Basic Principles of Radiation Therapy Shielding Design

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Outline

1. *Basic principles and definitions*
2. *Calculations*
3. *Workload, use and occupancy factors*
4. *Shielding materials*
5. *Tenth value layers (TVL)*
6. *Room layout & features, construction details*
7. *Neutrons & laminated barriers*
8. *Mazes and doors*
9. *Ducts*

Definitions

P:	*Weekly design dose limit (Sv/wk)*
d:	*Distance from target to measurement point*
W:	*Workload (Gy/wk)*
U:	*Use Factor*
T:	*Occupancy factor*
a:	*Scatter fraction; (θ, E)*
d_{sec}:	*Distance from scatterer to measurement point*
d_{sca}:	*Distance from target to scatterer*
d_l:	*Distance from the target to measurement point*
F:	*Area of the beam in the plane of the scatterer (cm^2)*
B:	*Barrier transmission factor*

Also IPEM Report #75

Basic Principles

The purpose of radiation shielding is to reduce the effective equivalent dose from a linear accelerator to a point outside the room to a level that is determined by individual states.

Public or uncontrolled area - 0.02 mSv per week
- 0.02 mSv in any one hour

Controlled area - 1 mSv/wk (in practice 0.1 mSv/wk)

Basic Shielding Equations: NCRP #151 Methodology

Primary:

$$B_p = \frac{Pd^2}{WUT}$$

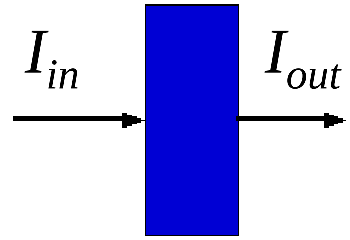
Scatter:

$$B_s = \frac{P}{aWT} d_{sec}^2 d_{sca}^2 \frac{400}{F}$$

Leakage:

$$B_l = \frac{1000 * Pd_l^2}{WT}$$

The factor 1000 is due to the 0.1% leakage requirement



$$B_x = \frac{I_{out}}{I_{in}}$$

B_x is the barrier transmission factor

Number of Tenth Value Layers (Primary & Leakage)

The number, n, of tenth value layers (TVLs) required to reduce the dose to the value P is given by:

$$n = -\log_{10}(B)$$

and the thickness for primary and leakage radiation is given by:

$$T = {}_{p,l}TVL_1 + (n-1)\,{}_{p,l}TVL_e$$

NCRP report No. 151 Table B.2

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Number of Tenth Value Layers for Scattered Radiation

Scatter TVLs are dependent only on energy and scattering angle, so:

$$\boxed{T_s = n_s\, TVL_s(\vartheta)}$$

NCRP report No. 151, Table B.5a

Tenth Value Layers

Primary TVLs (cm)*

Energy (MV)	4	6	10	15	18	20
Concrete	35(30)	37(33)	41(37)	44(41)	45(43)	46(44)
Steel	9.9	10	11	11	11	11
Lead	5.7	5.7	5.7	5.7	5.7	5.7

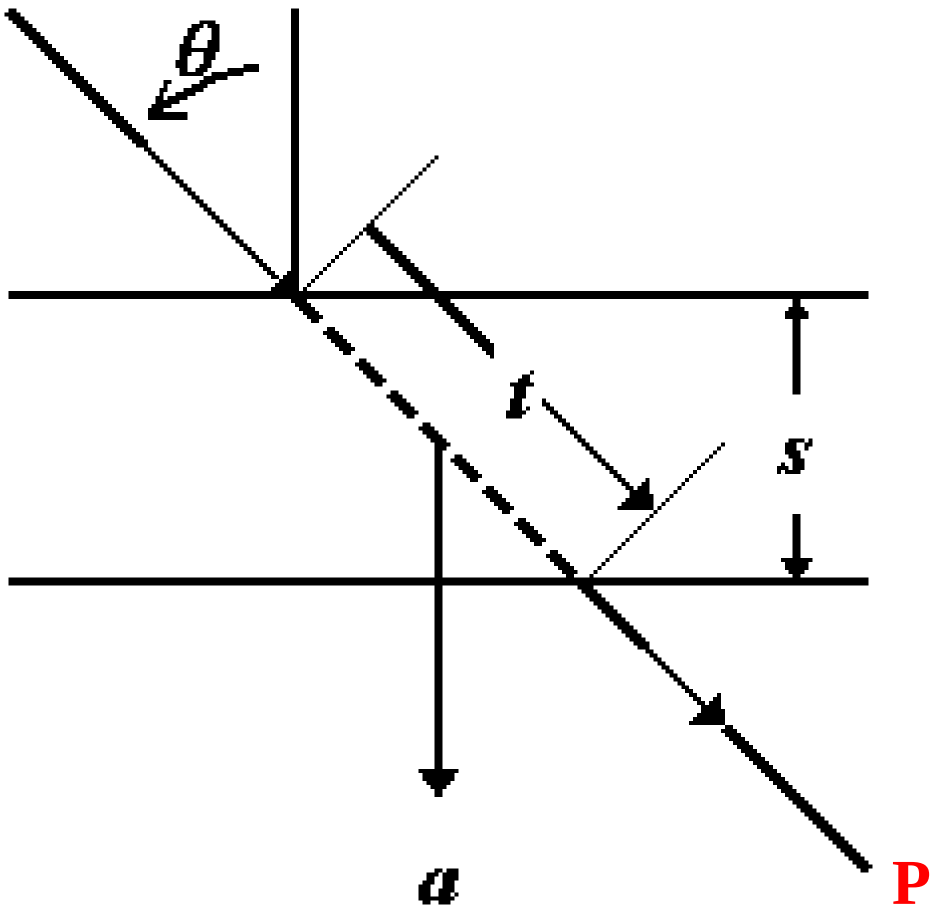
Leakage TVLs at 90°* (cm)

