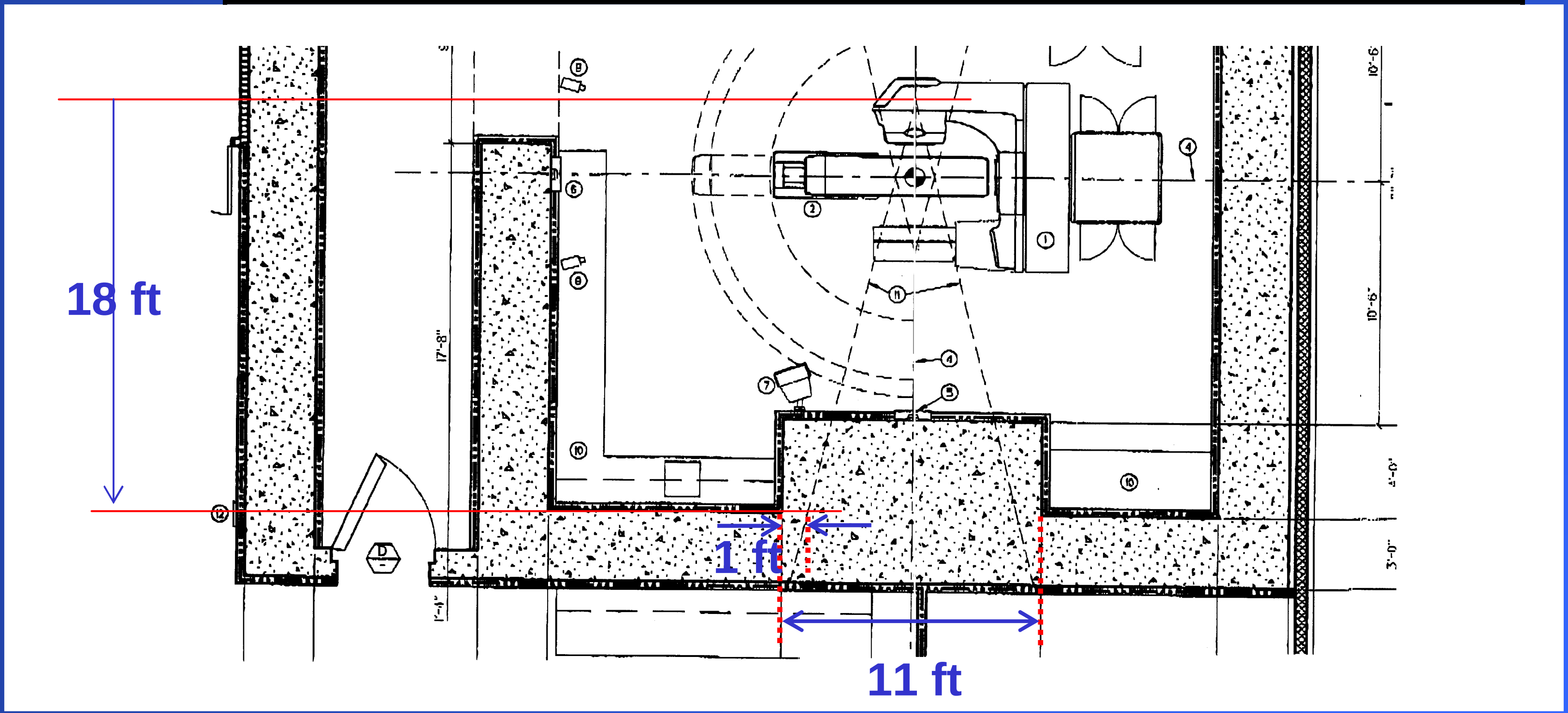
Corners clipped with tungsten block

35 cm effective field size (f)



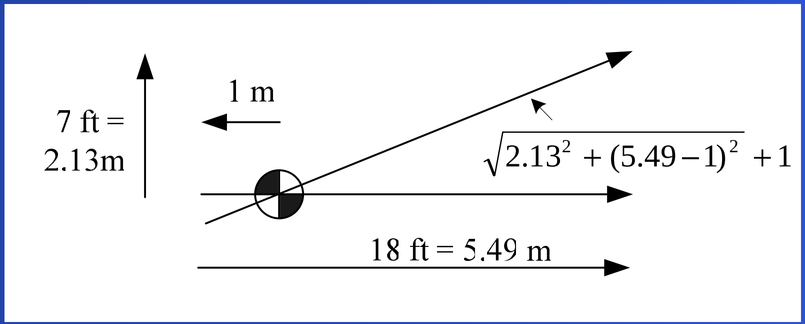
Example 2a. Traditional Primary Barrier Minimum Width

Line	Parameter	Units	Value	Calculation
a	Target to Narrow Point	ft	18	
b	Target to Narrow Point	m	5.49	a * 0.3048
c	Effective field size (corners)	cm	35	
d	Max Field Diameter	m	2.72	b * sqrt(2) * c / 100
e	Max Field Diameter	ft	8.9	d / 0.3048
f	Minimum Barrier Width	ft	10.9	e + 2 ft
g	Recommended Width	ft	11	



Example 2b. Recommended Primary Barrier Minimum Width in NCRP 151

- NCRP 151 recommends calculating barrier width at top of primary barrier
  - Requires ~ 1 ft increase in primary barrier width compared to traditional calculation in Example 2a.
  - Appropriate for new construction
  - Perhaps inappropriate for retrofit to existing vault
    - » Especially for ceiling or exterior wall with no occupancy above ceiling



Line	Parameter	Units	Value	Calculation
a	Distance from target to narrow point	ft	18	
b		m	5.49	a * 0.3048
c	Effective field size (corners)	cm	35	
d	Distance from isocenter to ceiling	ft	7	
e		m	2.13	d * 0.3048
f	Target to top of narrow point	m	5.97	sqrt(e^2+(b-1)^2) +1
g	Maximum Field Diameter	m	2.95	f * sqrt(2) * c / 100
h		ft	9.7	g / 0.3048
i	Minimum Barrier Width	ft	11.7	h + 2 ft
j	Recommended Width	ft	12	

Secondary Barrier Photon Leakage

- Leakage unshielded dose rate

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

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

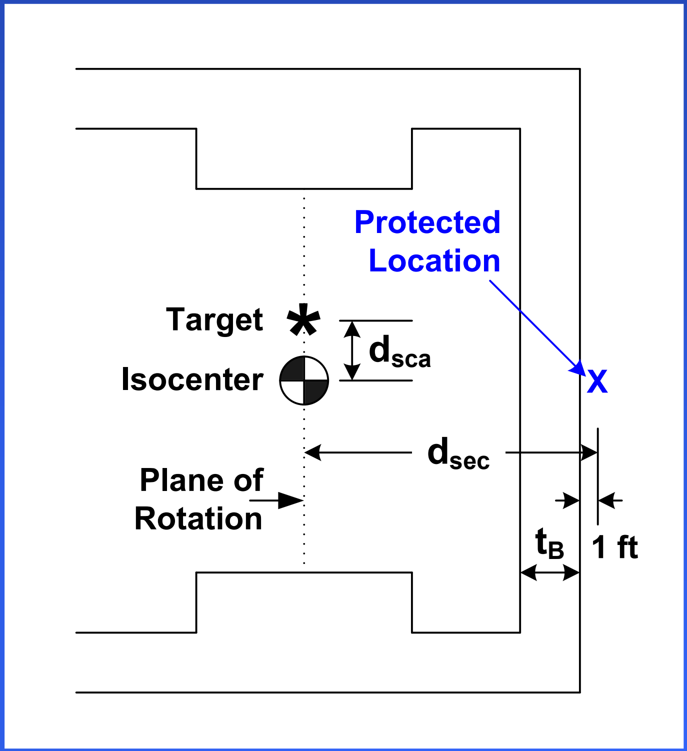


Table 2: Leakage TVLs (mm)

Linac MV	Lead		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
TVL ratio
relative
concrete

Est. by density vs. concrete

concrete = 2.35 g / cm^3 [NCRP 151, p. 69]

earth density =1.5 g / cm^3 [NCRP 151, p. 72]

BPE = 0.95 g / cm^3 [NCRP 151, p. 162]

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

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

Conservative Leakage TVL for Steel: 96 mm

- Leakage TVLs from Varian Document #12004
  - Concrete leakage TVLs slightly less than NCRP 151
  - Steel TVL calculated from ratio in Varian Document

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

From http://www.varian.com/shared/oncy/pdf/12004.pdf

- Varian ratio applied to NCRP 151 concrete leakage TVLs
  - Average TVL = $(TVL_1 + 2\ TVL_e)/3$
    - » Secondary barrier has at least 3 TVLs

MV	Concrete		Varian	Steel Calculated		
	TVL_1	TVL_e	Ratio	TVL_1	TVL_e	TVL Ave
6	340	290	3.2	106	91	96
10	350	310	3.5	100	89	92
15	360	330	3.7	97	89	92
18	360	340	3.7	97	92	94
25	370	350	4	93	88	89

  - Average TVL between 89 and 96 mm
    - » Calculated TVL varies since concrete TVLs rounded to cm
  - 96 mm upper bound steel leakage TVL

Leakage TVLs from 2007 Summer School*

Tenth Value Layers

Primary TVLs (cm)*

Energy (MV)	4	6	10	15	18	20
Concrete	35(30)	37(33)	41(37)	44(41)	45(53)	46(44)
Steel	9.9	10	11	11	11	11
Lead	5.7	5.7	5.7	5.7	5.7	5.7

Leakage TVLs (90°)*

Energy (MV)	4	6	10	15	18	20
Concrete	33(28)	34(29)	35(31)	36(33)	36(34)	36(34)
Steel**		8	8.5	8.7	8.7	
Lead**		4.5	4.6	4.7	4.7	

* *First term is 1st TVL and term in brackets is for all other TVLs. Data from NCRP #151*

** *Data from McGinley*

AAPM Summer School – July 28, 2007

* Peter Biggs, *Primary & Secondary Composite Wall Materials*, 2007 AAPM Summer School (Slide # 4)

- **Caution: Pat McGinley at 2007 AAPM Summer School used a lead leakage TVL of 6.1 cm for a direct-shielded door example (not the 4.7 cm TVL above)**

Table 2 lead & steel TVLs may be somewhat conservative

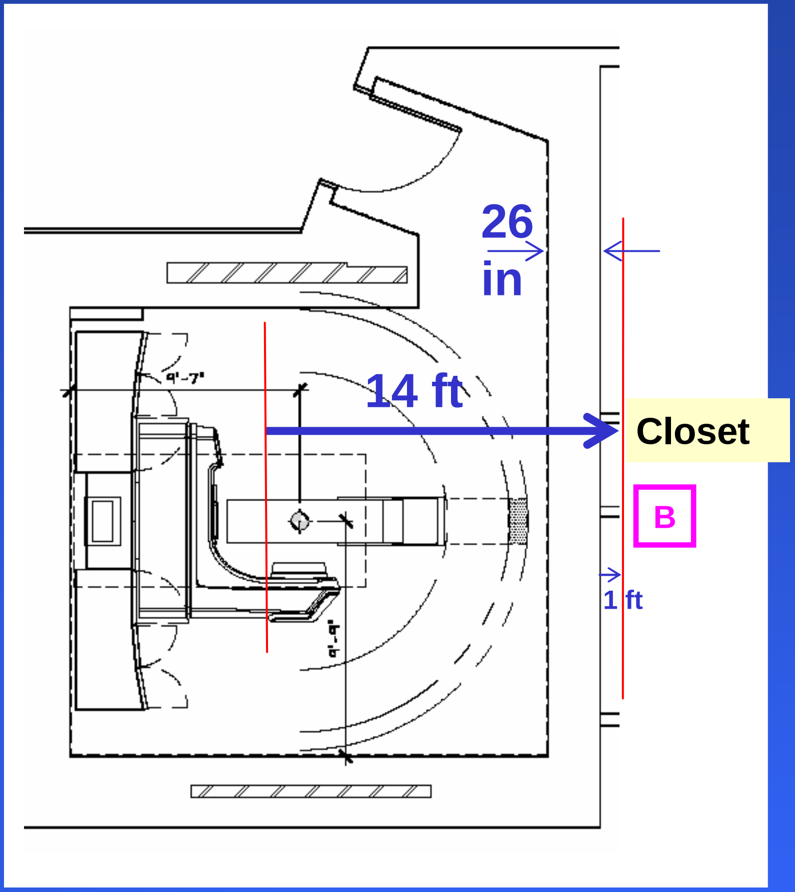
Example 3: 6 MV Secondary Barrier Leakage (Existing Construction)

1. **Establish P/T for protected location:**
   - Uncontrolled location P = 0.02 mSv/wk
   - Low occupancy location (closet)
     - » T = 0.05
   - P/T = 0.400

2. **Measure distance from isocenter to protected location**
   - 14 ft from isocenter to 1 ft beyond wall

3. **Measure (or read from annotations) the barrier material thickness (26 in)**

4. **Low usage facility in small town justifies lower than typical workload**
   - 25 patients per day at 3 Gy/treatment
   - Yields 375 Gy/wk vs. 450 Gy/wk typical assumption
   - IMRT not available at facility



5. **Calculate unshielded dose rate, transmission, & shielded dose rate**

(add or increase material until shielded dose rate < P/T)

Example 3: Leakage Calculation (Existing Construction)

Line	Parameter	Units	Value	Calculation
a	Workload / Treatment	Gy/pt	3	Default value
b	Patients per Day	pt/day	25	Anticipated
c	Workload (W)	Gy/wk	375	5 * a * b
d	Use Factor	Ratio	1	
e	Leakage Fraction	Ratio	1.0E-03	
f	Isocenter to Protected Point Distance	ft	13.5	
g		m	4.11	f * 0.3048
h	Unshielded Dose	mSv/wk	2.21E+01	1000 *c *d *e / g^2
i	Transmission		7.86E-03	see below
j	Shielded Dose	mSv/wk	0.174	h * i

0.174 mSv is less than P/T = 0.400 mSv/wk

Barrier	Material Thickness		Material	X-Ray Leakage		Photon Trans.
	inches	mm		TVL1 (mm)	TVLe (mm)	
Inside Layer	26	660	Concrete	340	290	7.86E-03
Layer #2						1.00E+00
Layer #3						1.00E+00
Layer #4						1.00E+00
Outside Layer						1.00E+00
				6 MV	Total:	7.86E-03

Photon transmission through concrete = 0.1 * 10^[-(660 - 340)/ 290)] = 7.86E-3

Intensity Modulated Radiation Therapy (IMRT)

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

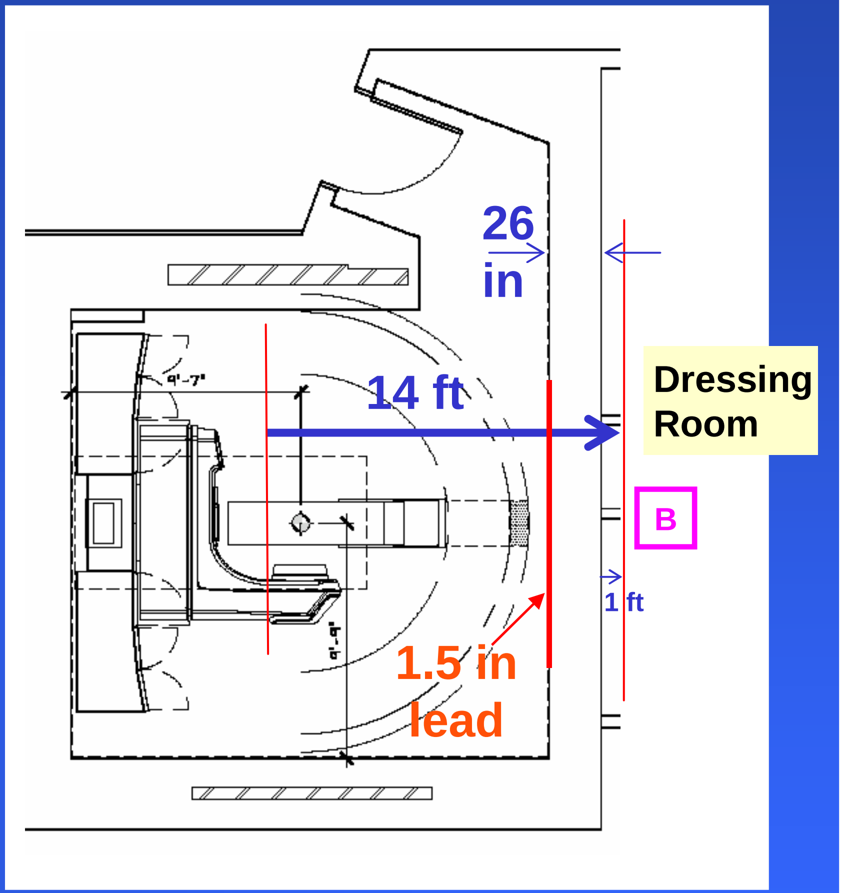
Table 3: IMRT Ratio Typical Values

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

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

Example 4: 6 MV Additional Shielding with IMRT

1. Establish P/T for protected location
   - Dressing room uncontrolled with partial occupancy (T=0.2)
   - P/T = 0.10 mSv/wk
2. Measure distance from target to protected location
   - 14 ft from target to 1 ft beyond wall
3. Measure (or read from annotations) the barrier material thickness (26 in)
4. IMRT factor 2
   - 50% IMRT workload with IMRT ratio 3
5. Facility expects increased usage
   - Default 30 patients per day assumed vs. 25
6. Add additional lead to barrier until shielded dose rate is less than P/T
   - Can be either inside or outside wall for secondary barrier



IMRT Factor Calculation

- Calculation for single MV

Line	Parameter	Units	Single MV	Calculation
a	IMRT Ratio	MU/cGy	3	Varian
b	Fraction with IMRT	Ratio	0.5	Typical
c	IMRT Factor	Ratio	2	a * b + (1 - b)

- Calculation for dual MV
  - Shielded dose rate calculated separately at each MV
    - Including appropriate % IMRT at each MV
  - Total shielded dose rate is total at the separate MVs
  - Generally appropriate only for retrofit
    - marginal shielding, expensive and difficult to modify
    - Calculation at single (highest) MV recommended for new construction

Example 4: Leakage Calculation with IMRT

Line	Parameter	Units	Value	Calculation
a	Workload / Treatment	Gy/pt	3	Default value
b	Patients per Day	pt/day	30	Default value
c	Workload (W)	Gy/wk	450	a * b
d	Use Factor	Ratio	1	
e	Leakage Fraction	Ratio	1.0E-03	
f	IMRT Factor		2	
g	Isocenter to Protected Point Distance	ft	13.5	
h		m	4.1	g * 0.3048
i	Unshielded Dose	mSv/wk	5.32E+01	1000*c*d*e*f/h^2
j	Transmission		1.29E-03	see below
k	Shielded Dose	mSv/wk	0.069	i * j

0.069 mSv is less than P/T = 0.10 mSv/wk

Barrier	Material Thickness		Material	X-Ray Leakage		Photon Trans.
	inches	mm		TVL1 (mm)	TVLe (mm)	
Inside Layer	1.5	38	Lead	57	57	2.15E-01
Layer #2	26	660	Concrete	340	290	6.02E-03
Outside Layer						1.00E+00
				6 MV	Total:	1.29E-03

1.5" additional lead

Photon transmission through lead = 10^(-38 / 57) = 0.215 **340* (1 - 38/57) = 113**

Photon transmission through concrete = 10^(-113 / 340) * 10^[-(660 – 113) / 290)] = 6.0 E-3

Total transmission = transmission through lead x transmission through concrete

Secondary Shielding for High Energy Linacs

- May need to consider neutron leakage as well as photons
  - Not necessary if barrier consists solely of concrete
  - Is necessary for thin barrier containing significant metal
    - » e.g., door or laminated barrier
- Calculation is of the same form as photon leakage calculation
  - But with different leakage fraction and TVLs
- Shielding typically calculated only at higher energy for dual energy linacs
  - Easier calculation than performing separate calculations for the two energies

Neutron IMRT Factor Calculation

- **IMRT factor lower for neutrons than photons for dual MV**
  - Typically split between low and high energy for dual MV machine
  - Neutrons not produced below 10 MV
- **Typical: 50% High-X & 50% Low-X with 50% IMRT at each MV**
  - Conservative since far more IMRT at 6 MV than at 15 or 18 MV
  - Neutron IMRT factor 1 with these conservative assumptions
- **Neutron Leakage Workload:** $W_{Ln} = W \times$ Neutron IMRT Factor

			Photon		Neutron		
Line	Parameter	Units	Low-X	High-X	Low-X	High-X	Calculation
a	IMRT Ratio	MU/cGy	3	3	0	3	Varian
b	Fraction with IMRT	Ratio	0.5	0.5	0.5	0.5	Typical
c	IMRT Factor per MV	Ratio	2	2	0	2	a * b + (1 - b)
d	Fraction at each MV	Ratio	0.5	0.5	0.5	0.5	Expected usage
e	IMRT Factor * Fraction	Ratio	1	1	0	1	c * d
f	IMRT Factor	Ratio	2		1		Sum Line e

NCRP 151 Neutron Leakage

- Neutron leakage unshielded dose rate

$$H_n = \frac{W_{Ln} \times H_o}{(d_{\sec} / 1.41)^2}$$

  - H_n in Sv and W_{Ln} in Gy
  - dsec is secondary distance from isocenter to protection location (in meters)
- H_o from Table B.9 of NCRP 151
  - Normalized at 1.41 meters from isocenter
  - Leakage data in NCRP 151 is for older machines
  - Best to use manufacturers' data for newer machines (next chart)

NCRP 151 Table B.9

Vendor	Model	MV	Ho @1.41 m mSv/Gy
Varian	1800	18	1.02 to 1.6
	1800	15	0.79 to 1.3
	1800	10	0.04
	2100C	18	
	2300CD	18	
	2500	24	
Siemens	KD	20	1.1 to 1.24
	KD	18	
	MD	15	0.17
	MD2	10	
	Primus	10	
	Primus	15	
Philips/ Elekta	SL25	25	2
	SL20	20	0.44
	SL20	18	
	SL25	18	
GE	Saturne41	12	0.09
	Saturne41	15	0.32
	Saturne43	18	0.55
	Saturne43	25	1.38

Table 4: Neutron Leakage Fraction

- **Neutron leakage unshielded dose rate**

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

  - H_n in Sv and W_{Ln} in Gy
  - H_0 is neutron leakage dose equivalent fraction normalized to 1 m from target

- **H_o in Table 4 normalized to 1 m**
  - Varian* and Siemens** values based on manufacturer data
  - Elekta data from Site Planning Guide***
  - GE data based on NCRP 151 Table B.9 normalized to 1 m

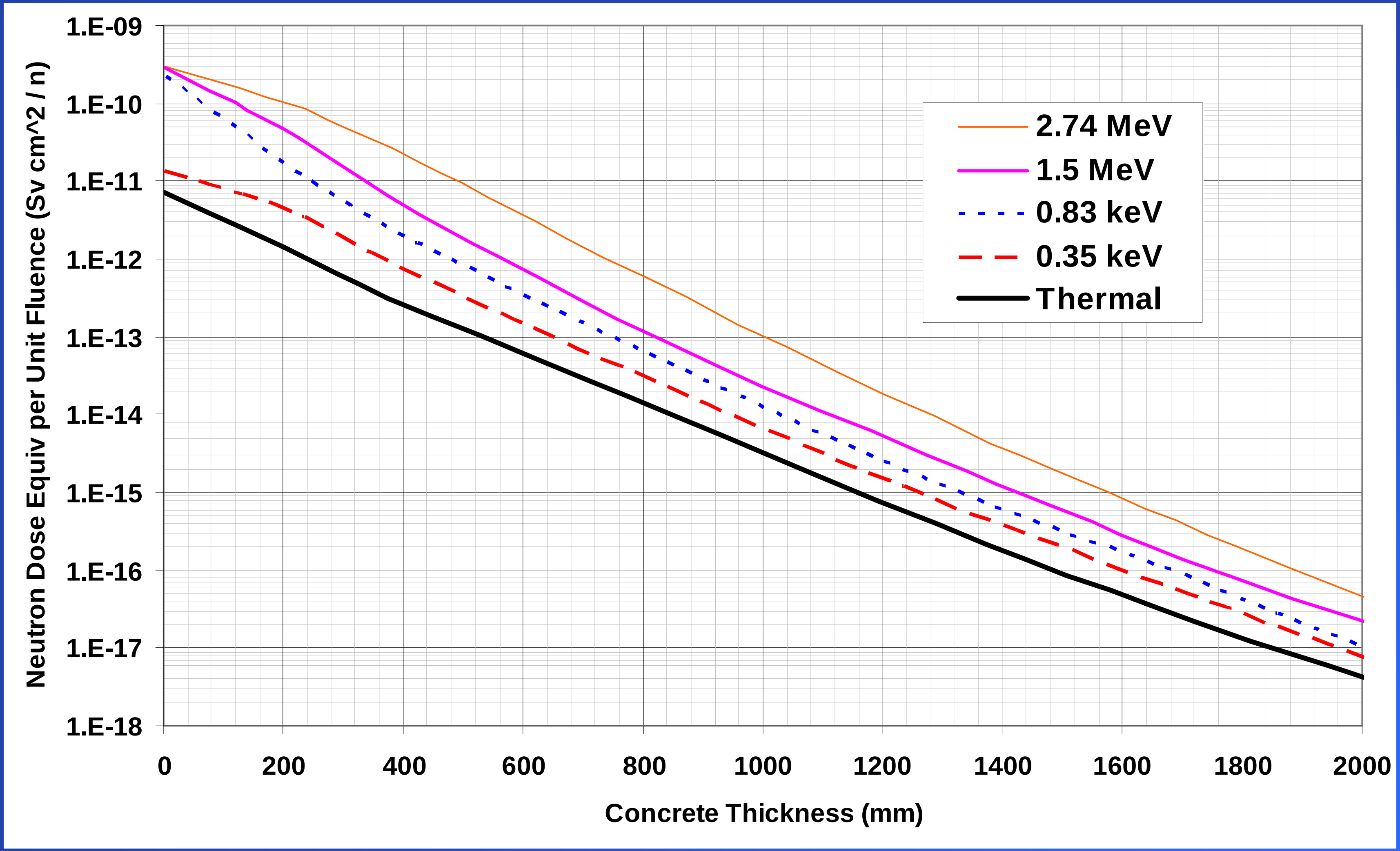
Vendor	MV	Ho @1 m Sv/Gy
Varian	10	4.0E-05
	15	7.0E-04
	18	1.5E-03
	20	1.9E-03
	24	2.0E-03
Siemens	10	2.0E-05
	15	4.2E-04
	18	9.9E-04
	20	1.4E-03
	24	2.3E-03
Elekta / Philips	10	3.0E-04
	15	7.0E-04
	18	1.5E-03
	20	2.0E-03
	24	3.0E-03
GE	12	1.8E-04
	15	6.4E-04
	18	1.1E-03
	25	2.7E-03

* Varian: http://www.varian.com/osup/pdf/12000.pdf [Page 12, Average of 4 positions]

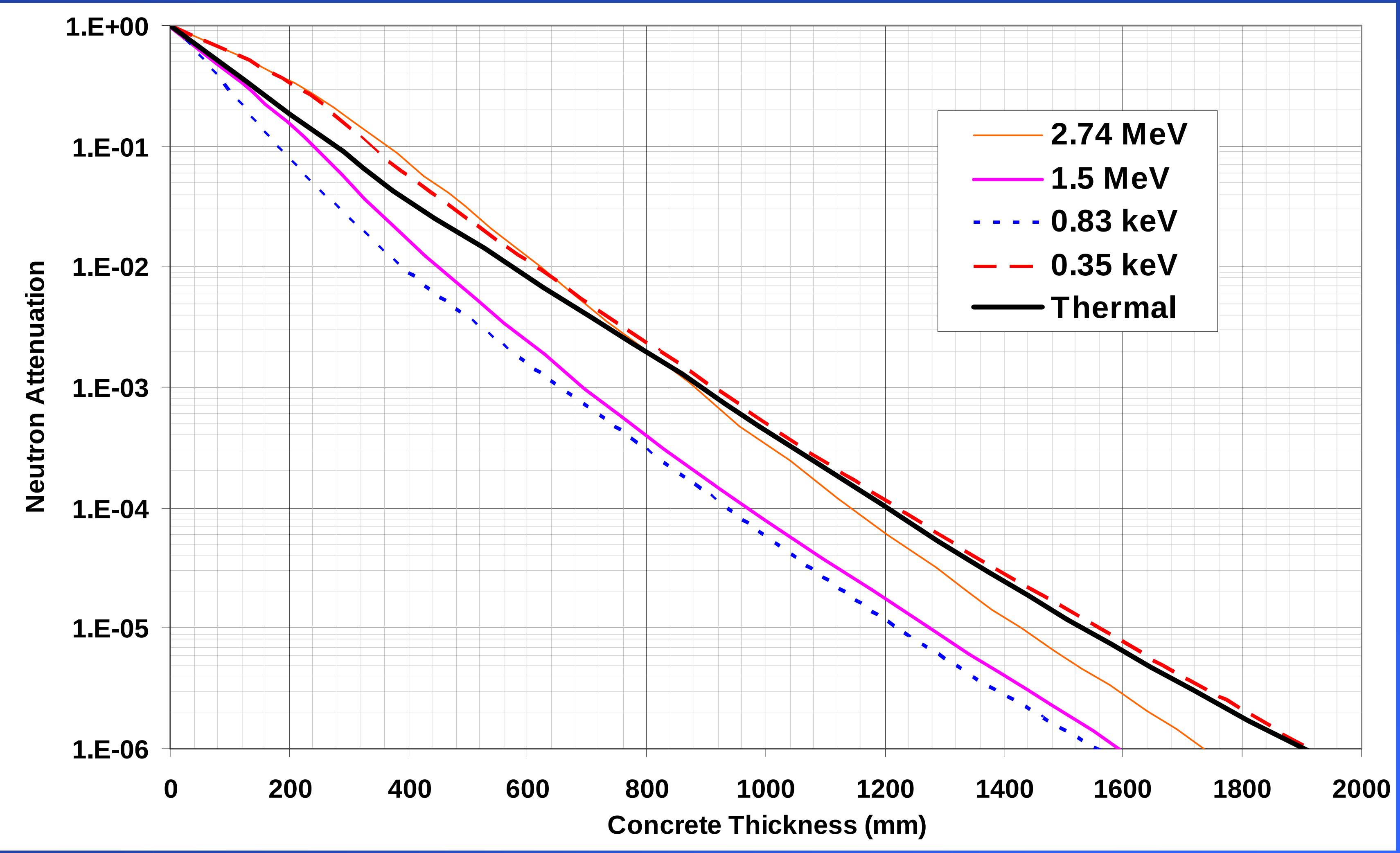
** Siemens: Conservative neutron leakage dose rates in patient plane with Q=10

*** Elekta: Nisy Ipe, "*Neutron Shielding Design and Evaluations*", 2007 AAPM Summer School

NCRP 151 Cites Figure A.2 (from NCRP 51) as Basis for Neutron TVL



NCRP 151 Figure A.2
Normalized to Maximum Fluence



Neutron Leakage TVL Recommendation

- TVLs based on Figure A.2 are somewhat inconsistent
  - Curves originally in NCRP 51

TVL #	Cummulative Concrete Neutron TVLs				
	Thermal	0.35 keV	0.83 keV	1.5 MeV	2.7 MeV
1	277	337	176	246	367
2	288	307	193	226	312
3	298	304	217	232	295
4	301	305	232	243	286
5	307	312	243	256	286

- NCRP 151 recommends 250 mm as "conservatively safe estimate of the TVL_n"

Recommendation for laminated primary barriers, neutron leakage not specifically addressed

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

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

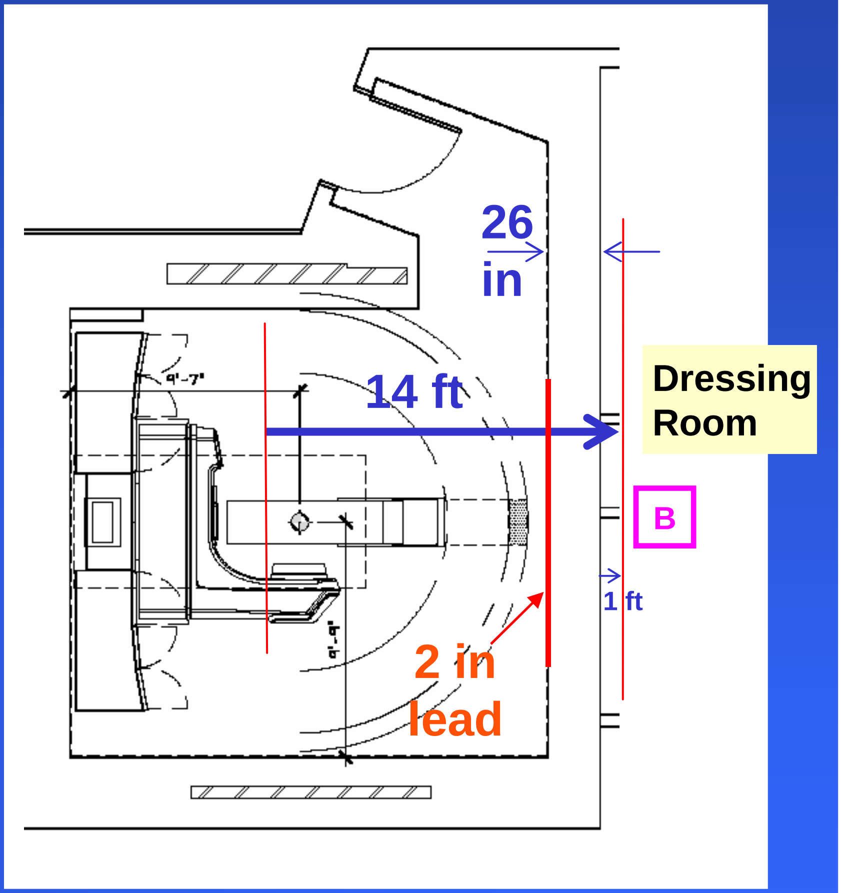
Continuing to use the NCRP 79 neutron leakage TVLs is recommended

Neutron TVLs for Other Material

- Concrete of varying density
  - Neutron density for high density concrete assumed the same as for normal weight concrete
    - High density concrete has slightly lower hydrogen content than normal concrete
    - High density concrete typically has boron added to maintain same neutron TVL as normal concrete
  - TVL for light concrete adjusted based on density like photon TVL
    - » Likely a conservative assumption
- Asphalt has high hydrogen content
  - Same TVL as borated polyethylene assumed
    - » e.g., McGinley reports 10 cm neutron skyshine TVL due to asphalt, which is comparable to primary BPE TVL

Example 5: 15 MV Secondary Barrier Photon & Neutron Leakage (Additional Shielding)

1. Establish P/T (0.10 mSv/wk)
2. Isocenter to protected location distance
   – 14 ft from target to 1 ft beyond wall
3. Existing barrier 26 in concrete
4. IMRT factor 2 for photons, 1 neutrons
   – Most IMRT is performed at 6 MV energy
5. Default 450 Gy/wk workload
6. Calculate unshielded dose rate, transmission, and shielded dose rate
7. Add additional lead to barrier until shielded dose rate is less than P/T
   – 2” lead added to inside of barrier
   – Can be outside if space inadequate inside
      – No photoneutron generation for lead in secondary barriers



Example 5: 15 MV Secondary Barrier Photon and Neutron Leakage Calculation

Line	Parameter	Units	Photon Leakage	Neutron Leakage	Calculation
a	Workload / Treatment	Gy/pt	3	3	Default value
b	Patients per Day	pt/day	30	30	Default value
c	Workload (W)	Gy/wk	450	450	5 * a * b
d	Use Factor	Ratio	1	1	
e	Leakage Fraction	Ratio	1.0E-03	7.0E-04	15 MV values
f	IMRT Factor		2	1	
g	Isocenter to Protected Point Distance	ft	13.5	13.5	
h		m	4.1	4.1	g * 0.3048
i	Unshielded Dose	mSv/wk	5.32E+01	1.86E+01	1000*c*d*e*f/h^2
j	Transmission		1.31E-03	7.42E-04	see below
k	Shielded Dose	mSv/wk	0.070	0.014	i * j
L	Total Shielded Dose	mSv/wk	0.083		Sum row k

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

Barrier	Material Thickness		Material	X-Ray Leakage		Photon Trans.	Neutron TVL (mm)	Neutron Trans.
	inches	mm		TVL1 (mm)	TVLe (mm)			
Inside Layer	2	51	Lead	57	57	1.28E-01	N/A	1.00E+00
Layer #2	26	660	Concrete	360	330	1.02E-02	211	7.42E-04
Outside Layer						1.00E+00		1.00E+00
				15 MV	Total:	1.31E-03	Total:	7.42E-04

2" additional lead

Neutron leakage calculation similar in form to photon leakage calculation, except using different leakage fraction and TVLs

Secondary Barrier Patient Scatter

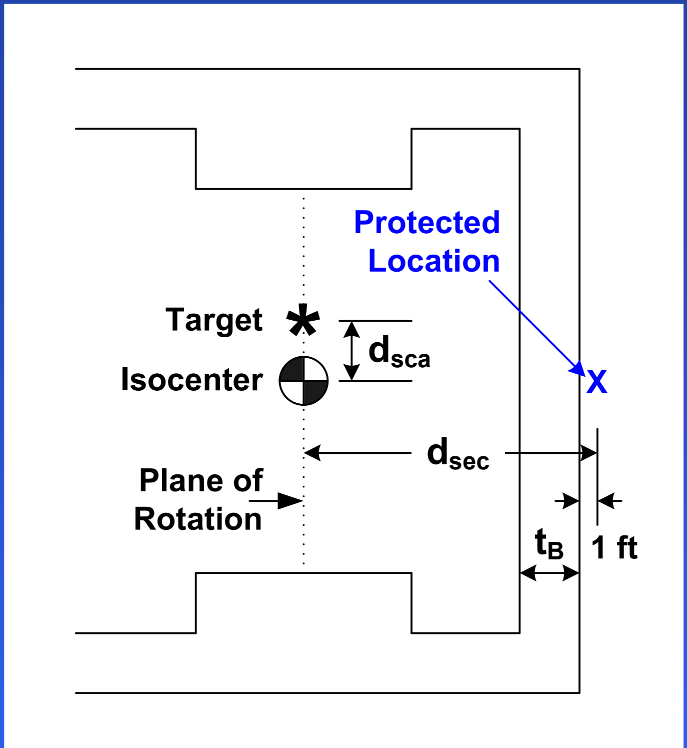
- **Patient scatter unshielded dose rate**

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

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

  F = (1-% IMRT) × 1600 + % IMRT × 225

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



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

Use Factor (U) and Scatter

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

Table 5: NCRP 151 Table B.4
Patient Scatter Fraction for 400 cm^2 Field

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

Linac 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

NCRP 151 Table B.6: Patient Scatter Energy

- Based on simulation by Taylor et.al. (1999)

MV	Scatter Angle (degrees)							
	0	10	20	30	40	50	70	90
6	1.6	1.4	1.2	0.9	0.7	0.5	0.4	0.25
10	2.7	2.0	1.3	1.0	0.7	0.5	0.4	0.25
18	5.0	3.2	2.1	1.3	0.9	0.6	0.4	0.3
24	5.6	3.9	2.7	1.7	1.1	0.8	0.5	0.3

0.2 MV in NCRP 151. but 0.25 in Taylor et.al.

Scatter TVL Recommendations from NCRP 151

- **Concrete TVL: NCRP 151 Table B.5a**
  - Same values in 1976 NCRP 49 report
  - "Values ... are <u>conservatively safe in nature</u>"

Conservative

- **Lead scatter TVL: NCRP 151 Table B.5b (Nogueira and Biggs -- 2002)**
  - Most accurate scatter TVLs in NCRP 151
    - » Measurements and simulation in close agreement
  - For up to 10 MV and scatter angles ≥ 30º

Accurate but limited

- **All other TVLs: NCRP 151 Figure A.1**
  - Curves of equilibrium TVLs of shielding materials
  - NCRP 151 recommends using TVL corresponding to mean energy from NCRP 151 Table B6
    - » Modifying the mean energy is recommended here

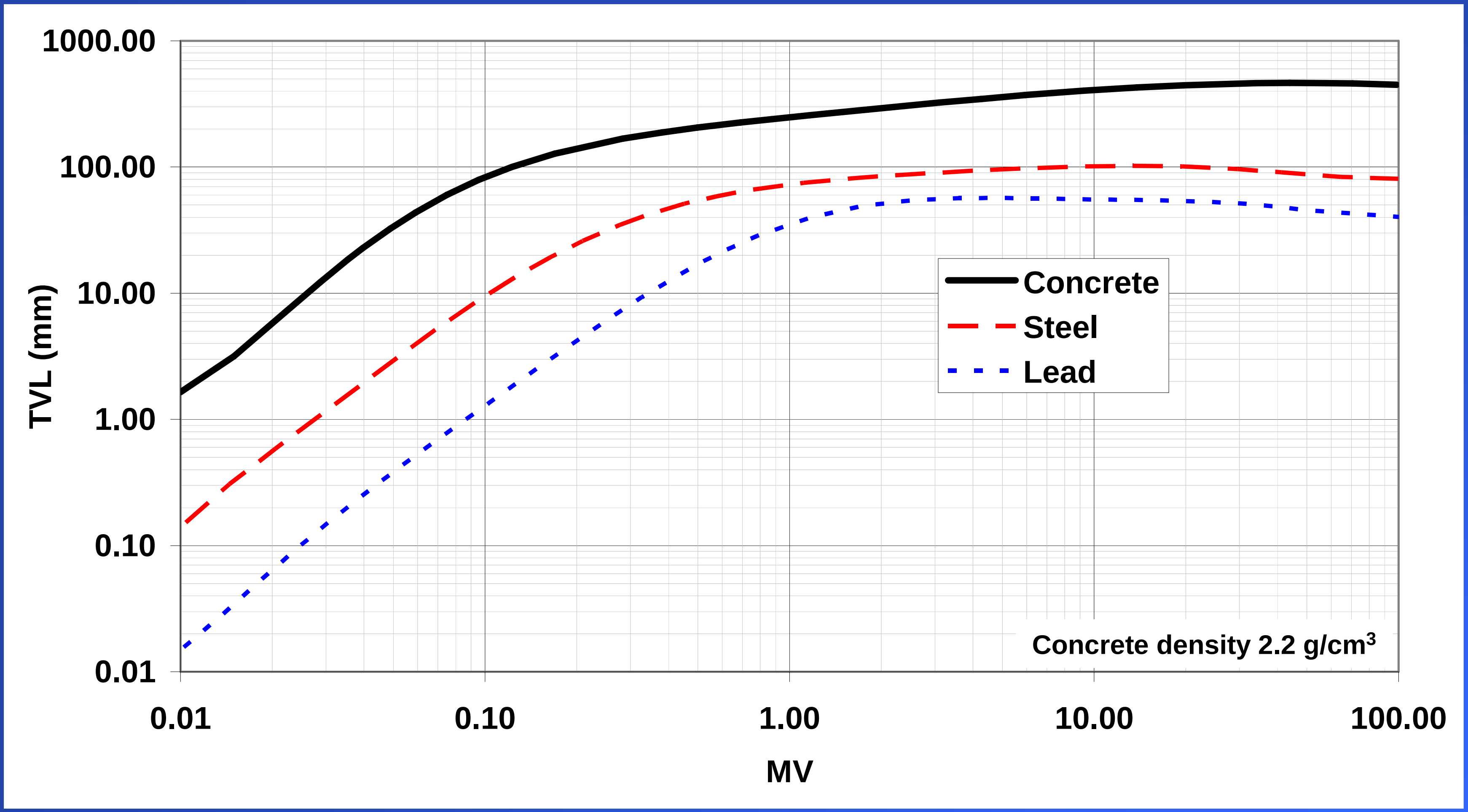
Rosetta Stone

Table 6a. Concrete Scatter TVLs

- Values directly from NCRP 151 Table B5.a
- Conservative at scatter angles less than 30º
  - Compared to lead and steel scatter TVLs

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

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



Lead Scatter TVL Recommendations Based on NCRP 151 [1 of 2]

- **NCRP 151 Table B.5b is the most reliable TVL data**

Lead scatter tenth-value layers (mm) vs. scatter angle										
	30		45		60		75		90	
MV	TVL1	TVLe	TVL1	TVLe	TVL1	TVLe	TVL1	TVLe	TVL1	TVLe
4	33	37	24	31	18	25	13	19	9	13
6	38	44	28	34	19	26	14	19	10	15
10	43	45	31	36	21	27	15	19	12	16

- **First step: reconcile NCRP 151 Figure A.1 (broad beam transmission curves) with Table B.5b**
  - TVLs in Table B.5b do not match NCRP 151 Figure A.1 using mean energy from NCRP 151 Table B.6
  - Equilibrium TVLs match if mean energy is multiplied by following adjustment factors

Broad Beam Energy Adjustment Factors					
MV	30	45	60	75	90
4	1.16	1.41	1.51	1.49	1.66
6	1.53	1.57	1.57	1.49	1.83
10	1.44	1.68	1.63	1.49	1.91

Lead Scatter TVL Recommendations Based on NCRP 151 [2 of 2]

- Step 2: Select appropriate broad beam energy adjustments for other MVs

Broad Beam Energy Adjustment Factors						
MV	20	30	45	60	75	90
4	1.2	1.16	1.41	1.51	1.49	1.66
6	1.5	1.53	1.57	1.57	1.49	1.83
10	1.5	1.44	1.68	1.63	1.49	1.91
15	1.5	1.5	1.7	1.7	1.7	2.0
18	1.5	1.5	1.7	1.7	1.7	2.0
20	1.5	1.5	1.7	1.7	1.7	2.0
25	1.5	1.5	1.7	1.7	1.7	2.0

Adjusted Broad Beam Energy (MV)						
MV	20	30	45	60	75	90
4	1.44	1.04	0.85	0.68	0.54	0.42
6	1.80	1.38	0.94	0.71	0.54	0.46
10	1.95	1.44	1.01	0.73	0.54	0.48
15	2.70	1.78	1.18	0.82	0.63	0.56
18	3.15	1.95	1.28	0.85	0.64	0.60
20	3.45	2.15	1.39	0.94	0.68	0.60
25	4.05	2.55	1.62	1.11	0.77	0.60