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*

Obliquity Factor - I



slant thickness (t)

$t = s/\cos\theta$

s = shield thickness

Obliquity factor - II

Rule of thumb:

- for $\theta > 45°$

- and B<0.001

- Add ~2 HVL for low-energy photons
- And ~1 HVL for high-energy photons

Obliquity factor - III

- Experimental data by Kirn et. al. (1954)
- verified by Biggs (1996) using the Monte Carlo for a large range of clinical energies
- Monte Carlo results are in good agreement with previous recommendations at low energy, but more detail is given
- Caveat: beware of applying obliquity factor corrections for large angles!!

Conventional Workload

- Number of patients treated per week multiplied by the average dose (MU)/patient at isocenter
- Include calibration, service, if indicated
- Recommended values: 500 or 1000 Gy wk^{-1}
- Survey shows values from 250 to 450 Gy wk^{-1}
- Balance between high energy and low energy use? Using high energy is conservative approach
- Electron-only (IORT) machines?

Workload TBI

- Workload for TBI >> workload for conventional therapy due to the extended distances:

$$\boxed{W_{TBI} = D_{TBI} d_{TBI}^2}$$

- Leakage workload is also higher, but patient- and wall-scattered workload is not.

- Radiation is usually directed at one barrier

Workload IMRT (1)

- Workload for IMRT is complicated by the fact that the #MU is much larger than for conventional therapy. The IMRT factor is defined as:

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

  and varies between 2 and 10 or more

- This only affects leakage radiation, not primary or scattered radiation.

Workload IMRT (2)

- Helical tomotherapy has the highest "C" values, >10.
- Linac based IMRT at MGH gives an average "C" value of about 5
- Impact of IMAT on MUs (VMAT, Rapid Arc) – reduction of MUs
- Anecdote: For a 6/18 MV machine the energy use prior to IMRT was 20%/80% (MU). With 28% IMRT patient load, the use was 70%/30%. Hence need to consider balancing the workload for two energies