- Step 3: Read equilibrium lead TVLs From NCRP 151 Figure A.1 (conservatively use TVLe for TVL1)

Table 6b: Lead Scatter TVLs

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

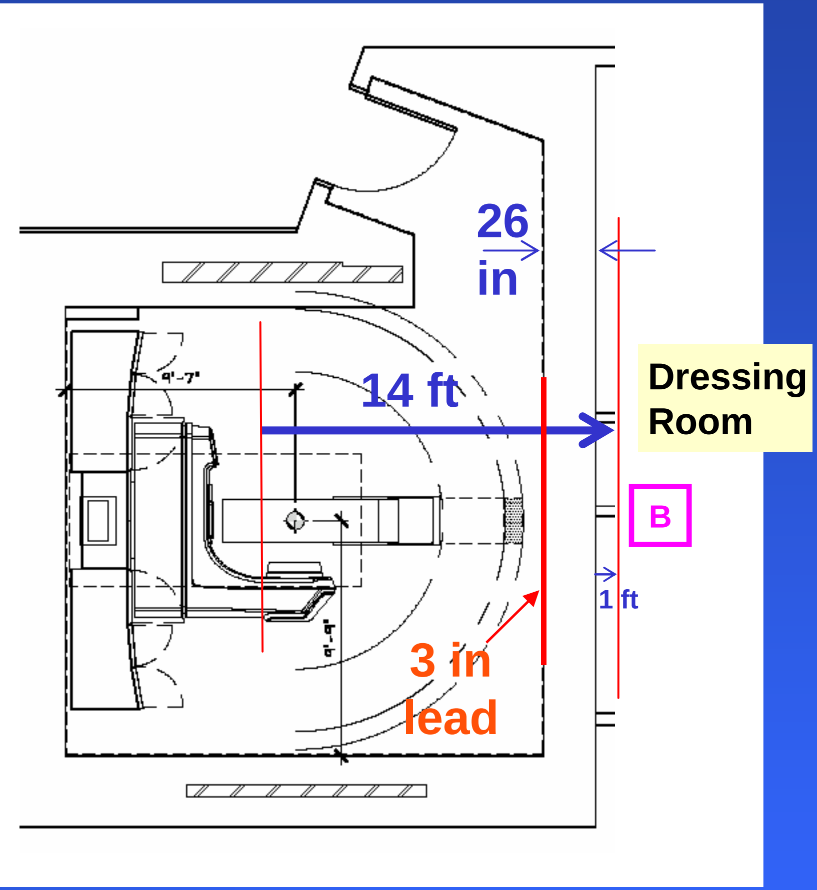
Table 6c. Steel Scatter TVL Recommendations Based on NCRP 151

- **Steel broad beam TVLs that correspond to the lead TVLs**

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

Example 6: 15 MV Secondary Barrier Including Leakage and Scatter

1. Follow same first steps of Example 5 leakage calculation (establish P/T, distances, material thickness & type, IMRT factors)
2. Determine scatter fraction per 400 cm^2 by interpolating scatter fraction as a function of MV and scatter angle (Table 6)
3. Calculate effective field size
4. Determine scatter fraction by adjusting scatter per 400 cm^2 with effective field size
5. Calculate unshielded dose rate
6. Interpolate TVL using Table 7 as a function of machine MV, material type and scatter angle
7. Calculate transmission and shielded dose rate (add or increase material until shielded dose rate < P/T)



Example 6: Secondary Barrier Scatter Fraction Calculation

Line	Parameter	Units	Value	Calculation
a	Design Dose Limit (P)	mSv/wk	0.02	
b	Occupancy Factor (T)		0.2	
c	P/T	mSv/wk	0.100	a / b
d	Machine X-ray Energy	MV	15	
e	Vendor		Varian	

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)
e	Scatter Angle	deg	90		
f	Machine X-ray Energy	MV	15		
g	Scatter / 400 cm^2		2.61E-04		Function of e & f
h	Scatter Fraction		0.00060		g * c / 400

Illustrates using effective field size with 15x15 cm IMRT field

Example 6: Secondary Barrier Shielded Dose Rate Calculation Including Leakage & Scatter

Line	Parameter	Units	Leakage	Scatter	Leakage	Calculation
a	Workload / Treatment	Gy/pt	3	3	3	NCRP 151 Default
b	Patients per Day	pt/day	30	30	30	NCRP 151 Default
c	Workload (W)	Gy/wk	450	450	450	a * b
d	Use Factor	Ratio	1	1	1	
e	Fraction	Ratio	1.0E-03	6.0E-04	7.0E-04	15 MV values
f	IMRT Factor		2	1	1	
g	Isocenter to Protected	ft	13.5	13.5	13.5	
h	Point Distance	m	4.1	4.1	4.1	g * 0.3048
i	Unshielded Dose	mSv/wk	5.32E+01	1.58E+01	1.86E+01	1000*c*d*e*f/h^2
j	Transmission		4.59E-04	5.04E-08	7.42E-04	see below
k	Shielded Dose	mSv/wk	0.024	0.000	0.014	i * j
L	Total Shielded Dose	mSv/wk		0.038		Sum row k

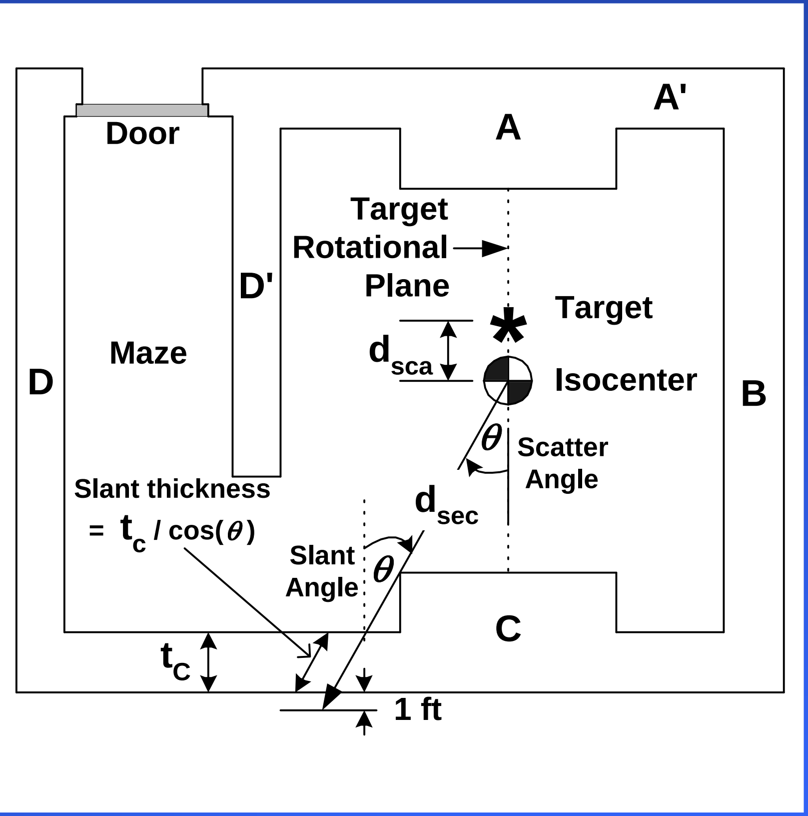
> 0.038 mSv is less than P/T = 0.100 mSv/wk

Barrier	Material Thickness		Material	Photon Leakage			Scatter			Neutron	
	inches	mm		TVL1(mm)	TVLe(mm)	Trans.	TVL1(mm)	TVLe(mm)	Trans.	TVL (mm)	Trans.
Inside Layer	3	76	Lead	57	57	4.60E-02	21	21	2.35E-04	N/A	1.00E+00
Layer #2	26	660	Concrete	N/A	330	9.97E-03	180	180	2.14E-04	211	7.42E-04
Layer #3						1.00E+00			1.00E+00		1.00E+00
Outside Layer						1.00E+00			1.00E+00		1.00E+00
				15 MV	Total:	4.59E-04		Total:	5.04E-08	Total:	7.42E-04

Scatter is typically negligible for lateral secondary barrier, but neutron leakage can be significant

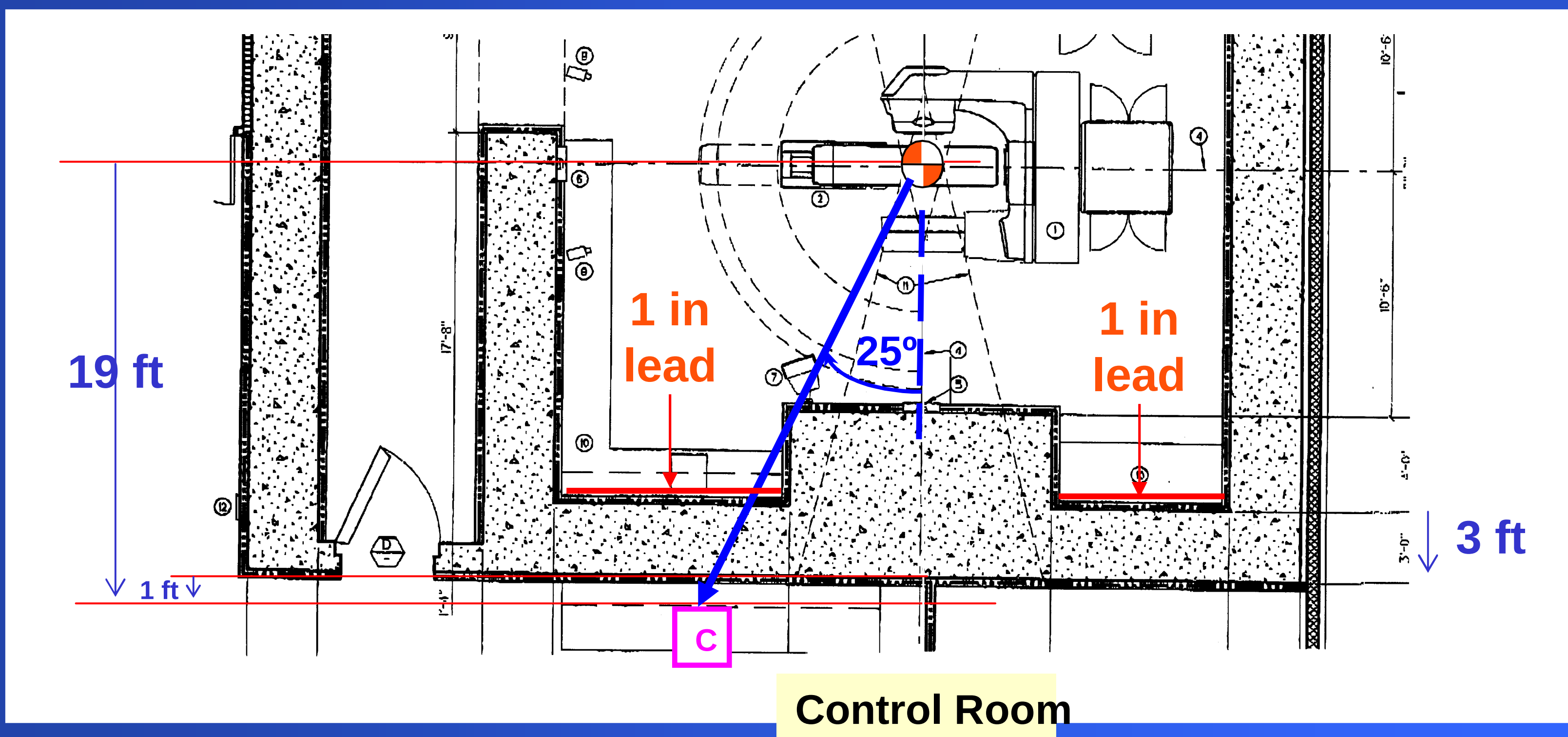
Patient Scatter Can Be Significant Adjacent to Primary Barrier

- Both scatter fraction and scatter energy increase as scatter angle decreases
- Slant thickness compensates for the increased scatter
  - Required barrier thickness reduced by cos(θ), where θ is slant angle
- Barrier thickness comparable to lateral barrier is typically adequate for same P/T



Example 7: Secondary Barrier Adjacent to Primary

1. Establish P/T for protected location C: P/T = 0.1 mSv/wk
2. Distance from isocenter to protected location: 22 ft
3. Secondary barrier 3 ft concrete, slant thickness 3 ft / cos(25º)
4. Calculate scatter fraction based on scatter angle and average field size
5. Calculate shielded dose rate comprised of photon leakage, neutron leakage and scatter using slant thickness for transmission (add material or increase thickness until < P/T)



Example 7: Secondary Barrier Scatter Fraction Calculation

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

Line	Parameter	Units	Value		Calculation
			w/o IMRT	with IMRT	
a	Max Field Size	cm	40	40	
b	Fraction of Workload		50%	50%	
c	Effective Field Area	cm^2	1600.0		b_1*a_1^2 + b_2*a_2^2
d	Effective Field Size	cm	40.0		sqrt (c)
e	Scatter Angle	deg	25		
f	Machine X-ray Energy	MV	18		
g	Scatter / 400 cm^2		3.69E-03		Function of e & f
h	Scatter Fraction		0.01477		g * c / 400

Illustrates using conservative F = 1600 cm^2 field area assumption

Example 7: Secondary Barrier Calculation Including Leakage, Scatter, & Slant Thickness

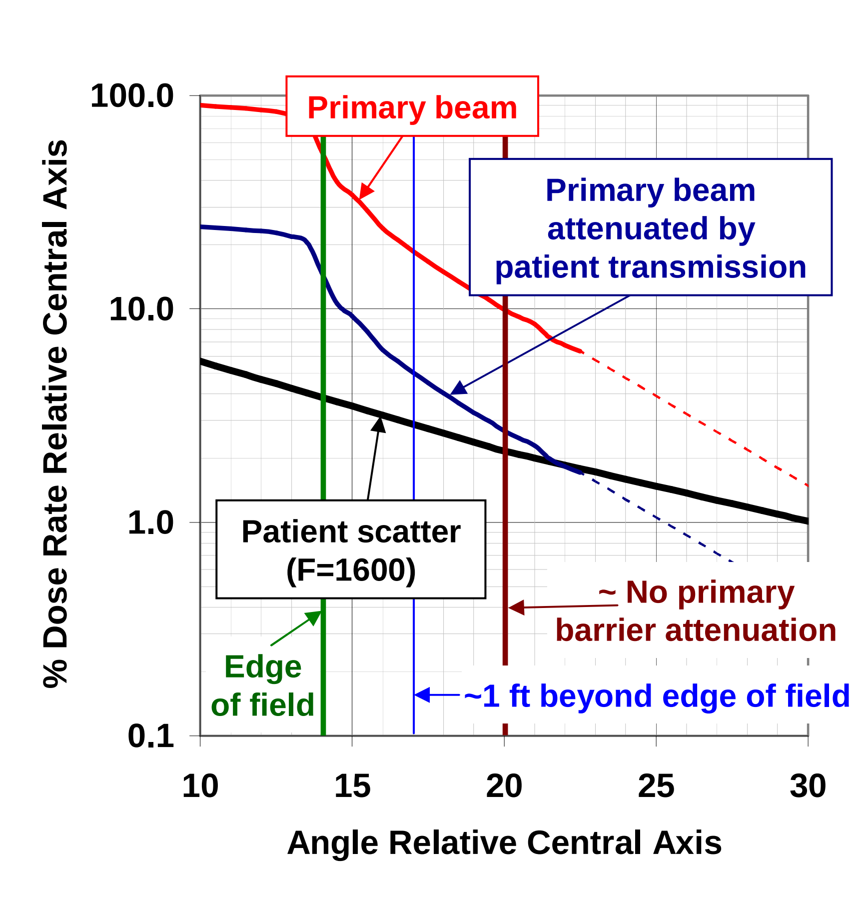
Line	Parameter	Units	Photon Leakage	Photon Scatter	Neutron Leakage	Calculation
a	Workload / Treatment	Gy/pt	3	3	3	NCRP 151 default
b	Patients per Day	pt/day	30	30	30	NCRP 151 default
c	Workload (W)	Gy/wk	450	450	450	a * b
d	Use Factor	Ratio	1	1	1	adjacent to pri barrier
e	Fraction	Ratio	1.0E-03	1.5E-02	1.5E-03	Varian at 18 MV
f	IMRT Factor		2	1	1	
g	Isocenter to Protected Point Distance	ft	21.0	21.0	21.0	
h		m	6.4	6.4	6.4	g * 0.3048
i	Unshielded Dose	mSv/wk	2.20E+01	1.62E+02	1.65E+01	1000*c*d*e*f/h^2
j	Transmission		3.72E-04	4.66E-04	1.65E-05	see below
k	Shielded Dose	mSv/wk	0.008	0.076	0.000	i * j
L	Total Shielded Dose	mSv/wk		0.084		Sum row k

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

Barrier	Material Thickness	Slant Thickness	Material	Photon Leakage			Scatter			Neutron	
	inches	mm		TVL1 (mm)	TVLe (mm)	Trans.	TVL1 (mm)	TVLe (mm)	Trans.	TVL (mm)	Trans.
Inside Layer	1	28	Lead	57	57	3.22E-01	53	53	2.96E-01	N/A	1.00E+00
Layer #2	36	1009	Concrete	360	340	1.15E-03	360	360	1.58E-03	211	1.65E-05
Layer #3						1.00E+00			1.00E+00		1.00E+00
Layer #4						1.00E+00			1.00E+00		1.00E+00
Outside Layer						1.00E+00			1.00E+00		1.00E+00
Slant Angle (degrees):		25		18 MV	Total:	3.72E-04		Total:	4.66E-04	Total:	1.65E-05

Primary Beam Remains Significant at Small Scatter Angles

- **Primary beam remains significant 1 ft beyond beam edge**
  - 40x40 cm field rotated 45 degrees
  - Primary beam angle measured from target
  - Scatter angle measured from isocenter
- **Conservatism in patient scatter shielding (i.e., F=1600) increases confidence edge of primary beam is adequately shielded**
- **Implications**
  - Laminated primary barriers may need to extend more than 1 ft beyond the edge of beam
  - Recommend new primary barriers to be square, not tapered

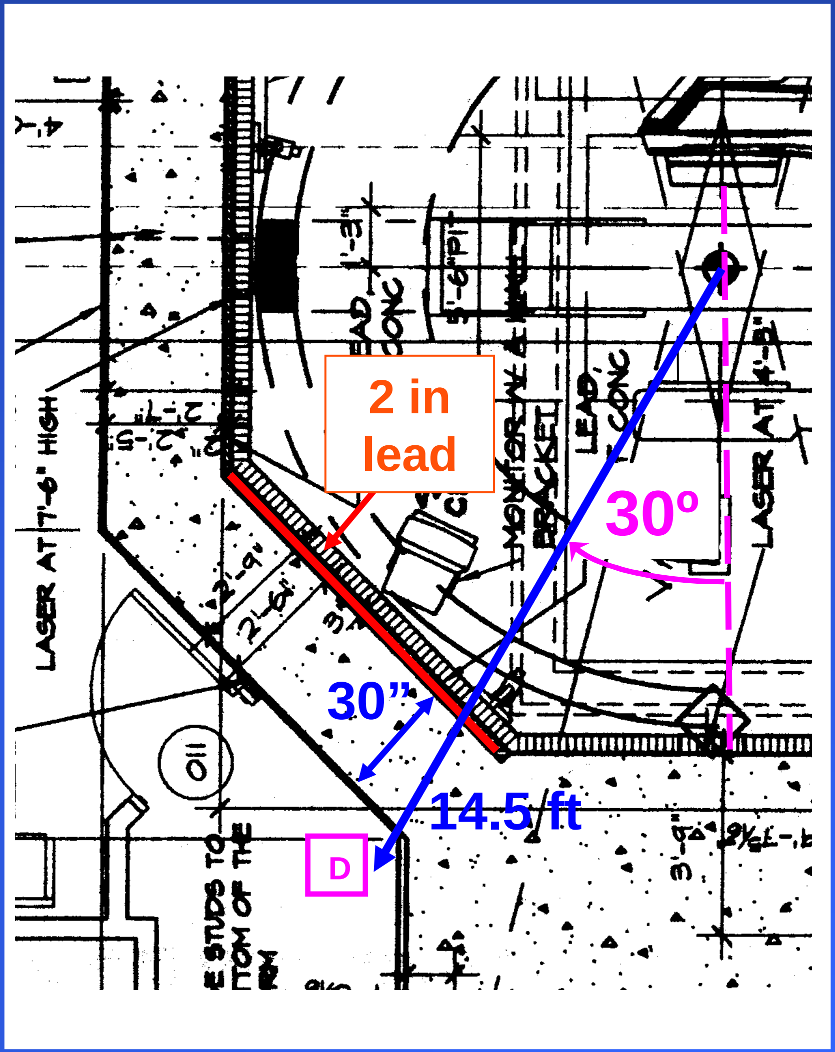


Scatter Observations

- Scatter is typically negligible for lateral barriers
- Must include scatter calculation for barrier next to primary
  - Particularly if slant factor is used when calculating photon leakage transmission
- General calculation procedure would include wall scatter also
  - Not addressed here since negligible for traditional secondary barriers
  - Vital to include for maze calculation for low energy linac

Example 8: Scatter Adjacent to Primary Barrier

1. Establish P/T for location D: P = 0.02 mSv, T = 0.2, P/T = 0.10 mSv/wk
2. Distance from isocenter to protected location: 14.5 ft
3. Secondary barrier 2" lead and 30" concrete, 15º slant angle
4. Determine scatter fraction per 400 cm^2 by interpolating scatter fraction table as a function of MV (18) and scatter angle (30º)
5. Calculate effective field size, scatter fraction
6. Calculate shielded dose rate comprised of photon leakage, neutron leakage and scatter using slant thickness for transmission



Example 8: Secondary Barrier Scatter Fraction Calculation

Line	Parameter	Units	Value	Calculation
a	Design Dose Limit (P)	mSv/wk	0.02	
b	Occupancy Factor (T)		0.2	
c	P/T	mSv/wk	0.100	a / b
d	Machine X-ray Energy	MV	18	
e	Vendor		Varian	

Line	Parameter	Units	Value		Calculation
			w/o IMRT	with IMRT	
a	Max Field Size	cm	40	40	
b	Fraction of Workload		50%	50%	
c	Effective Field Area	cm^2	1600.0		b_1*a_1^2 + b_2*a_2^2
d	Effective Field Size	cm	40.0		sqrt (c)
e	Scatter Angle	deg	30		
f	Machine X-ray Energy	MV	18		
g	Scatter / 400 cm^2		2.53E-03		Function of e & f
h	Scatter Fraction		0.01012		g * c / 400

Example 8: Secondary Barrier Shielded Dose Rate Calculation Including Leakage & Scatter