Conventional Use Factors

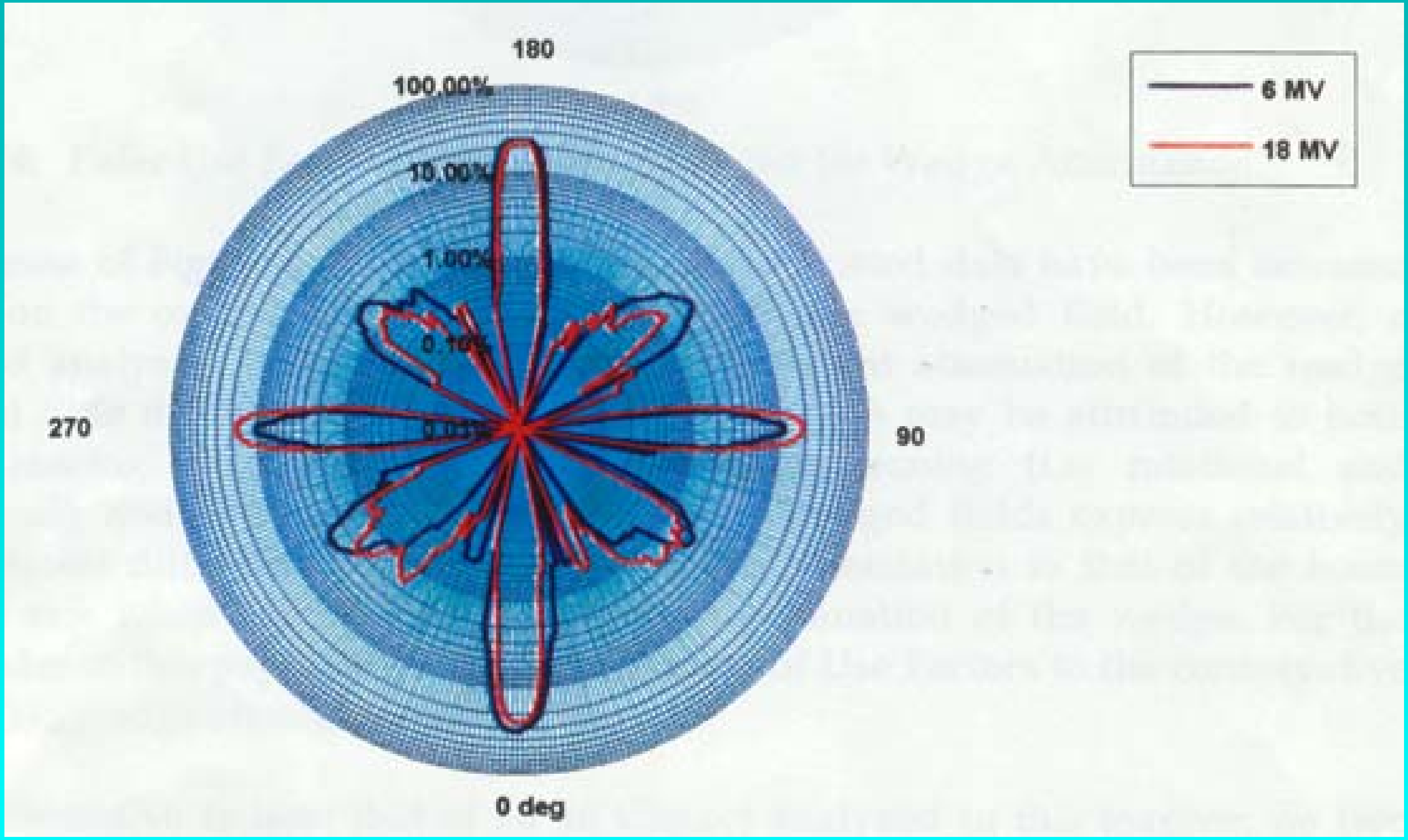
90° interval:

- *0° (31%); 90° and 270° (21.3 % each); 180° (26.3 %)*
  - *previously, all barriers were assigned 0.25*

45° interval:

- *0° (25.6 %); 45° and 315° (5.8 % each); 90° and 270° (15.9 % each); 135° and 225° (4 % each); 180° (23 %)*

Use Factor for Conventional Therapy



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Use Factors – Special Cases

- *A significant TBI load will require one wall to have an increased use factor*

- *IMRT may also require a change in the values assigned to the use factor for the primary barrier*