Line	Parameter	Units	Photon Leakage	Photon Scatter	Neutron Leakage	Calculation
a	Workload / Treatment	Gy/pt	3	3	3	NCRP 151 default
b	Patients per Day	pt/day	30	30	30	NCRP 151 default
c	Workload (W)	Gy/wk	450	450	450	5 * a * b
d	Use Factor	Ratio	1	0.25	1	adjacent to pri barrier
e	Fraction	Ratio	1.0E-03	1.0E-02	1.5E-03	Varian at 18 MV
f	IMRT Factor		2	1	1	
g	Isocenter to Protected Point Distance	ft	14.5	14.5	14.5	
h		m	4.4	4.4	4.4	g * 0.3048
i	Unshielded Dose	mSv/wk	4.61E+01	5.83E+01	3.46E+01	1000*c*d*e*f/h^2
j	Transmission		5.78E-04	3.19E-04	1.82E-04	see below
k	Shielded Dose	mSv/wk	0.027	0.019	0.006	i * j
L	Total Shielded Dose	mSv/wk		0.052		Sum row k

0.052 mSv is less than P/T = 0.10 mSv/wk

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.	Neutron TVL (mm)	Neutron Trans.
Inside Layer	2	53	Lead	57	57	1.19E-01	51	51	9.31E-02	N/A	1.00E+00
Layer #2						1.00E+00			1.00E+00		1.00E+00
Layer #3						1.00E+00			1.00E+00		1.00E+00
Outside Layer	30	789	Concrete	360	340	4.83E-03	320	320	3.43E-03	211	1.82E-04
Slant Angle (degrees):		15		18 MV	Total:	5.78E-04		Total:	3.19E-04	Total:	1.82E-04

Maze Calculation

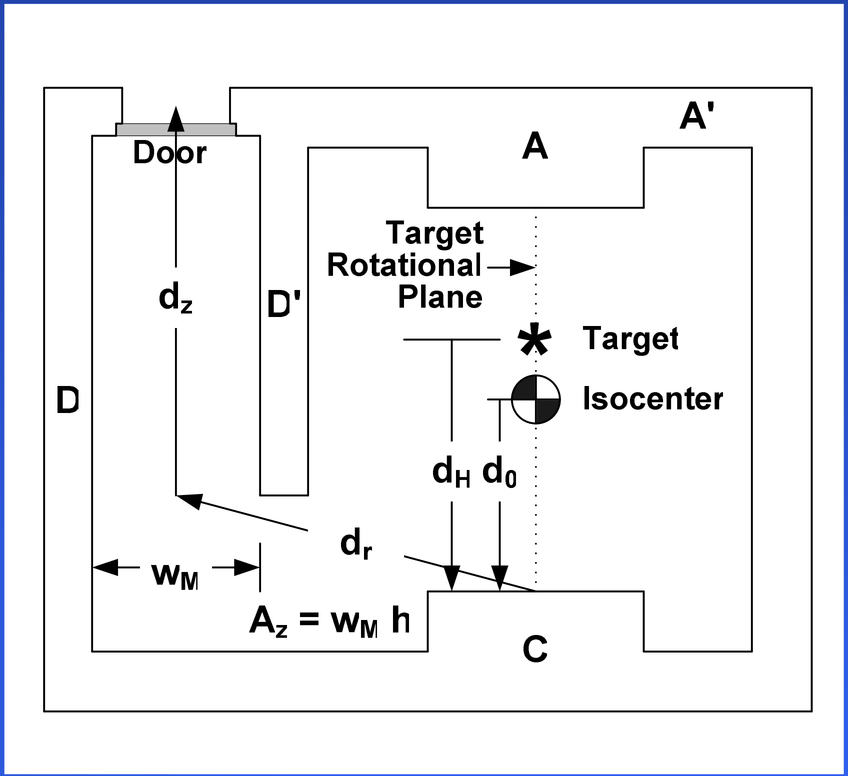
- Specific scatter mechanisms included in maze calculation
  - Wall Scatter and Patient Scatter
    - » Calculated at most stressing gantry orientation
  - Leakage scatter
- Direct leakage
  - Conventional secondary barrier calculation
  - If maze door lies beyond primary barrier, use primary barrier calculation instead
- High Energy accelerator mechanisms
  - Neutrons, capture gammas
  - Dominates the scatter mechanisms for high energy machines

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

Table 9. Reflection Coefficient for Concrete (NCRP 151 Tables B.8a and B.8b)

NCRP 151 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

NCRP 151 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

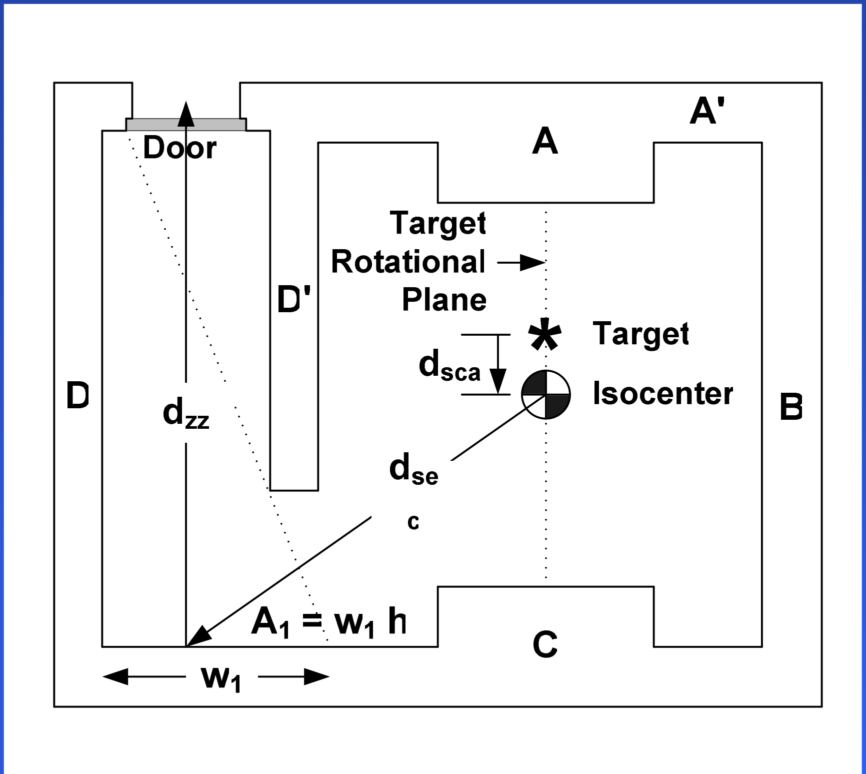
- **Reflection coefficient for steel or lead is 2x these values**

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 the door
  - Other constants as before, e.g.,
    - » a = patient scatter fraction
      - See NCRP 151 Table B.4
    - » F = field size in cm^2
    - » 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

Table 5: NCRP 151 Table B.4
Patient Scatter Fraction for 400 cm^2 Field

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

Linac 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

Repeat of Table 5 Used for Secondary Barrier Calculations

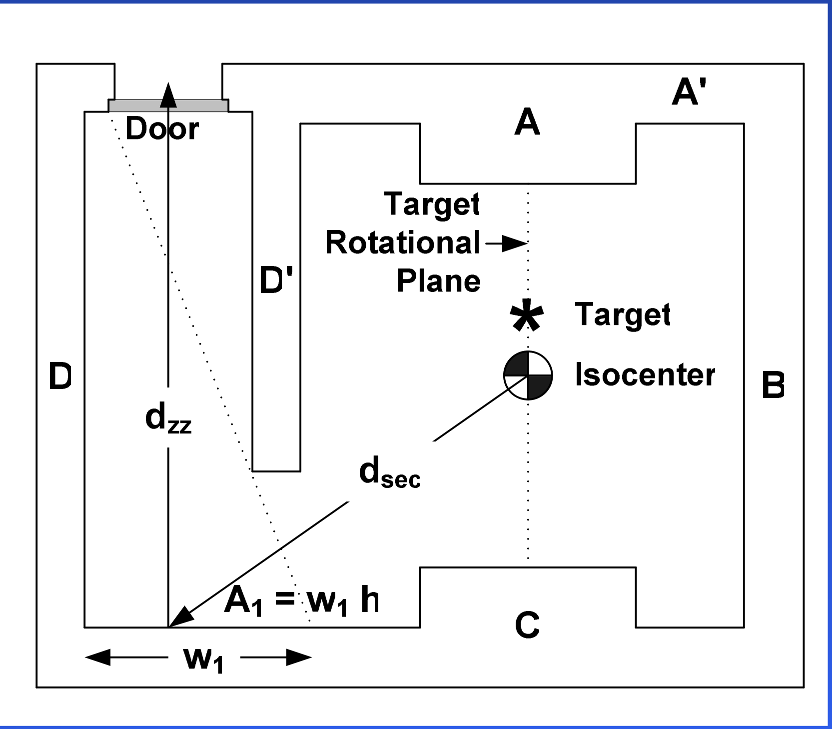
Leakage Scatter

- 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



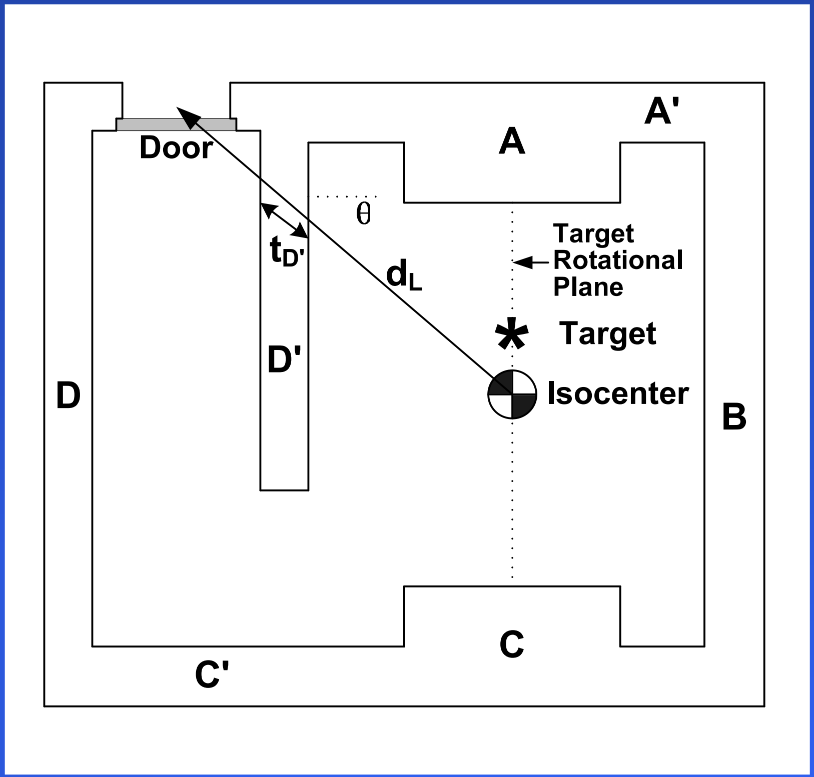
- Use factor adjustment
  - NCRP 151 recommends same adjustment as patient and wall scatter
  - U = 1 with no adjustment is assumed in the example calculations here
    - with d_{sec} measured from isocenter

Direct Leakage

- Unshielded dose rate

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

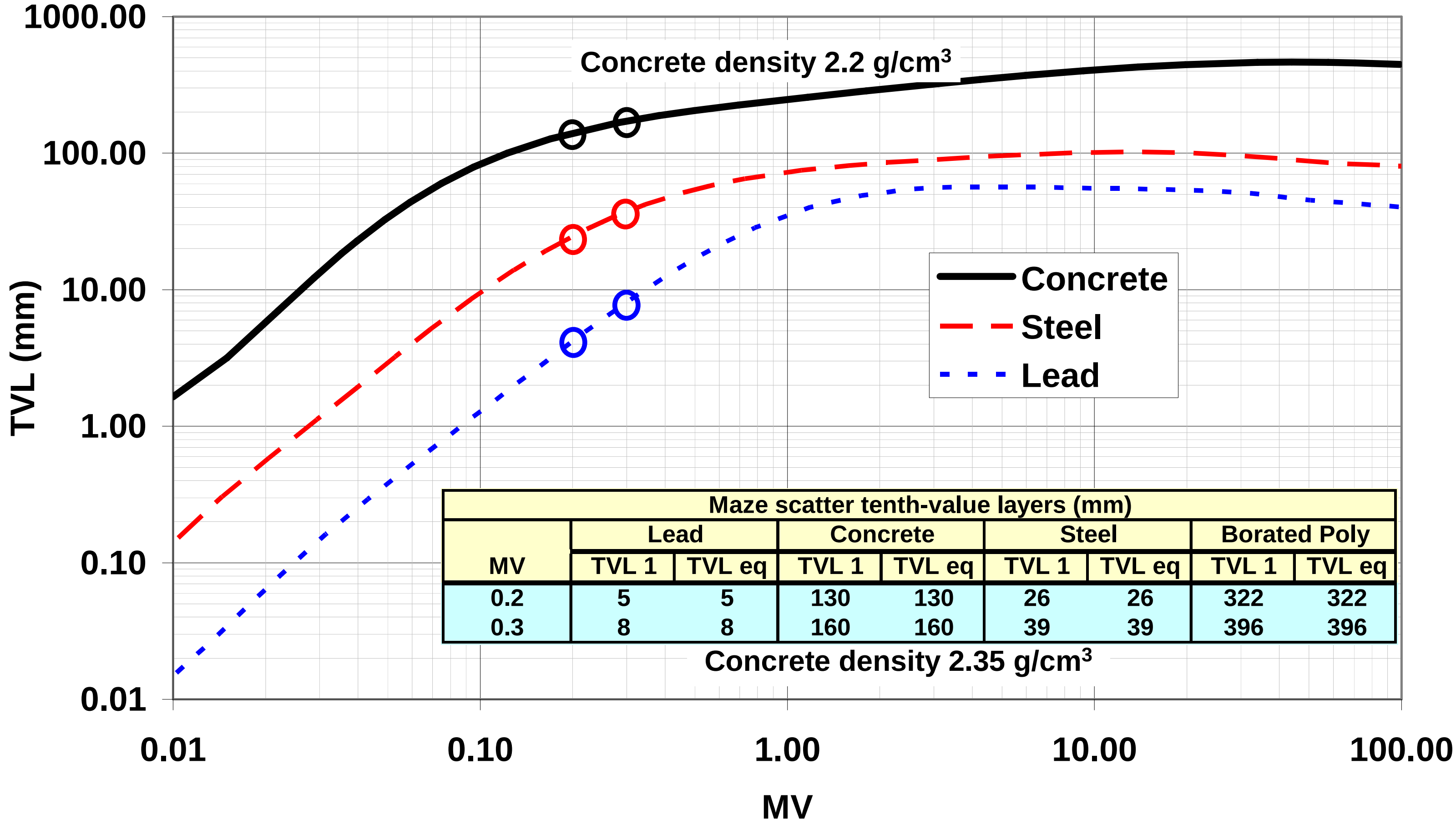
- Same as standard secondary photon leakage calculation
  - B is leakage transmission through wall
- Use factor adjustment
  - NCRP 151 recommends the same adjustment as patient and wall scatter
  - U = 1 with no adjustment is assumed in the example calculations here



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

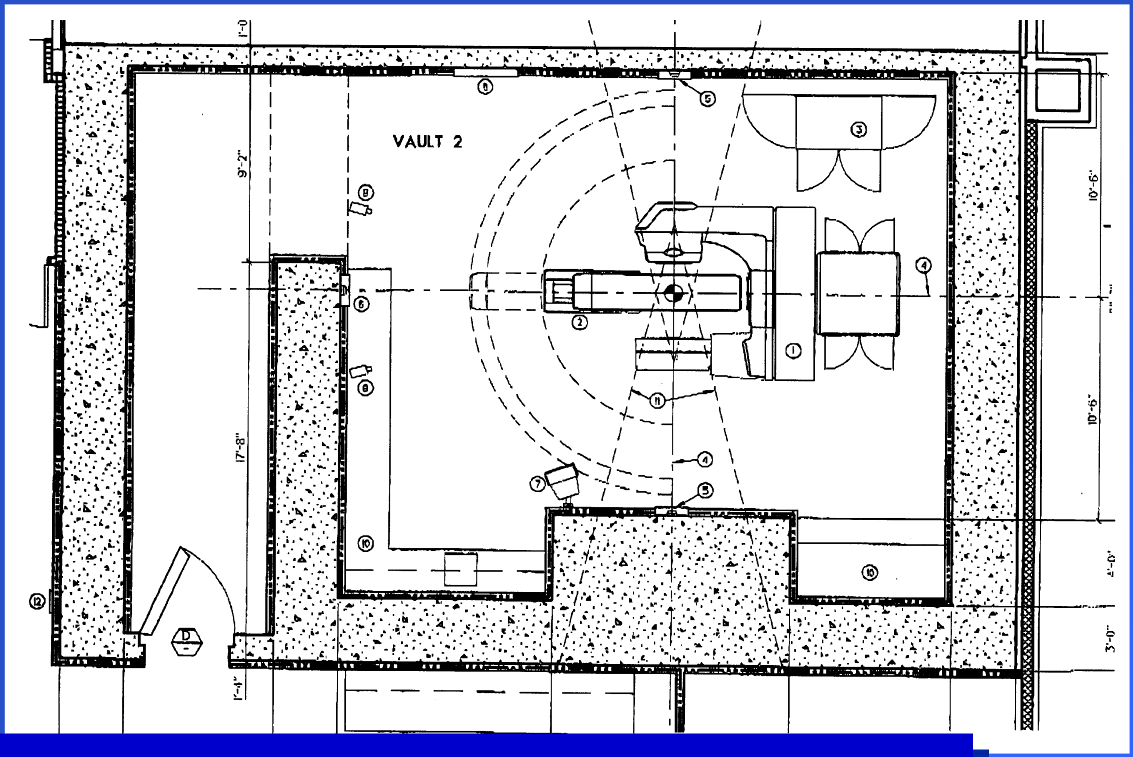
Broad Beam Equilibrium TVLs (NCRP 151 Figure A.1)



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

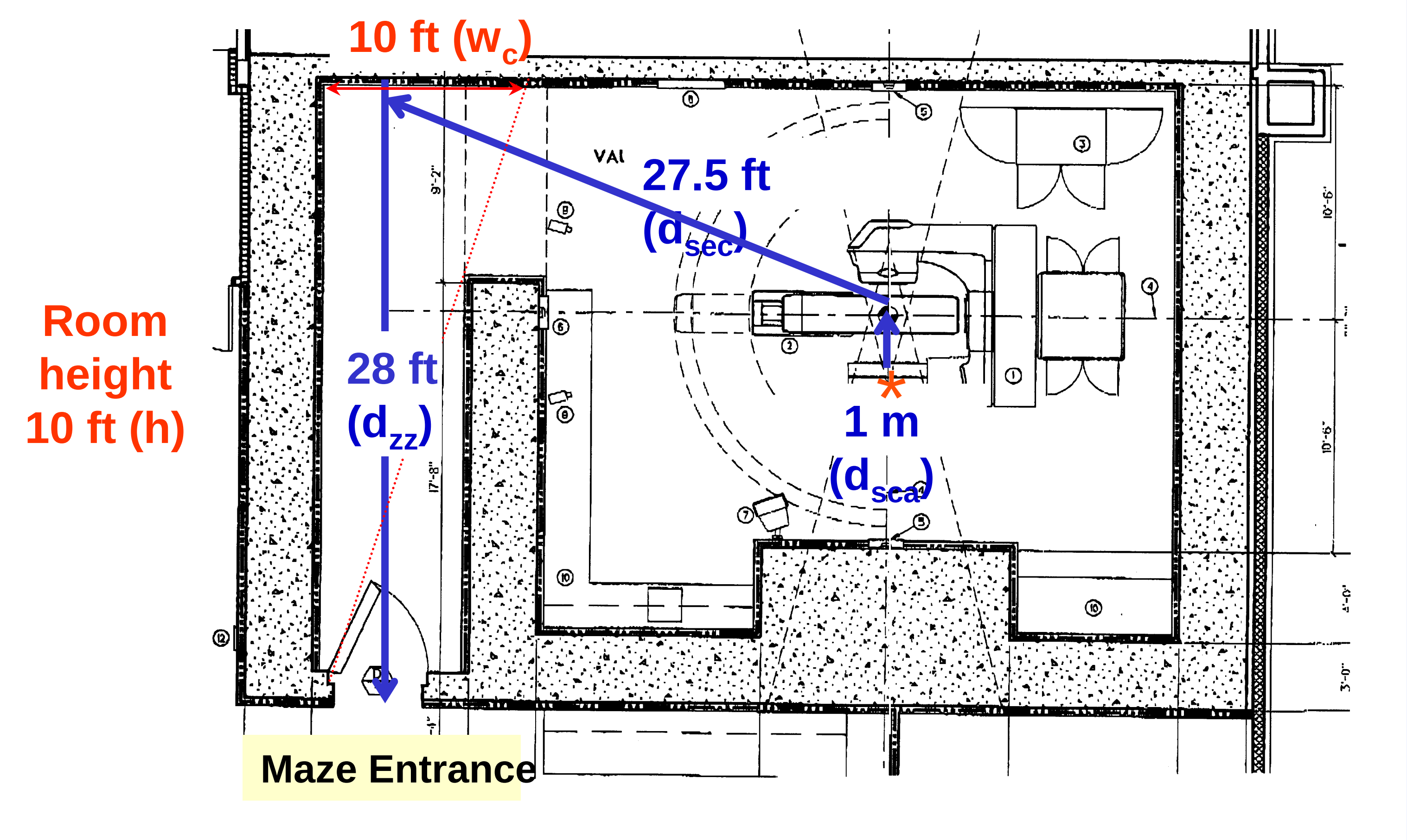
Example 9: Conventional Maze, 6 MV

- 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 9a: Patient Scatter



Example 9: P/T and Average Field Size Calculation

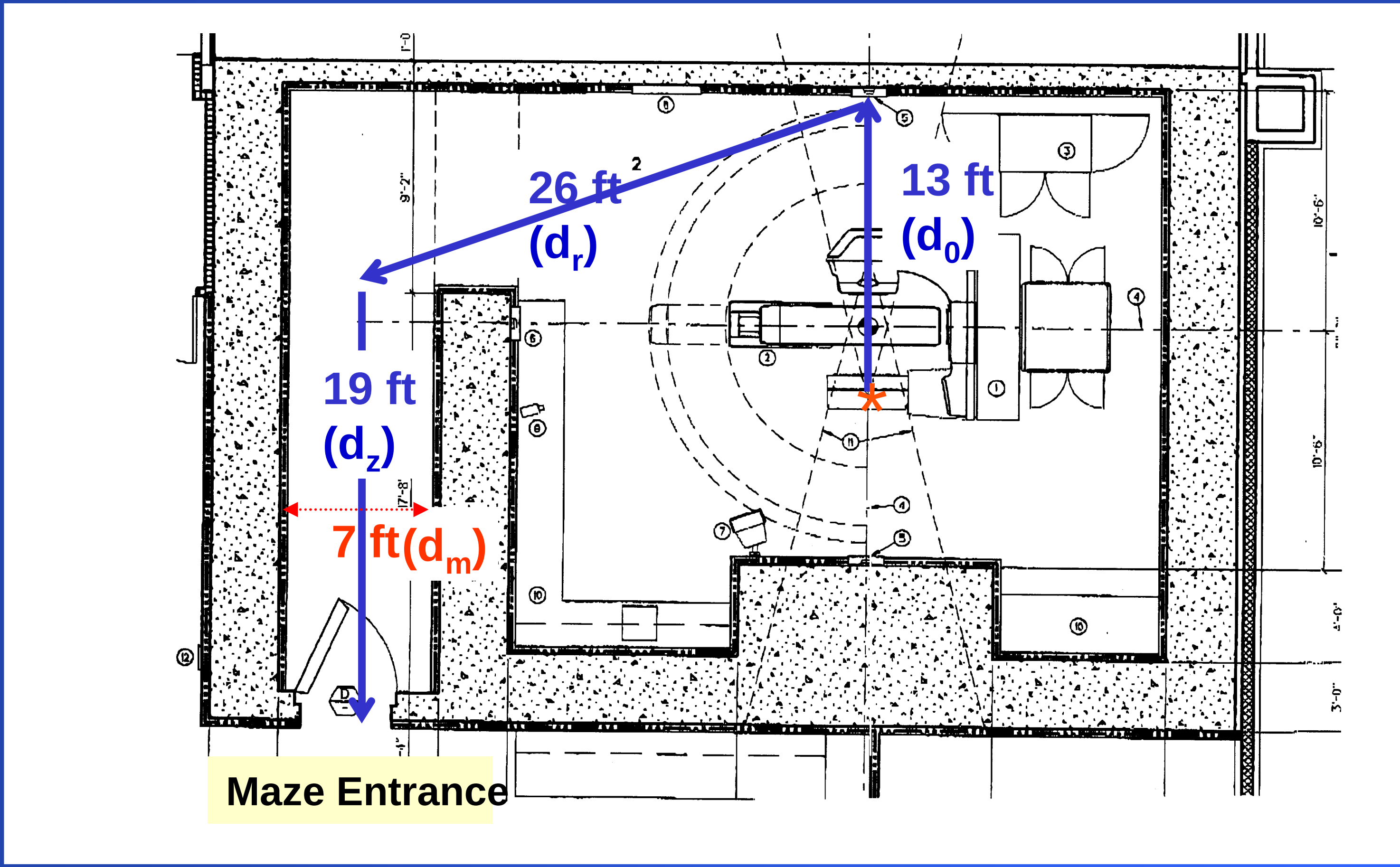
- Protected location is in a controlled area (P= 0.1 msv/wk)
  - NCRP 151 occupancy T=1/8 for extremely low traffic location
  - Higher occupancy appropriate if close proximity to control area
    - » e.g., T=0.5 or T=1 (T=1 is assumed in example)
  - Maximum shielded dose rate (P/T) is 0.1 mSv/wk for 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	40	
b	Fraction of Workload		50%	50%	
c	Effective Field Area	cm^2	1600		$b_1 * a_1$^2 + $b_2 * a_2$^2
d	Effective Field Size	cm	40.0		sqrt (c)

Example 9a: 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	See Table 5 (45º) Function of MV
n	α_1	Reflection Coefficient		2.20E-02	Table 8a, 0.5 MV, 45º
o	F	Average field area	cm^2	1600	See above
p	U	Use Factor		0.25	Orientation with highest dose rate
q	H_{PS}	Patient scatter unshielded dose rate	mSv/wk	2.50E-02	1000*m*b*p*(o/400)*L / (c^2 * e^2 * g^2)

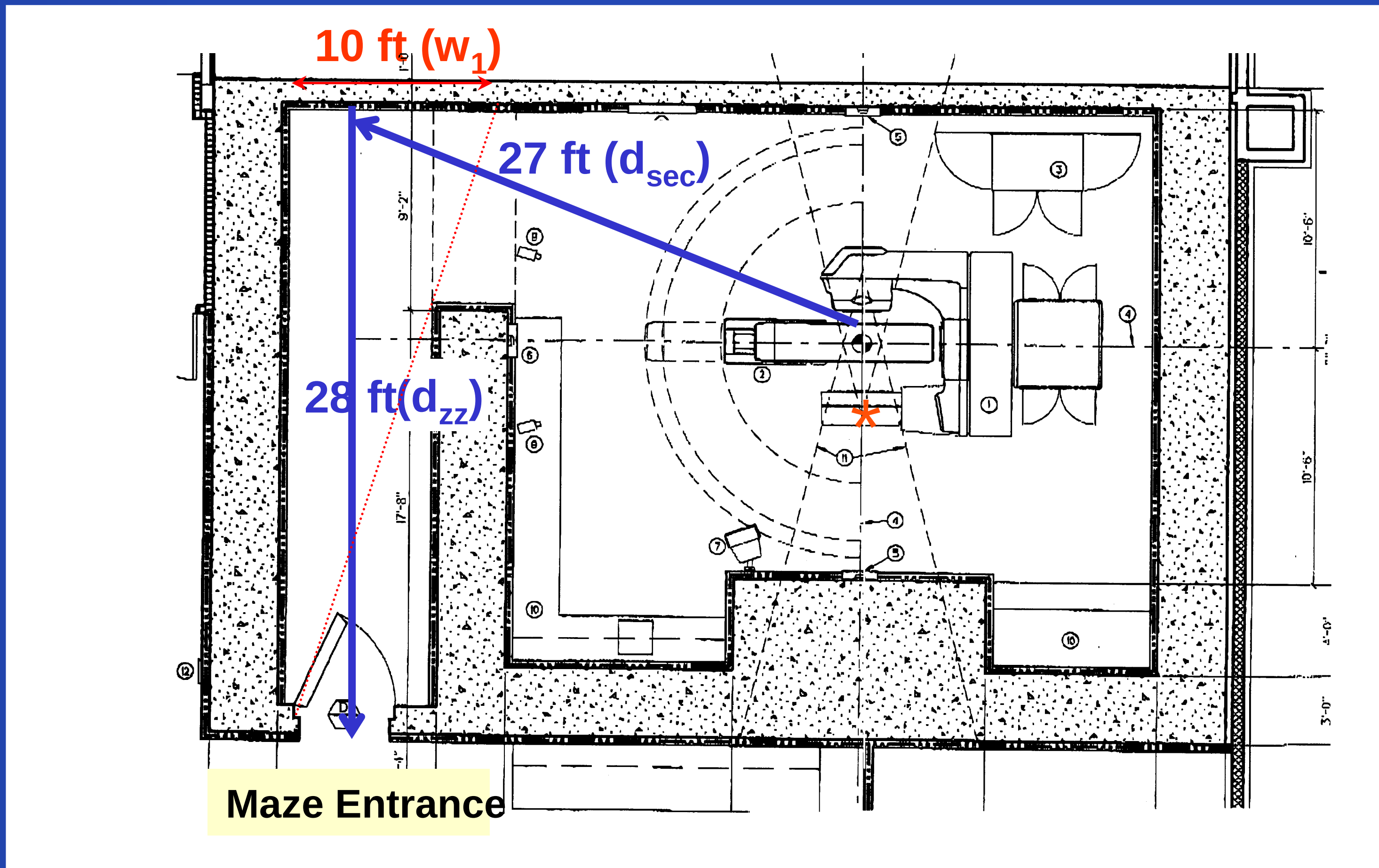
Example 9b: Maze with Secondary Leakage Through Door — Wall Scatter



Example 9b: 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 8a with 6 MV 75º scatter angle
o		Effective field size	cm	40.0	see above
p	A_0	Beam area at first reflection	m^2	2.51	(e * o/100)^2
q	α_z	2nd bounce scatter fraction / m^2		0.0080	Table 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	3.00E-04	1000*m*b*s*(o/400)* L / (e^2 * g^2 * i^2)

Example 9c: Maze with Secondary Leakage Through Door — Leakage Scatter

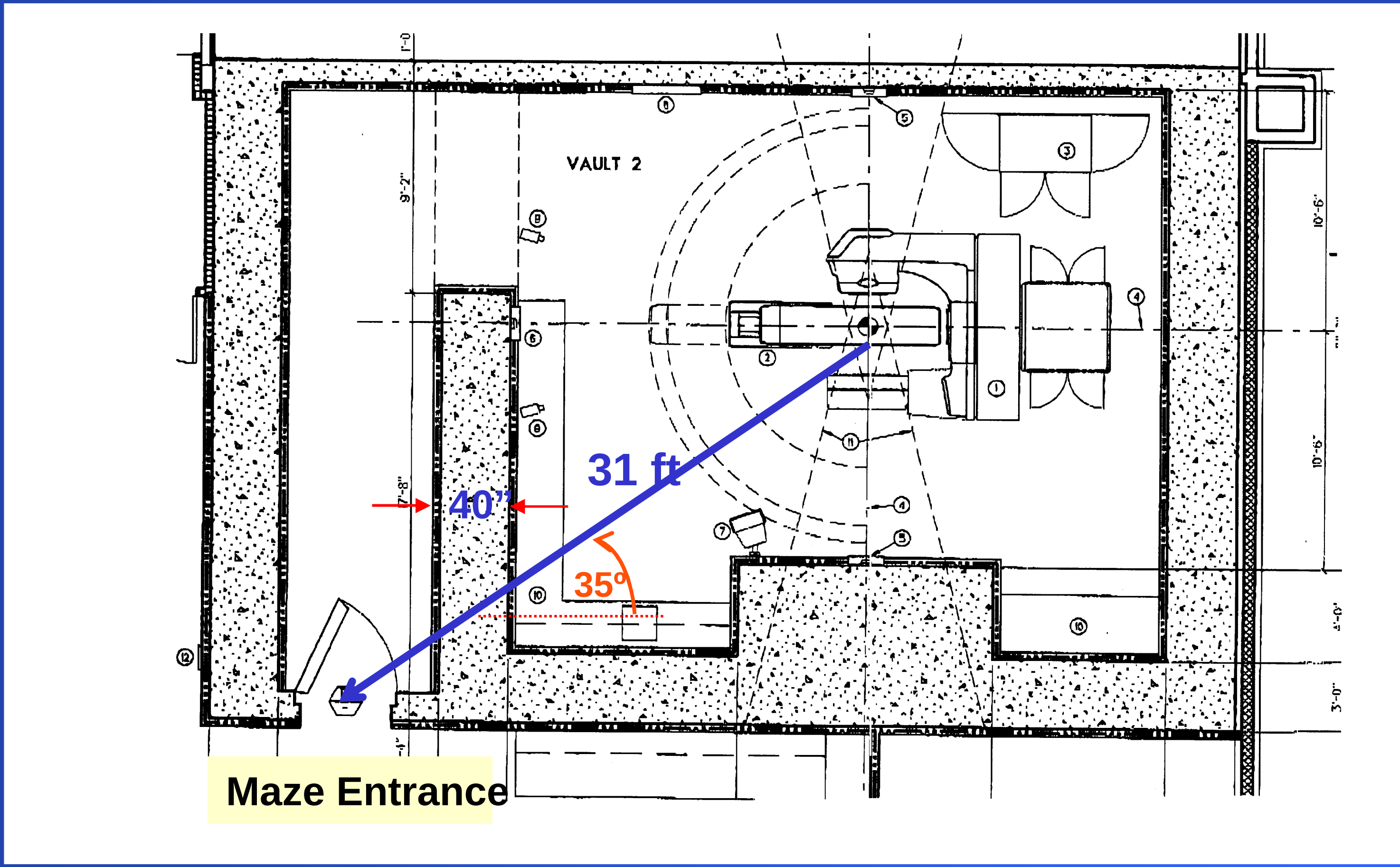


d_{sec} measured from isocenter (the average target location)

Example 9c: 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 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 9d: Maze with Secondary Leakage Through Door — Direct Leakage



Example 9d: 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 (degrees):		35		6 MV	Total:	7.86E-05

Example 9: 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 (degrees):		0		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 (degrees):		0		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 (degrees):		0		0.3 MV	Total:	1.61E-01

Example 9: 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 (degrees):		0		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	2.50E-02	3.00E-04	3.10E-02	7.92E-04	
b	Total / Calc. Dose Rate		2.64	2.64	1	1	McGinley
c	Total Unshielded Dose Rate	mSv/wk	6.60E-02	7.92E-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	0.00354	0.00004	0.00499	0.00061	c * e
g	Total Shielded Dose Rate	mSv/wk	0.0092				Sum Row f

0.0092 mSv/wk is less than
P/T = 0.100 mSv/wk

Example 9: 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 9: 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

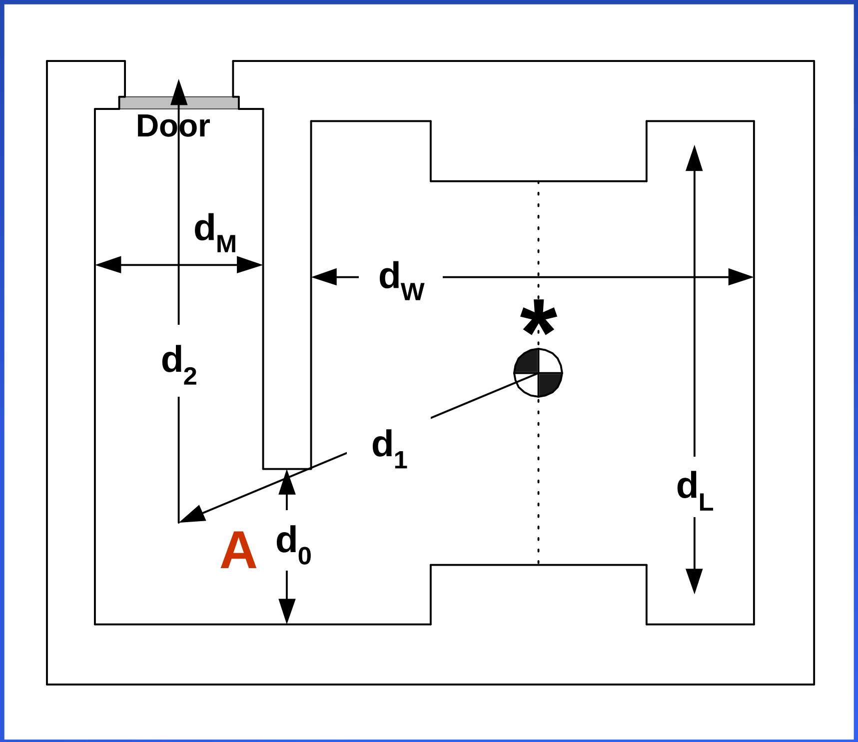
Line	Parameter	Units	Patient Scatter	Wall Scatter	Leakage Scatter	Direct Leakage	Calculation
a	Calc. Unshielded Dose Rate	mSv/wk	2.50E-02	3.00E-04	3.10E-02	7.92E-04	
b	Total / Calc. Dose Rate		2.64	2.64	1	1	McGinley
c	Total Unshielded Dose Rate	mSv/wk	6.60E-02	7.92E-04	3.10E-02	7.92E-04	a * b
d	Energy 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	0.0044	0.0001	0.0035	0.0002	c * e
g	Total Shielded Dose Rate	mSv/wk	0.0082				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: NCRP 151

- 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

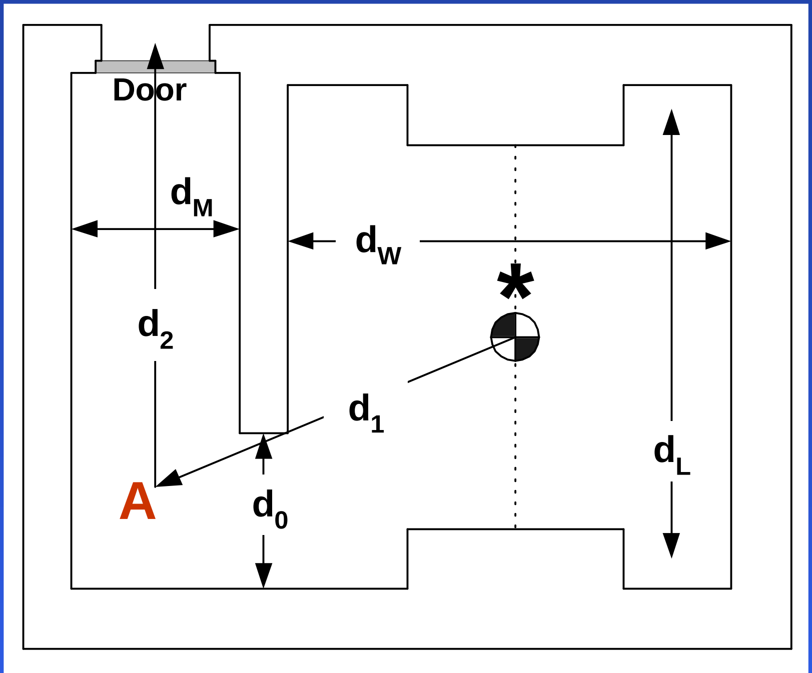


Neutron Fluence Calculation

- 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



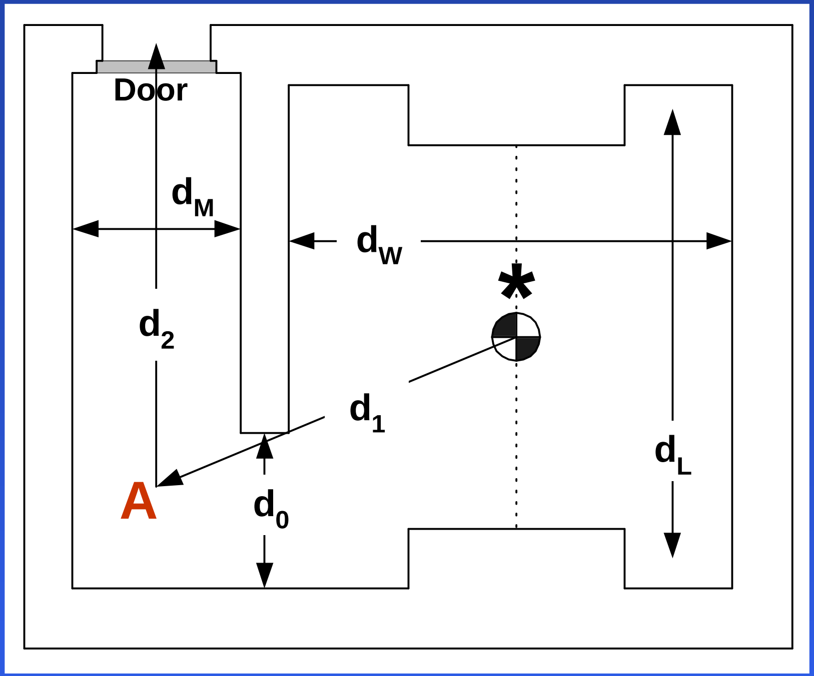
- where
  - β = head shielding transmission factor
    = 1.0 for lead, 0.85 for tungsten
  - d_1 = Distance from isocenter to point A
  - Q_n = Neutron source strength (Table 10)
  - S_r = Treatment room surface area (m²)

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

Table 10: NCRP 151 Table B.9 Total Neutron Source Strength (Q_n)

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

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**

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

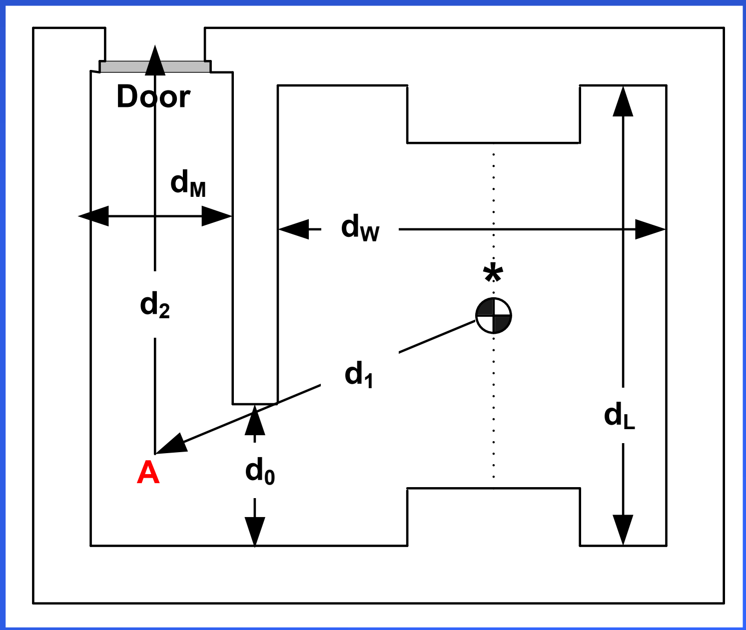
  - **W_{Ln} is neutron leakage workload**

Maze Neutron Unshielded Dose Rate Calculation

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

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

- **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 m $< d_2 \leq 5$ m maze also
    - » Interpolate NCRP 151 Table B.2 TVLs at 7.2 MV for concrete / steel

Table 11. Maze Neutron and Capture Gamma TVL Summary

Maze Neutron tenth-value layers (mm)

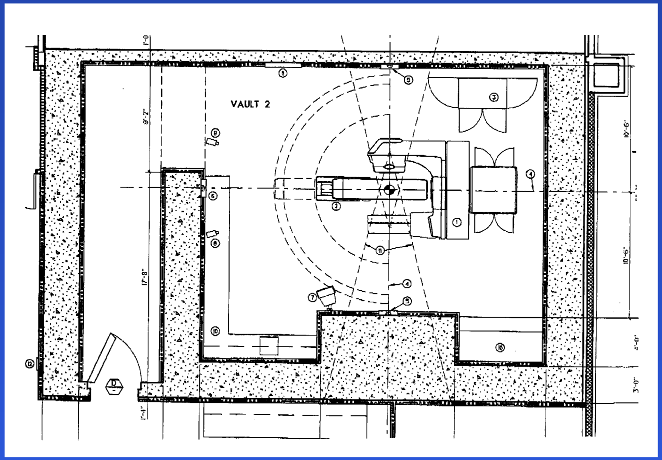
MV	Lead		Concrete		Steel		Borated Poly	
	TVL 1	TVL eq	TVL 1	TVL eq	TVL 1	TVL eq	TVL 1	TVL eq
0.1	N/A	N/A	161	161	N/A	N/A	45	45

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 10: Conventional Maze, 18 MV