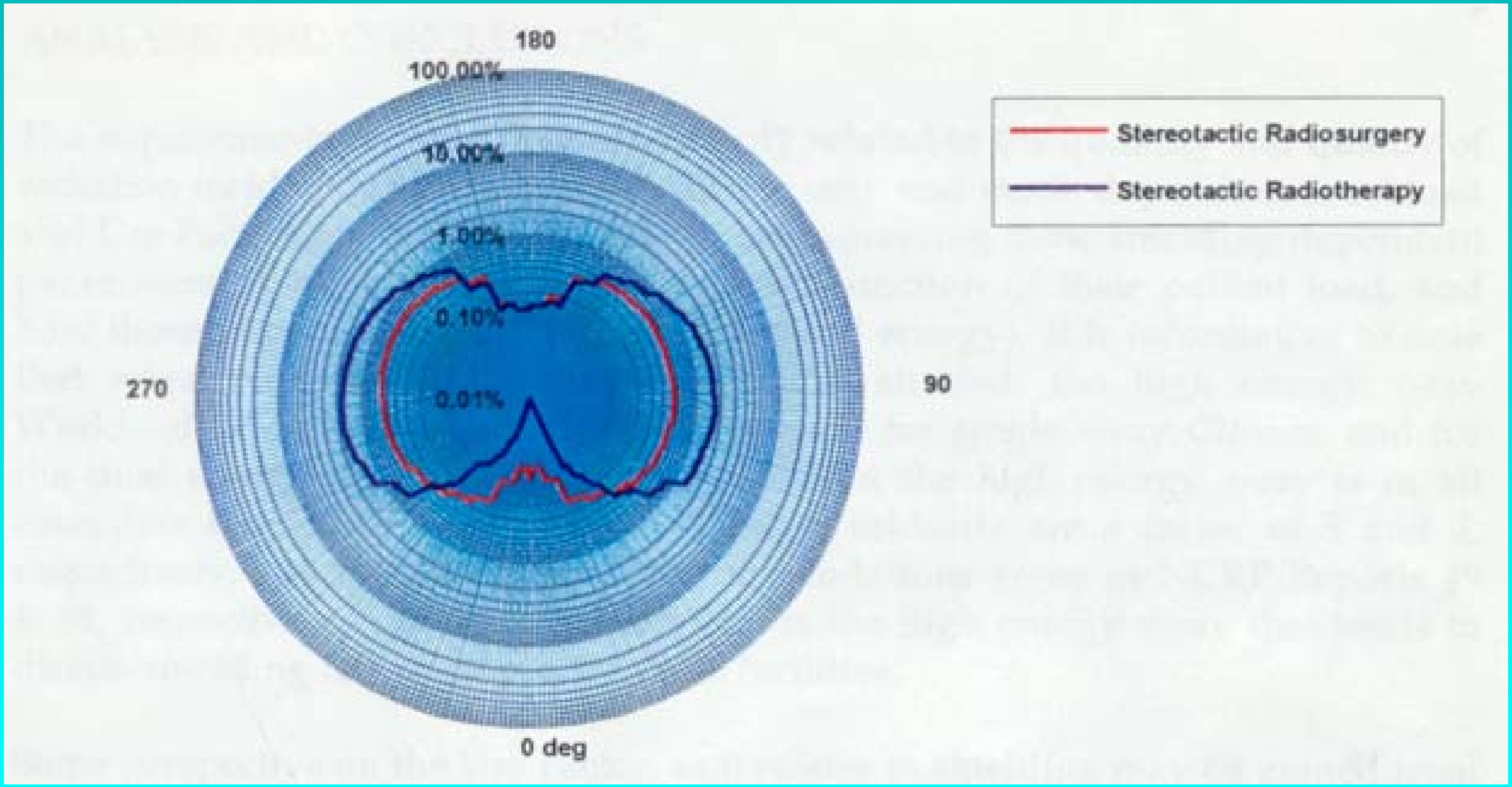
Use Factor – Dedicated Machines

- One should pay attention to the types of procedures to be carried out in new room

- A room dedicated to SRS and SRT requires different considerations from a general therapy room

- A room dedicated to breast treatments will use specific ranges of primary beam angles

Example: Use Factor for Stereotactic Radiosurgery



Workload - Summation (1)

Primary:

$$WU_p = WU_{wall\ scat} =$$
$$(W_{conv}U_{conv} + W_{TBI}U_{TBI} + W_{IMRT}U_{IMRT} + W_{QA}U_{QA} + ...)$$

Patient scatter:

$$W_{scatter,iso} = (W_{conv} + W_{IMRT} + W_{QA} + ...)$$

(note that the TBI contribution is calculated separately – source not at isocenter)

Workload - Summation (2)

Leakage:

$$W_L = (W_{conv} + W_{TBI} + C_I W_{IMRT} + C_{QA} W_{QA} + ...)$$

Occupancy Factors

- Occupancy factors down to 1/40 are now allowed
- This is the limiting factor to permit 0.02 mSv in any one hour using an MPD of 0.02 mSv/wk
- Area beyond vault door can now have an occupancy of 1/8
- Caveat: be sure to check not only the occupancy of the immediately adjacent area, but also the area beyond. For example, an office beyond a corridor becomes the dominant factor in the calculation. Also future development plans foreseen.

If the Dose Rate is High, Should I Freak Out?

Note that even for a weekly limit of 0.02 mSv/wk, the dose rate outside a barrier could be quite high.

e.g. for a primary barrier, an occupancy of 1/40 would imply a weekly dose of 3.8 mSv and for a beam on time of 2.8 hr, the instantaneous dose rate is 1.34 mSv/hr!!

Moral: Choose factors wisely!!