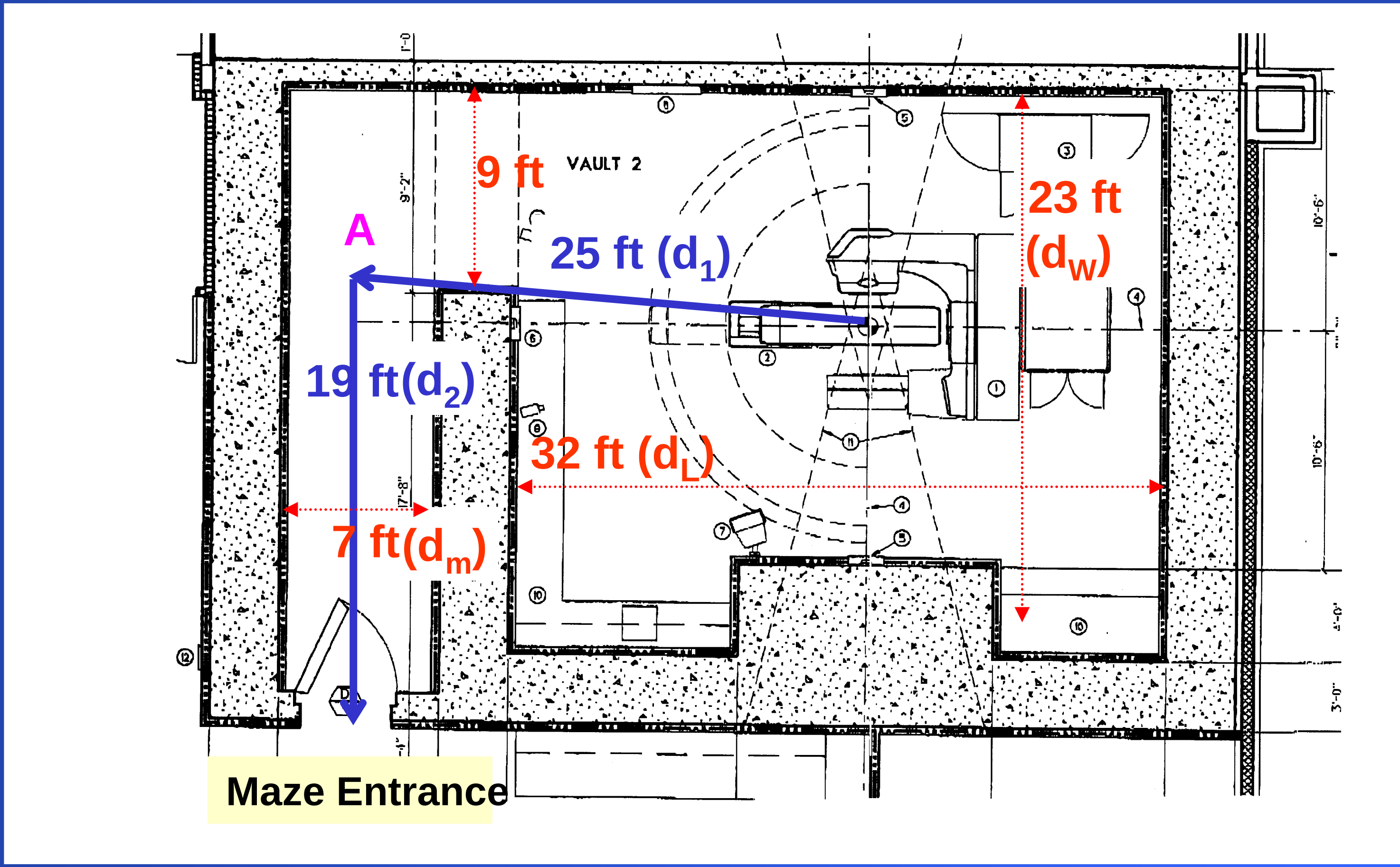
- Same maze layout as Example 1
  - Conventional maze similar to examples in NCRP 151
- Mechanisms included in door calculation
  - Neutron mechanisms dominate shielded dose



- 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 10e: Maze with Secondary Leakage Through Door — Maze Neutrons



Example 10e: 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)]

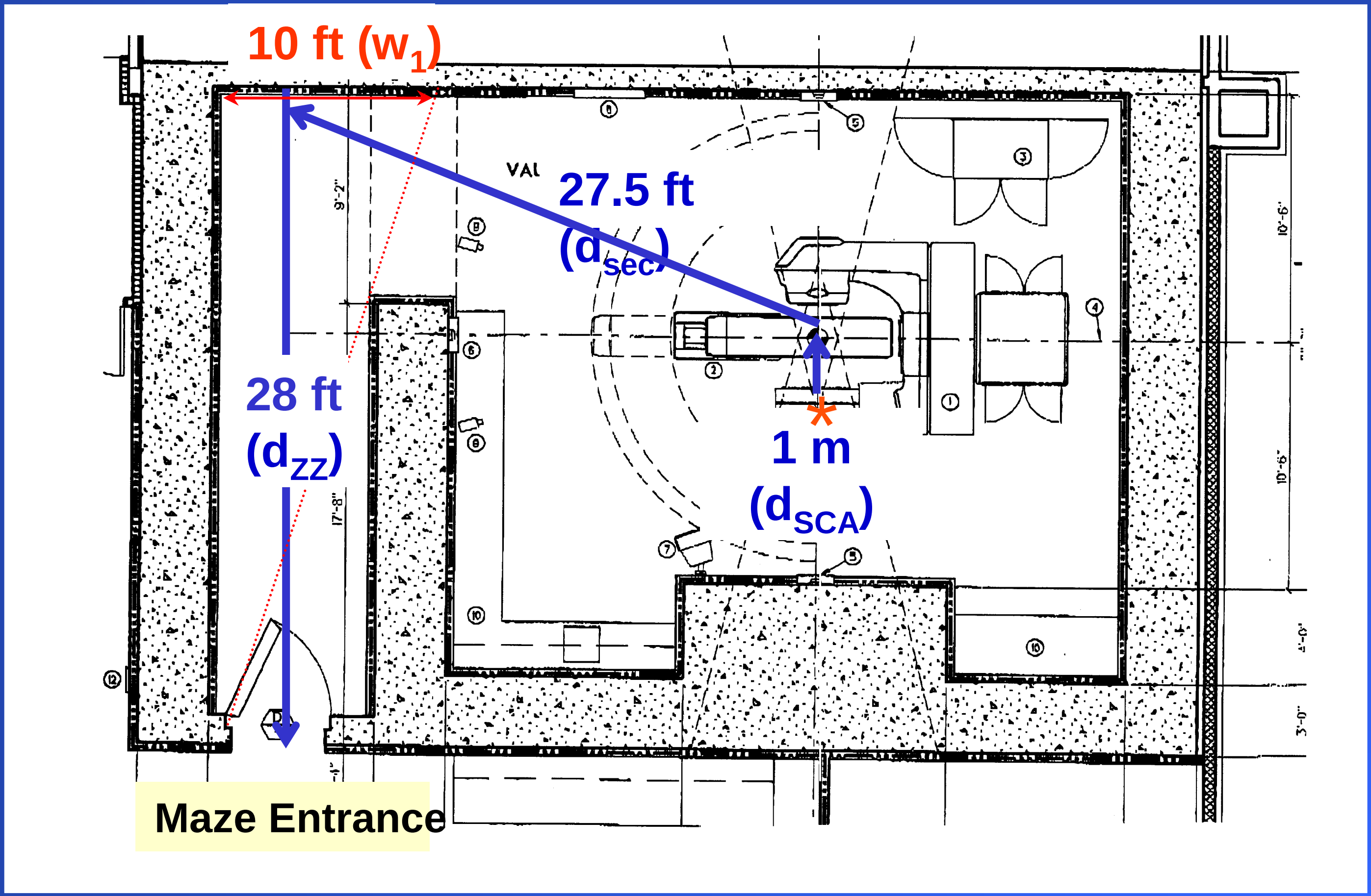
Example 10e: Capture Gamma Unshielded Dose Rate Calculation

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 10e: 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 10a: Maze with Secondary Leakage Through Door — Patient Scatter



Example 10 P/T and Average Field Size Calculation

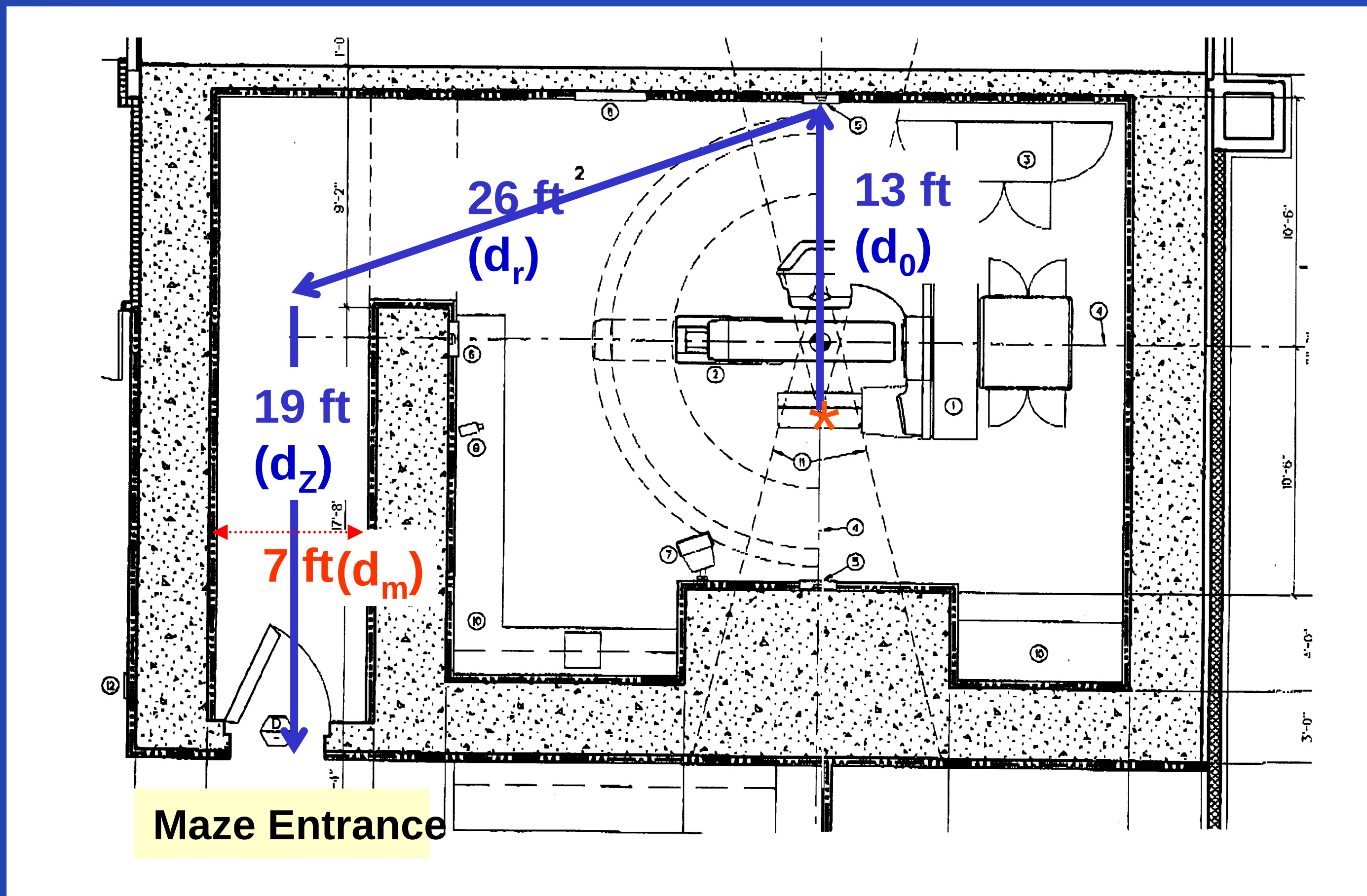
Line	Parameter	Units	Value	Calculation
a	Machine X-ray Energy	mSv/wk	18	
b	Workload / Treatment	Gy/pt	3	NCRP 151 Default
c	Patients per Day	pt/day	30	NCRP 151 Default
d	Workload (W)	Gy/wk	450	5 * b * c
e	Design Dose Limit (P)	mSv/wk	0.1	
f	Occupancy Factor (T)		1	
g	P/T	mSv/wk	0.100	e / f

Line	Parameter	Units	Value		Calculation
			w/o IMRT	with IMRT	
a	Max Field Size	cm	40	40	
b	Fraction of Workload		50%	50%	
c	Effective Field Area	cm^2	1600		$b_1 * a_1$^2 + $b_2 * a_2$^2
d	Effective Field Size	cm	40.0		sqrt (c)

Example 10a: 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	See Table 5 (45º) Function of MV
n	α_1	2nd bounce scatter fraction / m^2		2.20E-02	Table 8a, 0.5 MV, 45º
o	F	Average field area	cm^2	1600	See above
p	U	Use Factor		0.25	Orientation with highest dose rate
q	H_{PS}	Patient scatter unshielded dose rate	mSv/wk	1.55E-02	1000*m*b*p*(o/400)*L / (c^2 * e^2 * g^2)

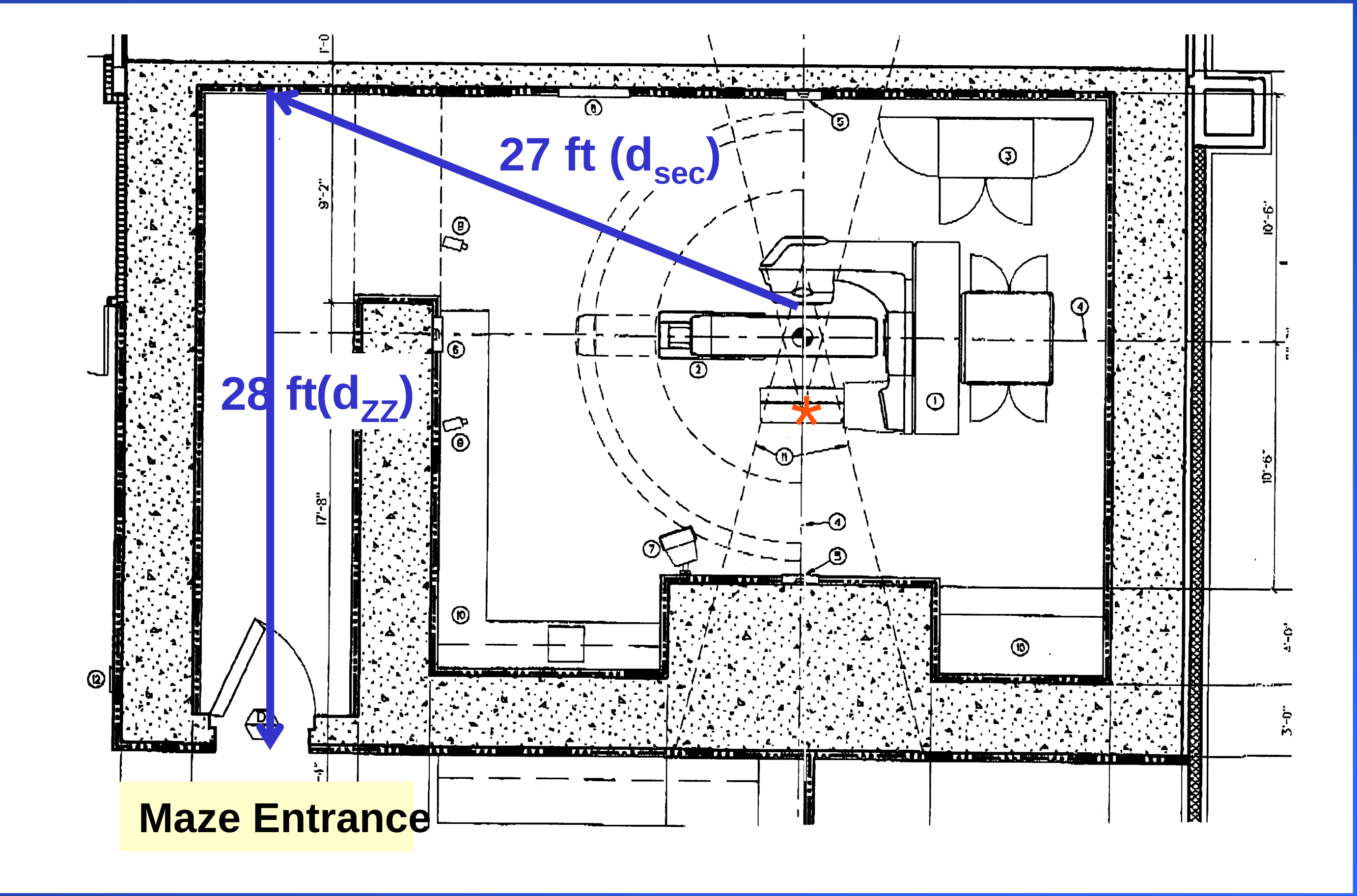
Example 10b: Maze with Secondary Leakage Through Door — Wall Scatter



Example 10b: 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 8a with 6 MV 75º scatter angle
o		Effective field size	cm	40.0	see above
p	A_0	Beam area at first reflection	m^2	2.51	(e * o/100)^2
q	α_z	2nd bounce scatter fraction / m^2		0.0080	Table 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
s	$f\ H_S$	Wall scatter unshielded dose rate	mSv/wk	1.92E-04	1000*m*b*s*(o/400)* L / (e^2 * g^2 * i^2)

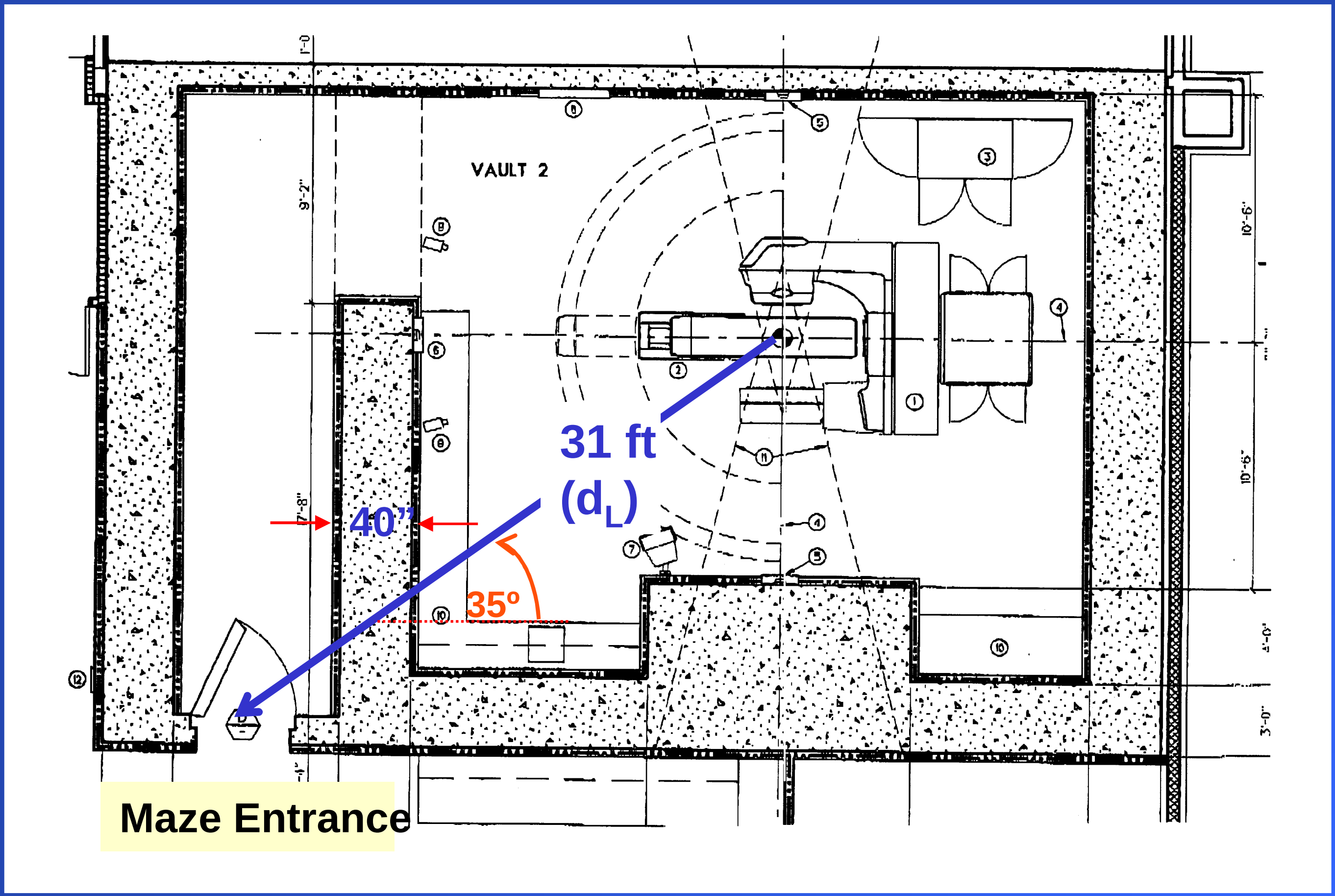
Example 10c: Maze with Secondary Leakage Through Door — Leakage Scatter



Example 10c: 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 1.4 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	3.03E-02	1000 *b *o *c *d *m *n / (f^2 * h^2)

Example 10d: Maze with Secondary Leakage Through Door — Direct Leakage



Example 10d: 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 (degrees):		35		18 MV	Total:	2.58E-04

Example 10: 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	26	26	5.70E-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	26	26	5.70E-01
Slant Angle (degrees):		0		0.2 MV	Total:	1.57E-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	26	26	5.70E-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	26	26	5.70E-01
Slant Angle (degrees):		0		0.2 MV	Total:	1.57E-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 (degrees):		0		0.3 MV	Total:	2.03E-04

Example 10: 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	96	96	8.59E-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	96	96	8.59E-01
Slant Angle (degrees):		0		18 MV	Total:	2.15E-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 (degrees):		0		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 (degrees):		0		3.6 MV	Total:	2.27E-01

Example 10: Maze Door Shielded Dose Rate

Line	Parameter	Units	Patient Scatter	Wall Scatter	Leakage Scatter	Direct Leakage	Neutrons	Capture Gammas
a	Calc. Unshield Dose Rate	mSv/wk	1.55E-02	1.92E-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
c	Total Unshield Dose Rate	mSv/wk	4.10E-02	5.07E-04	3.03E-02	2.60E-03	5.52E-01	1.47E-01
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	2.15E-01	2.03E-02	2.27E-01
f	Shielded Dose Rate	mSv/wk	0.0000	0.0000	0.0000	0.0006	0.0112	0.0335
g	Total Shielded Dose Rate	mSv/wk	0.0452					

- 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 10: 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 (degrees):		0		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 (degrees):		0		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 (degrees):		0		0.3 MV	Total:	1.24E-02

Example 10: 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 10: 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	1.55E-02	1.92E-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	4.10E-02	5.07E-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	0.0002	0.0000	0.0004	0.0003	0.0071	0.0175	c * e
g	Total Shielded Dose Rate	mSv/wk	0.0255						Sum Row f

Direct-Shielded Door

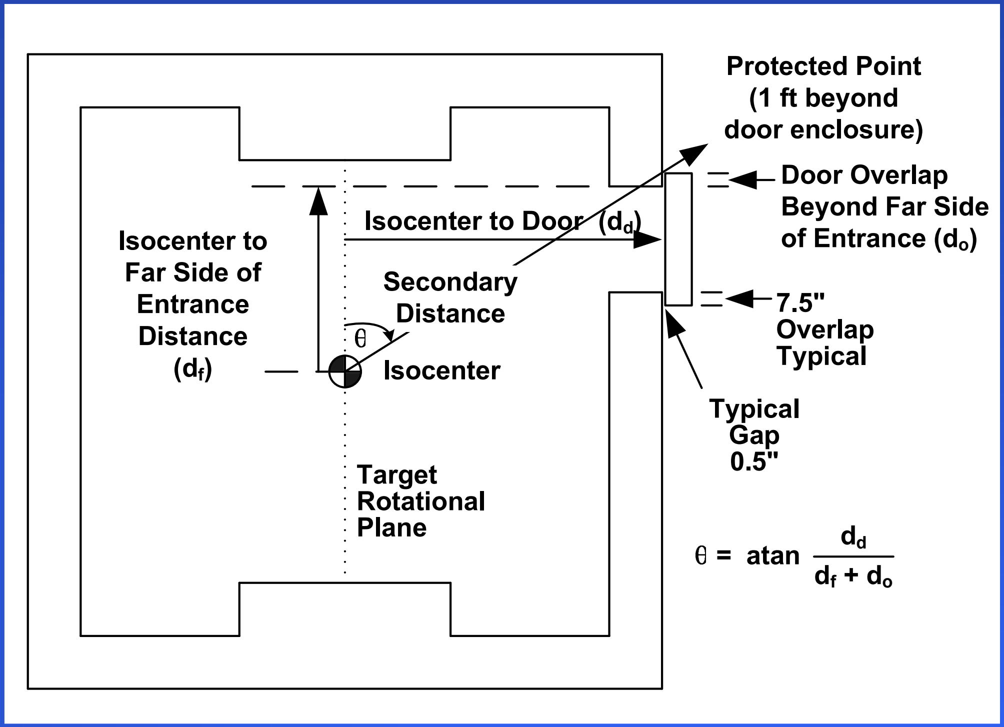
- Neutron Door is simply a secondary barrier
  - Typically more layers and different materials than a wall
    - » Lead to attenuate leakage photons
    - » Borated polyethylene to attenuate leakage neutrons
      - Typically sandwiched between layers of lead
    - » Steel covers
- Specialized shielding procedure adjacent to door
  - Compensates for relatively small slant thickness in this location
  - Vault entry toward isocenter similar to maze
  - Vault entry away from isocenter is secondary barrier
    - » But with specialized geometry

Factor of 2 to 3 Margin Recommended for Direct Shielded Doors

- NCRP 151 recommends considering capture gammas for direct-shielded doors (Section 2.4.5.2)
  - Recommendation is to add 1 HVL to leakage calculation for door only, but not for walls
    - » Rationale: Concrete in wall is more effective for capture gammas than material in door
  - Equivalently, factor of 2 margin on shielded dose rate relative P/T
- Dose rate from HVAC duct above door comparable to dose rate through door
  - Additional reason to provide margin on door calculation

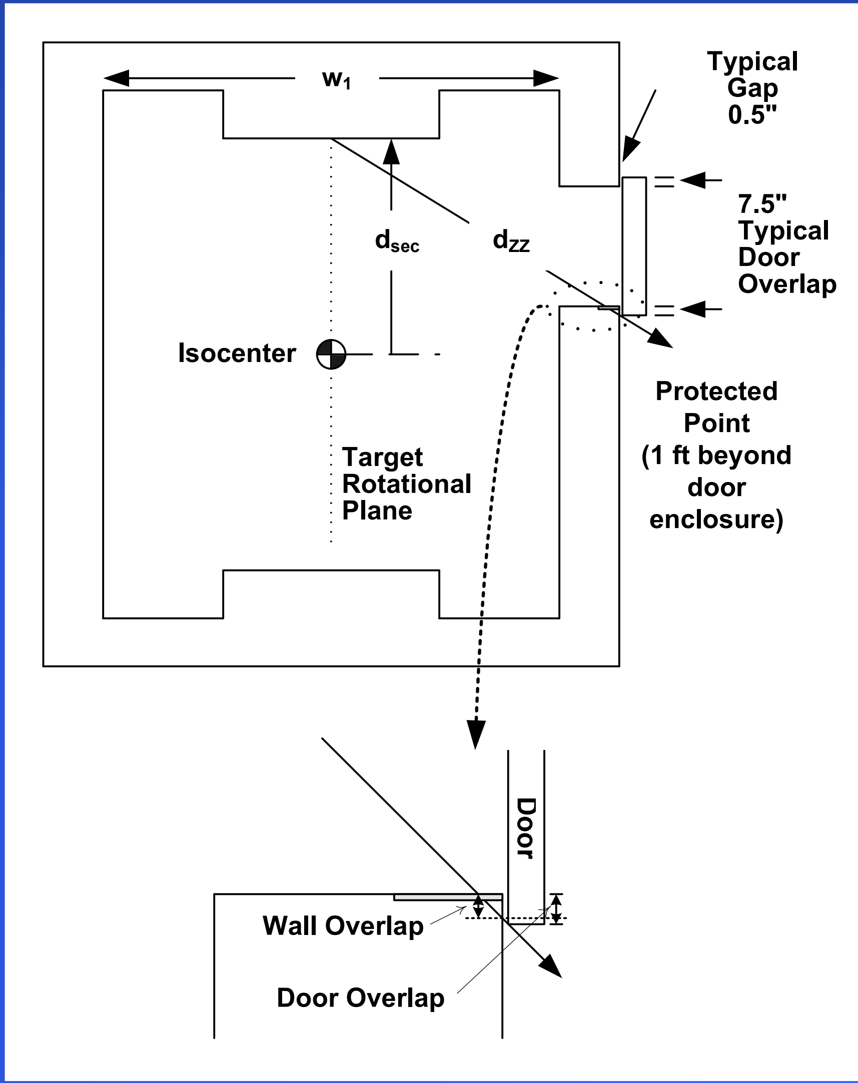
Direct-Shielded Door: Far Side of Entrance

- Extra material added to corner
  - Lead to entrance wall
  - Borated polyethylene or concrete beyond wall
- Uses standard secondary barrier calculation
- Goal: provide same protection as wall or door for path through corner



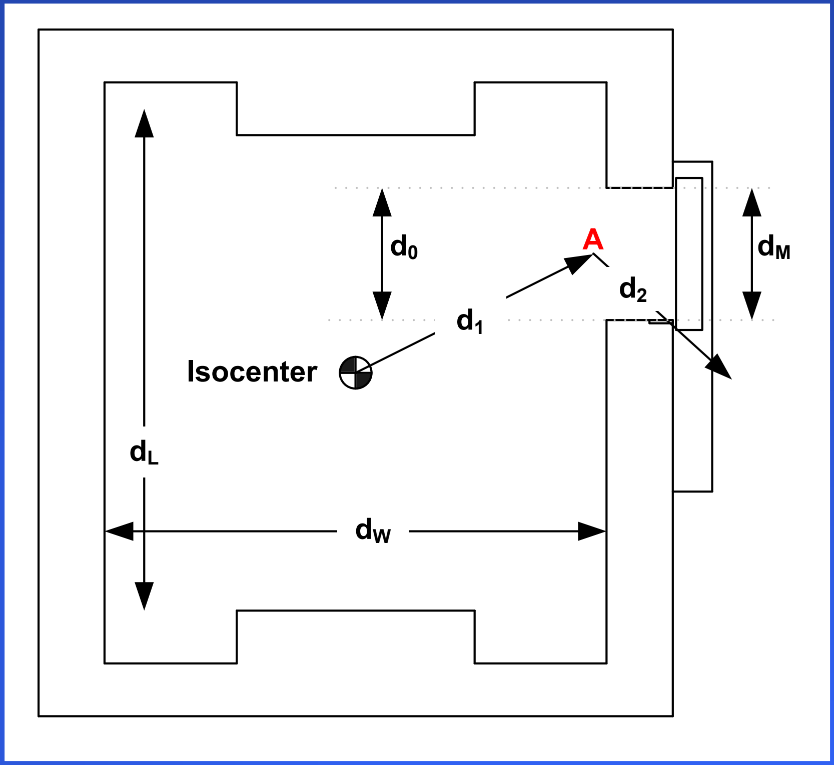
Direct-Shielded Door: Near Side of Entrance Wall Scatter

- Geometry similar to short maze
  - Maze calculation is reasonable to use
- Requires less material than far side of entrance
  - Lower unshielded dose rate
  - Lower energy
- Wall scatter determines shielding for < 10 MV
  - Not significant if high energy

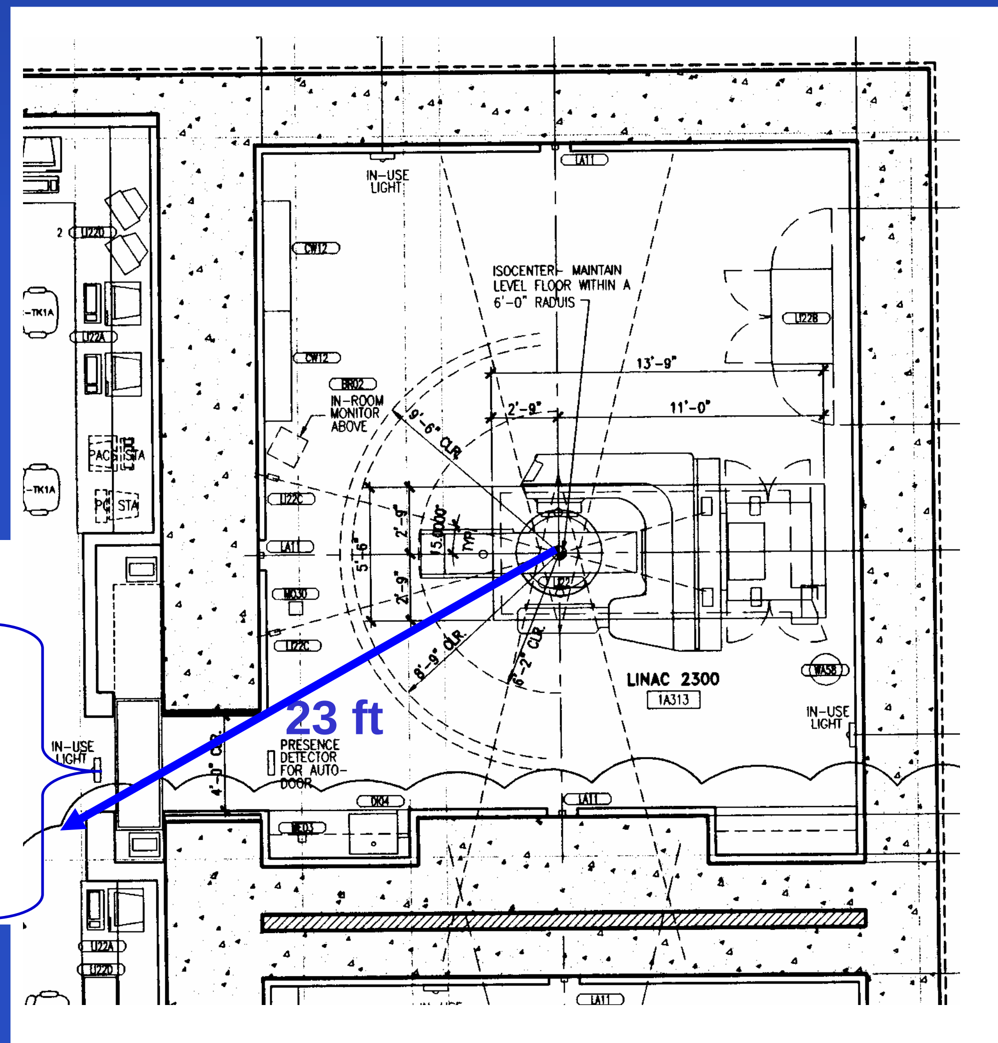


Direct-Shielded Door: Near Side of Entrance Neutrons / Capture Gammas

- Geometry similar to short maze
  - Maze calculation is reasonable to use
- Requires less material than far side of entrance
  - Lower unshielded dose rate
  - Lower energy



Example 11a: Direct Shielded Door — Door Thickness



Door

0.25 steel inner face
2.5" lead
10" borated poly
2.5" lead
0.25" steel outer face

Example 11a: Direct Shielded Door Thickness Calculation [1 of 2]

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

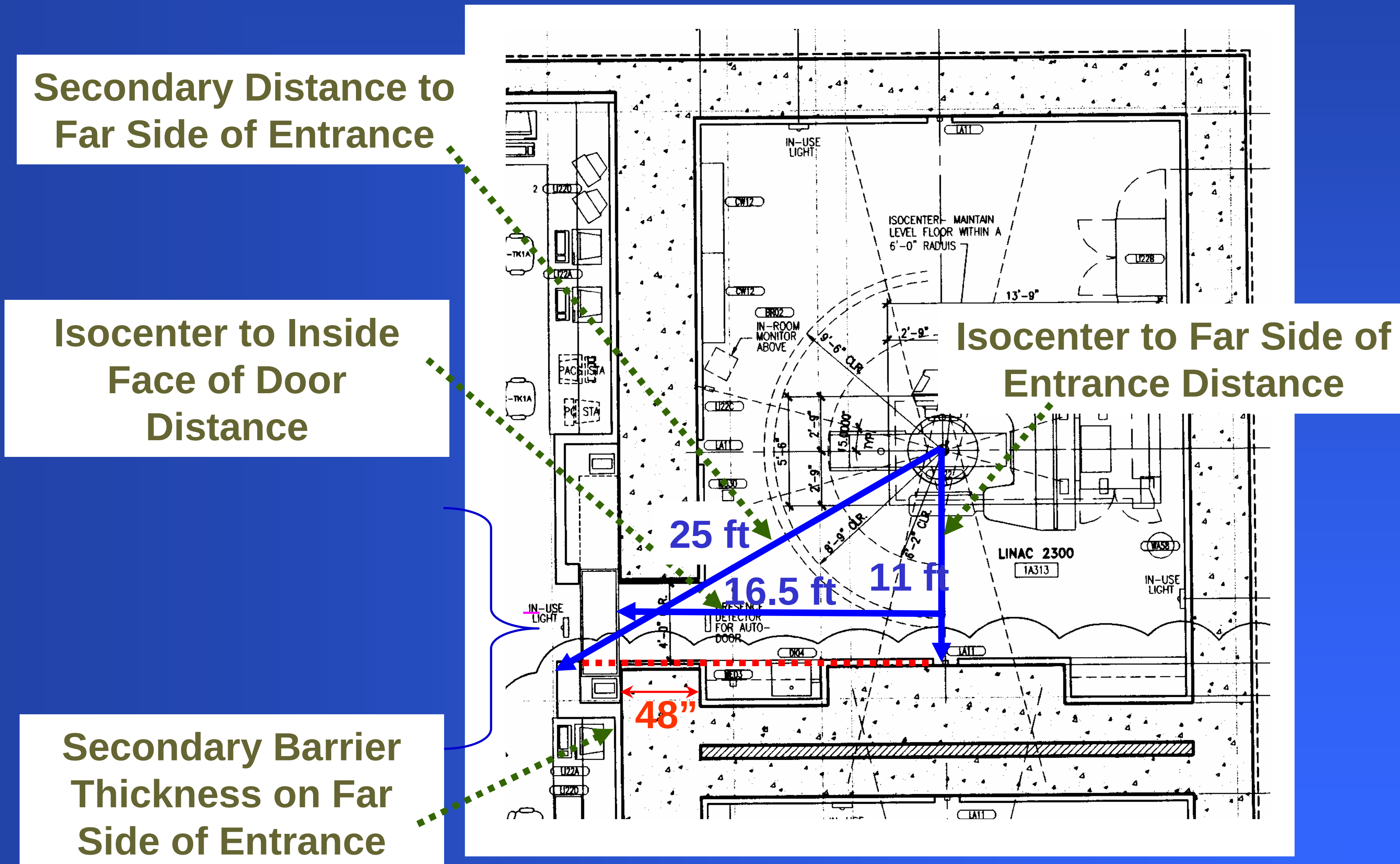
Line	Parameter	Units	Value		Calculation
			w/o IMRT	with IMRT	
a	Max Field Size	cm	40	40	
b	Fraction of Workload		50%	50%	
c	Effective Field Area	cm^2	1600.0		b_1*a_1^2 + b_2*a_2^2
d	Effective Field Size	cm	40.0		sqrt (c)
e	Scatter Angle	deg	60		
f	Machine X-ray Energy	MV	18		
g	Scatter / 400 cm^2		4.24E-04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

Example 11a: Direct Shielded Door Thickness Calculation [2 of 2]

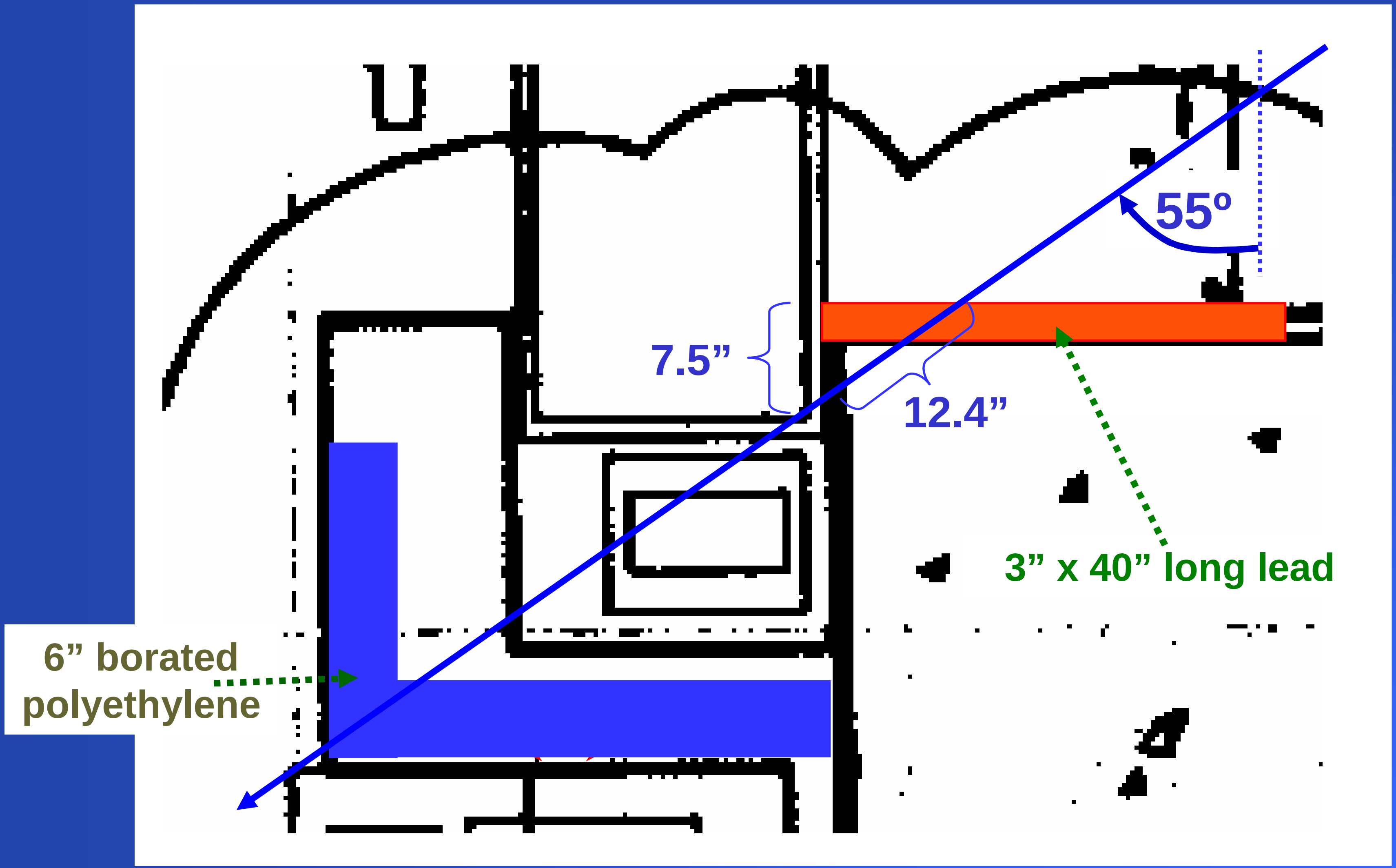
Line	Parameter	Units	Photon Leakage	Photon Scatter	Neutron Leakage	Calculation
a	Workload / Treatment	Gy/pt	3	3	3	NCRP 151 default
b	Patients per Day	pt/day	30	30	30	NCRP 151 default
c	Workload (W)	Gy/wk	450	450	450	5 * a * b
d	Use Factor	Ratio	1	1	1	
e	Fraction		1.00E-03	1.70E-03	1.5E-03	18 MV values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

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

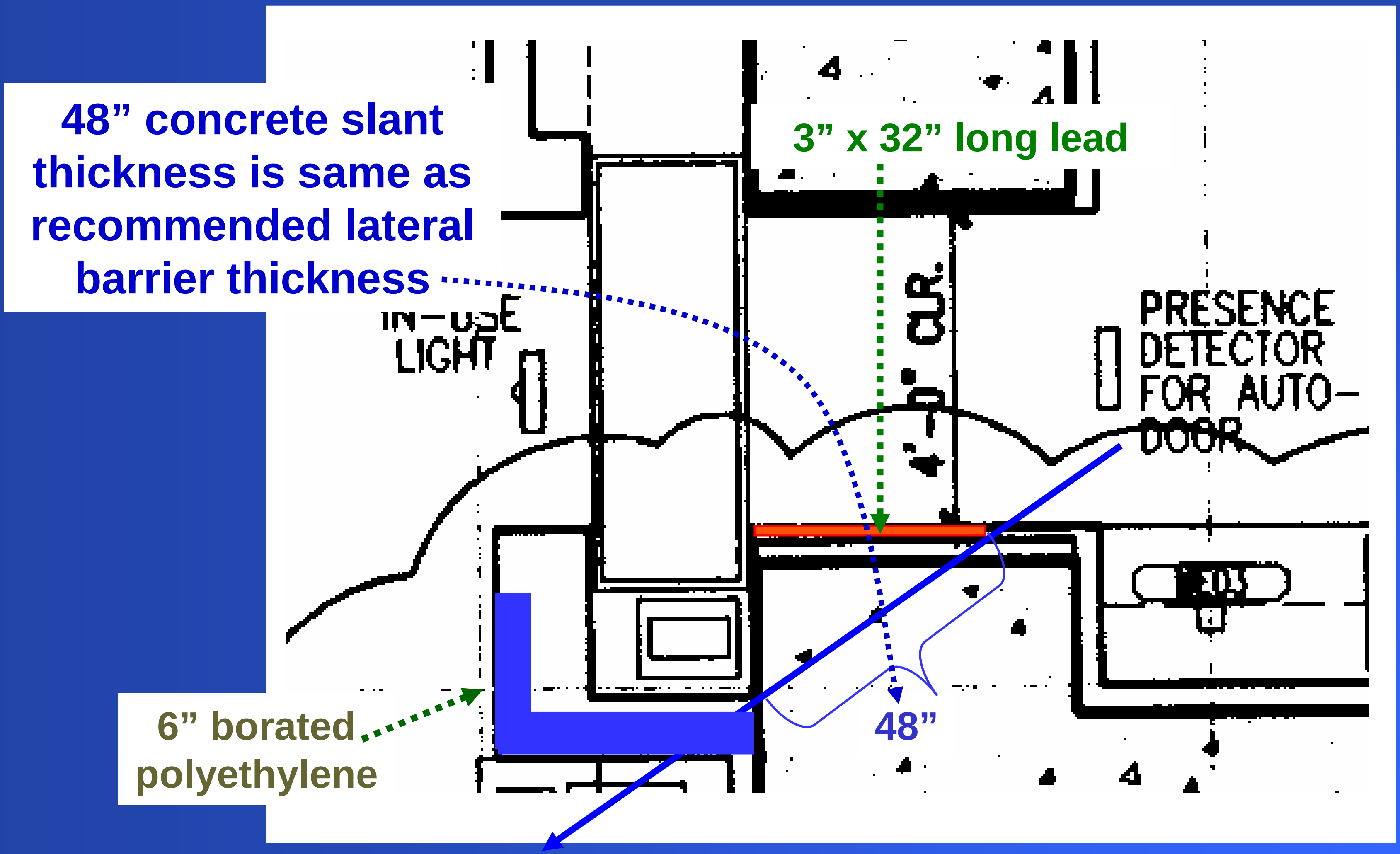
Example 11b: Direct Shielded Door — Additional Shielding for Far Side of Door