Instantaneous Dose Rate (IDR)

- NCRP recommends use of 1 hr as the minimum period for measuring IDR

- Compares with many places (e.g., Europe) where the instantaneous dose rate at the highest dose delivery rate is used

- Not an issue for occupancy of 1 for uniformly spaced treatments

- Only an issue when treatments are not given uniformly throughout the 40 hr week or occupancy is <1

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Shielding Materials

Materials	Density (g/cm^2)	Comments
Concrete	2.35; 3.85	High density concrete is very expensive
Concrete blocks	2.35; 3.85; 4.62	Lack structural integrity of concrete
Lead	11.35	Great for photons; bad for neutrons. Needs structural support
Steel	7.87	Not as efficient as lead for photons, but better for neutrons
Earth	1.5	Cheap! Therefore, build underground
Brick	1.65 - 2.05	
Polyethylene; borated polyethylene	~1.0	Used to shield against neutrons in doors, ducts etc.

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Width of Primary Barrier - I

- Allow 1 foot (0.3 m) either side of the primary beam

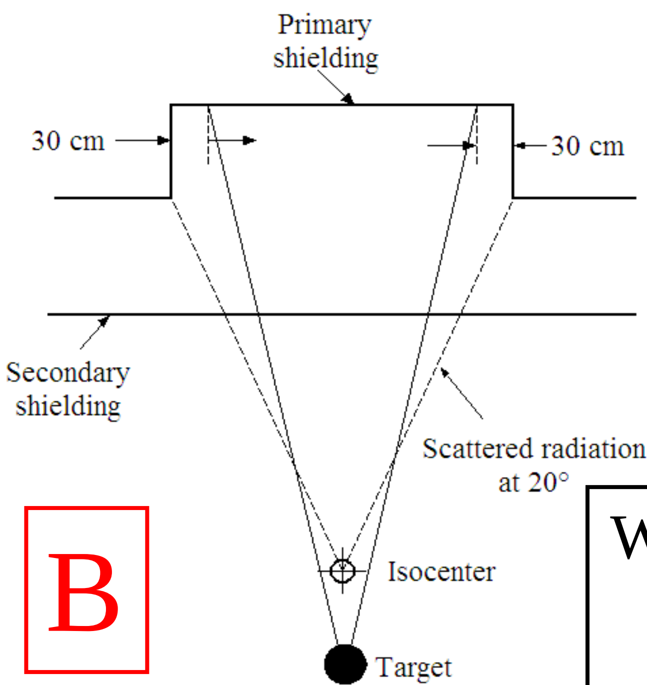
$$w = 0.4\sqrt{2}d + 0.6$$

- allow for fixed primary collimator diameter (0.5 m)

$$w = 0.5d + 0.6$$

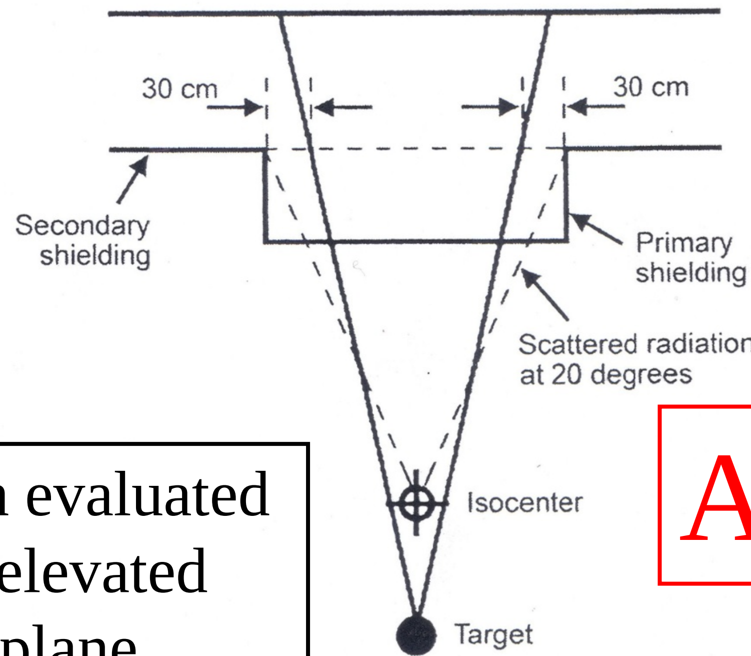
- Allow for greater width at the top of the wall