Example 11b: Direct Shielded Door — Additional Shielding for Far Side of Door



Example 11b: Direct Shielded Door — Additional Shielding for Far Side of Door



Example 11b: Direct Shielded Door Far Side of Entrance Shielded Dose Rate Calculation [1 of 3]

Far Side of Door Distance, Thickness, and Length Calculations

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

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

Example 11b: Direct Shielded Door Far Side of Entrance Shielded Dose Rate Calculation [2 of 3]

Far Side of Door Scatter Fraction Calculation

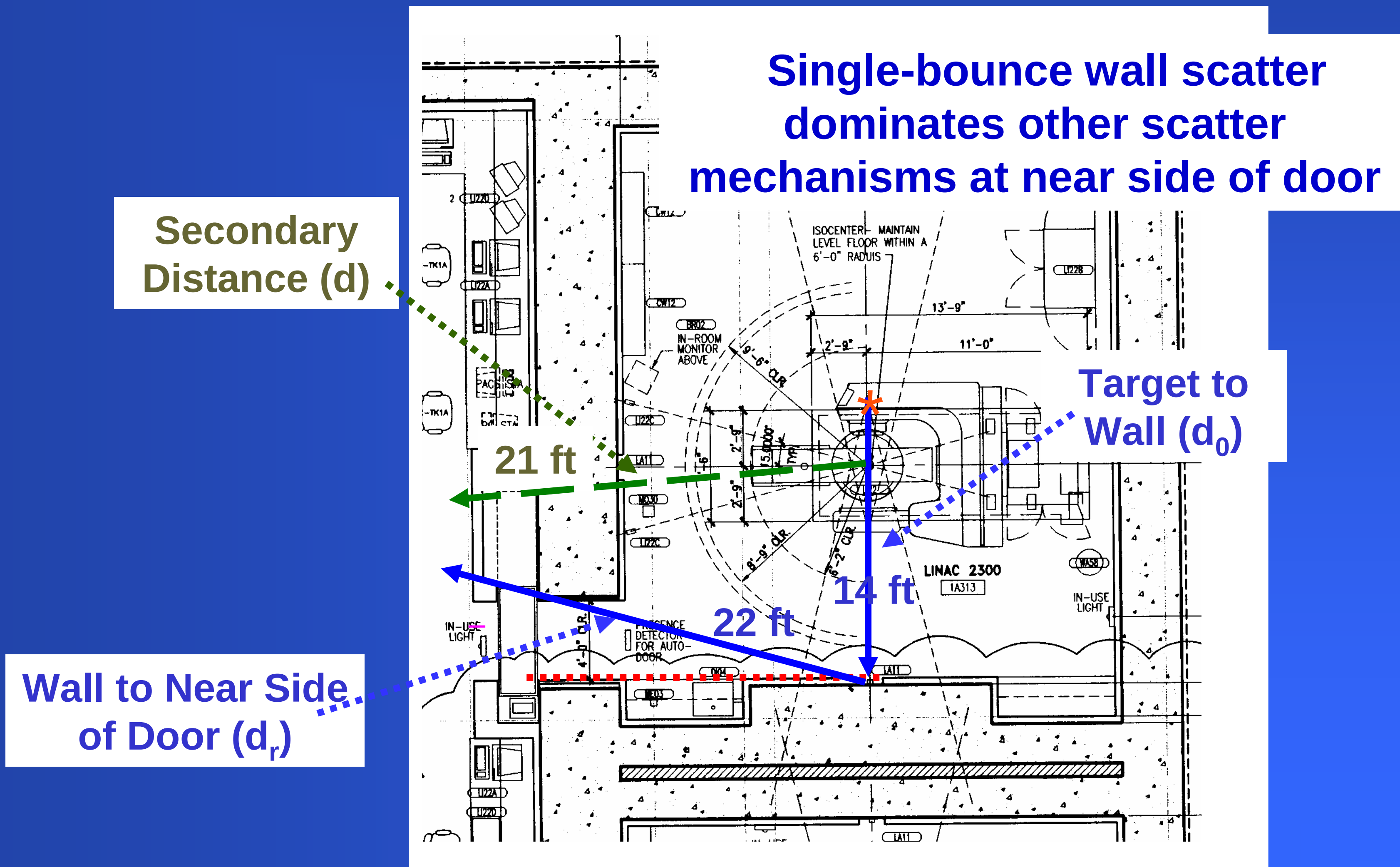
Line	Parameter	Units	Value		Calculation
			w/o IMRT	with IMRT	
a	Max Field Size	cm	40	40	
b	Fraction of Workload		50%	50%	
c	Effective Field Area	cm^2	1600.0		b_1*a_1^2 + b_2*a_2^2
d	Effective Field Size	cm	40.0		sqrt (c)
e	Scatter Angle	deg	54.8		
f	Machine X-ray Energy	MV	18		
g	Scatter / 400 cm^2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

Example 11b: Direct Shielded Door Far Side of Entrance Shielded Dose Rate Calculation [3 of 3]

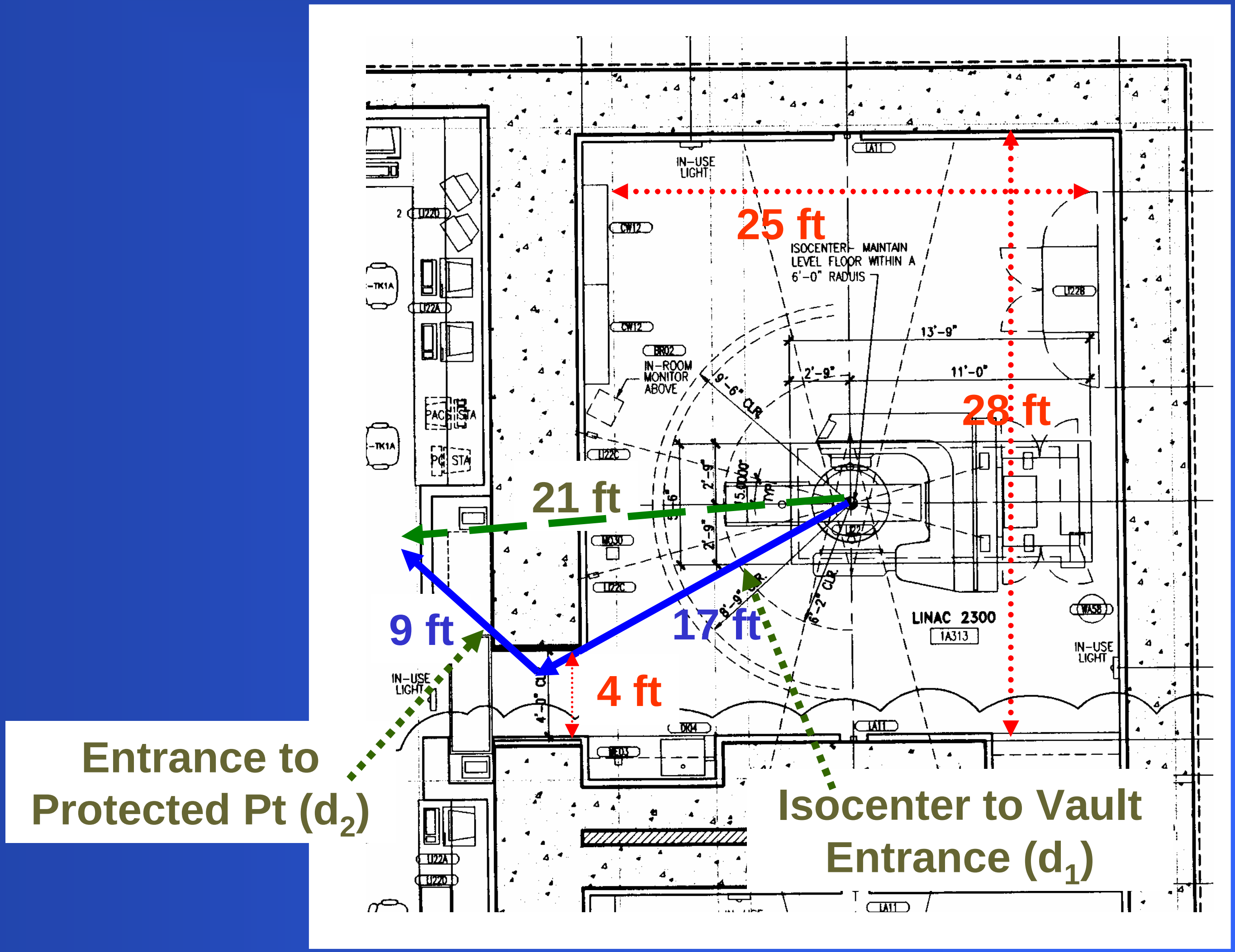
Line	Parameter	Units	Photon Leakage	Photon Scatter	Neutron Leakage	Calculation
a	Workload / Treatment	Gy/pt	3	3	3	NCRP 151 default
b	Patients per Day	pt/day	30	30	30	NCRP 151 default
c	Workload (W)	Gy/wk	450	450	450	5 * a * b
d	Use Factor	Ratio	1	1	1	
e	Fraction		1.00E-03	2.17E-03	1.50E-03	18 MV values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

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

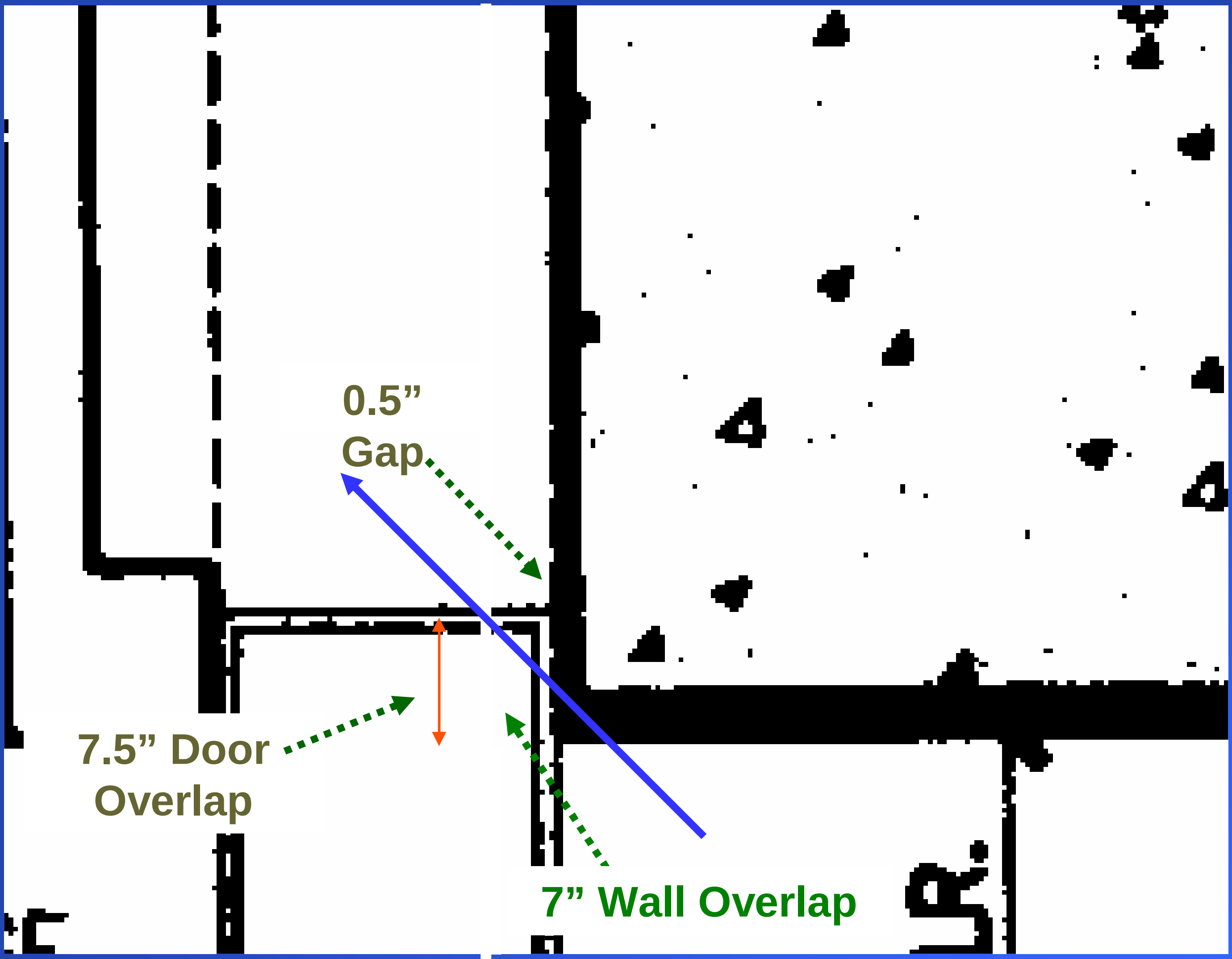
Example 11c: Direct Shielded Door— Additional Shielding for Near Side of Door (Wall Scatter)



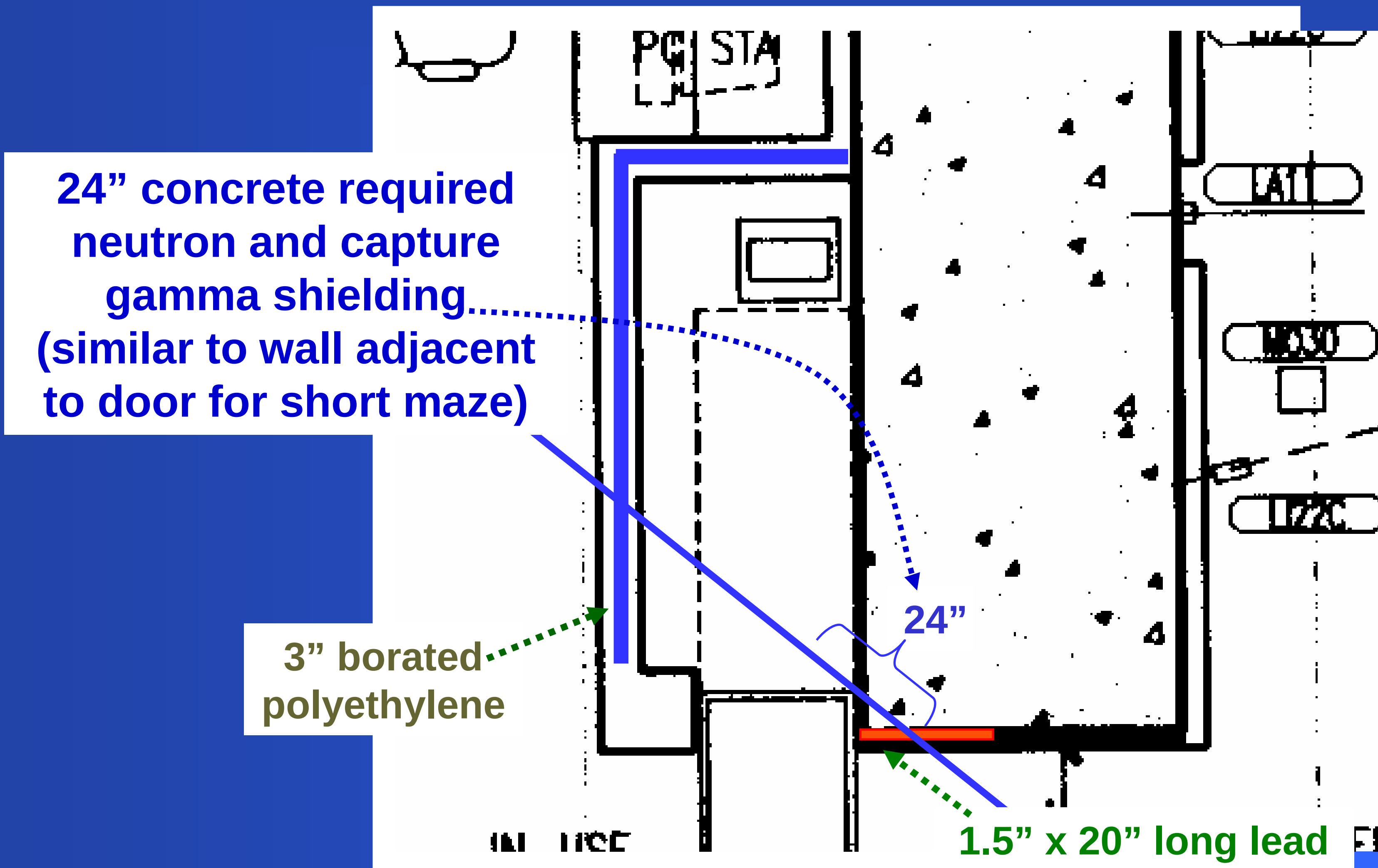
Example 11c: Direct Shielded Door— Additional Shielding for Near Side of Door (Neutrons / Capture Gammas)



Example 11c: Direct Shielded Door — Gap Between Wall and Door



Example 11c: Direct Shielded Door — Additional Shielding for Near Side of Door



Example 11c: Direct Shielded Door Near Side of Entrance Shielded Dose Rate Calculation [1 of 9]

Near Side of Door Material Thickness Calculation

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

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

Example 11c: Direct Shielded Door Near Side of Entrance Shielded Dose Rate Calculation [2 of 9]

Near Side of Door Scatter Fraction Calculation

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

Example 11c: Direct Shielded Door Near Side of Entrance Shielded Dose Rate Calculation [3 of 9]

Near Side of Door Shielded Dose Due to Direct Leakage

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

Transmission Calculation for Direct Leakage at Near Side of Door

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

Example 11c: Direct Shielded Door Near Side of Entrance Shielded Dose Rate Calculation [4 of 9]

Wall Scatter Transmission for Near Side of Door

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

Near Side of Door Wall Scatter Transmission Calculation

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

Example 11c: Direct Shielded Door Near Side of Entrance Shielded Dose Rate Calculation [5 of 9]

Maze Neutron Fluence Calculation

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

Example 11c: Direct Shielded Door Near Side of Entrance Shielded Dose Rate Calculation [6 of 9]

Capture Gamma Unshielded Dose Rate Calculation

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

Example 11c: Direct Shielded Door Near Side of Entrance Shielded Dose Rate Calculation [7 of 9]

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

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

Example 11c: Direct Shielded Door Near Side of Entrance Shielded Dose Rate Calculation [8 of 9]

Neutron Transmission for Near Side of Maze Entrance

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

Capture Gamma Transmission for Near Side of Maze Entrance

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

Example 11c: Direct Shielded Door Near Side of Entrance Shielded Dose Rate Calculation [9 of 9]

Maze Shielded Dose at Door

Line	Parameter	Units	Wall Scatter	Direct Leakage	Neutrons	Capture Gammas
a	Calc. Unshielded Dose	mSv/wk	1.03E+00	6.36E-03	2.08E+00	7.06E-01
b	Total / Calc. Dose Rate		2.64	1	1	1
c	Unshielded Dose Rate	mSv/wk	2.73E+00	6.36E-03	2.08E+00	7.06E-01
b	Energy for TVL	MV	0.3	18	0.1	10.0
c	Transmission		5.73E-09	1.00E+00	2.39E-04	3.00E-02
d	Shielded Dose	mSv/wk	0.0000	0.0064	0.0005	0.0212
e	Total Shielded Dose	mSv/wk	0.0281			

Shielding for Heating, Ventilation, and Air Conditioning (HVAC) Ducts

- HVAC penetration is located at ceiling level in the vault
  - For vaults with maze, typically located immediately above door
  - For direct-shielded doors, located in a lateral wall parallel to the plane of gantry rotation as far away from isocenter as possible
- Ducts shielded with material similar to the door at entrance
- For direct-shielded door, thickness 1/2 to 1/3 of the door
  - Path through material is at a very oblique angle due to penetration location with slant factor between 2 and 3
  - Factor of at least 5 reduction in dose at head level (the protected location) vs. at the HVAC duct opening
- Even less material is is required for maze duct
  - NCRP 151 example is 3/8" lead plus 1" BPE extending 4 ft

For purposes of shielding design for x-ray beams, the term high energy accelerator is defined as an accelerator with an x-ray beam of an energy:

24%	1.	at least 6 MV
14%	2.	at least 10 MV
49%	3.	greater than 10 MV
14%	4.	at least 15 MV
0%	5.	at least 20 MV

10

Answer: # 3 - greater than 10 MV

- Ref: "Structural Shielding Design and Evaluation for Megavoltage X- and Gamma-Ray Radiotherapy Facilities," NCRP Report 151 (2005), p. 9

When allowing for IMRT procedures in shielding design calculations, it is assumed that the prescribed total treatment absorbed dose per patient is unchanged by IMRT and that the number of patients treated with designated energy beams is unchanged. This results in the following modification to be made in the shielding calculations:

61%	1.	the leakage radiation workload increases
11%	2.	the patient-scattered-radiation workload increases
11%	3.	the leakage radiation workload does not change
0%	4.	the patient-scattered-radiation workload does not change
17%	5.	(a) and (d)

10

Answer: # 5 - Both patient-scattered radiation and leakage workloads increase

- Ref: "Structural Shielding Design and Evaluation for Megavoltage X- and Gamma-Ray Radiotherapy Facilities," NCRP Report 151 (2005), p. 123

For a maze door in a vault with an 18 MV linear accelerator operating in IMRT mode, the shielding requirements would typically consist of:

0%	1.	Lead shielding of approximately 30 mm
6%	2.	Borated Polyethylene shielding of approximately 70 mm
6%	3.	Steel encasements of 6.4 mm on each side of the door
77%	4.	(1) and (2) and (3)
11%	5.	(1) and (3) only

10

Answer: # 4 - all three components

- Ref: “Structural Shielding Design and Evaluation for Megavoltage X- and Gamma-Ray Radiotherapy Facilities,” NCRP Report 151 (2005), p. 138

For linear accelerator treatment rooms without mazes, the recommended location for duct penetrations is:

22% 1. over the sliding doors

19% 2. in the walls parallel to the gantry rotation plane

44% 3. in the walls perpendicular to the gantry rotation plane

16% 4. in the ceiling

0% 5. in the primary barrier

10

Answer: # 2 - in the walls parallel to the gantry rotation plane

- Ref: “Structural Shielding Design and Evaluation for Megavoltage X- and Gamma-Ray Radiotherapy Facilities,” NCRP Report 151 (2005), p. 79

Which of the following statements is correct?

89%	1.	Concrete and heavy concrete are effective shielding materials for both x-rays and neutrons
11%	2.	Lead shields both x-rays and neutrons in a thinner barrier than concrete
0%	3.	Steel shields both x-rays and neutrons in a thinner barrier than concrete
0%	4.	Polyethylene shields both x-rays and neutrons cheaper than concrete
0%	5.	Rebar is a significant shielding component in concrete barriers

10

Answer: # 1 - concrete and heavy concrete

- Ref: "Structural Shielding Design and Evaluation for Megavoltage X- and Gamma-Ray Radiotherapy Facilities," NCRP Report 151 (2005), p. 71-73.