$$w = 0.5d' + 0.6$$

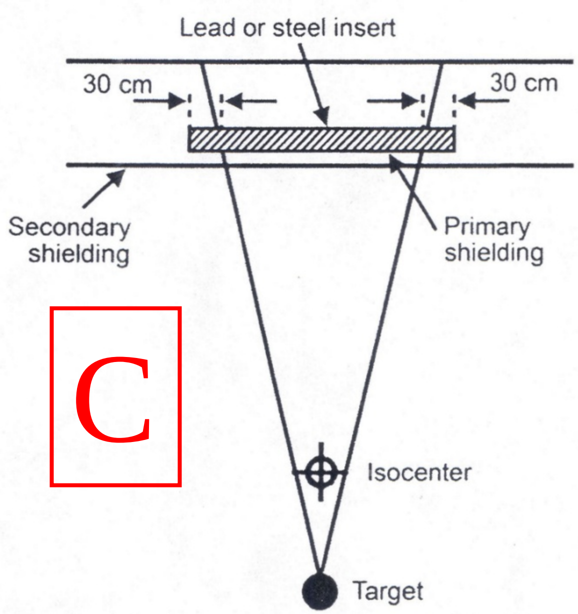


B

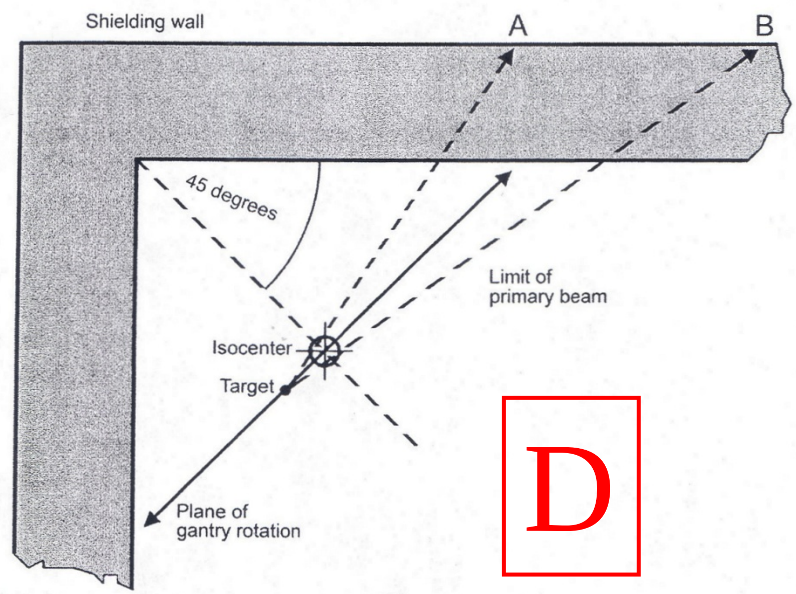
Width evaluated in elevated plane



A

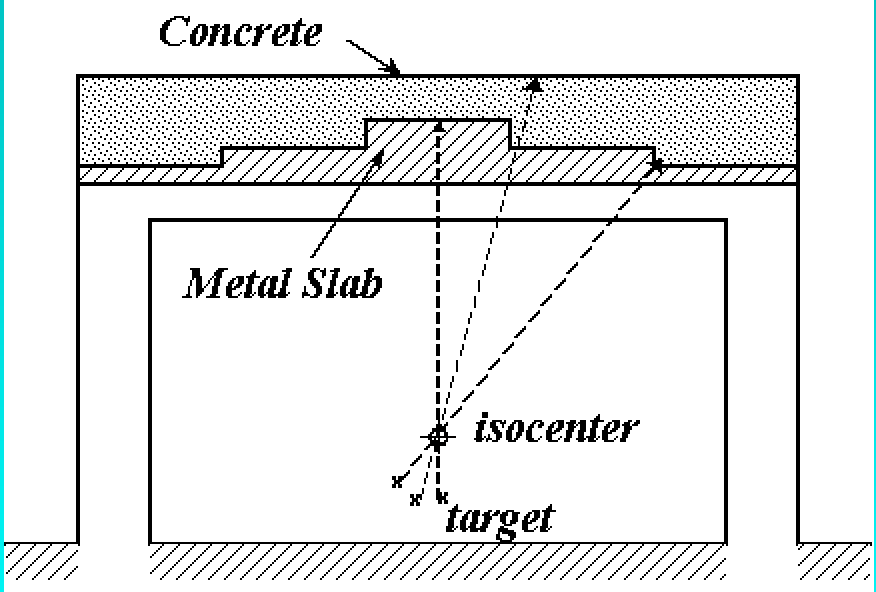


C

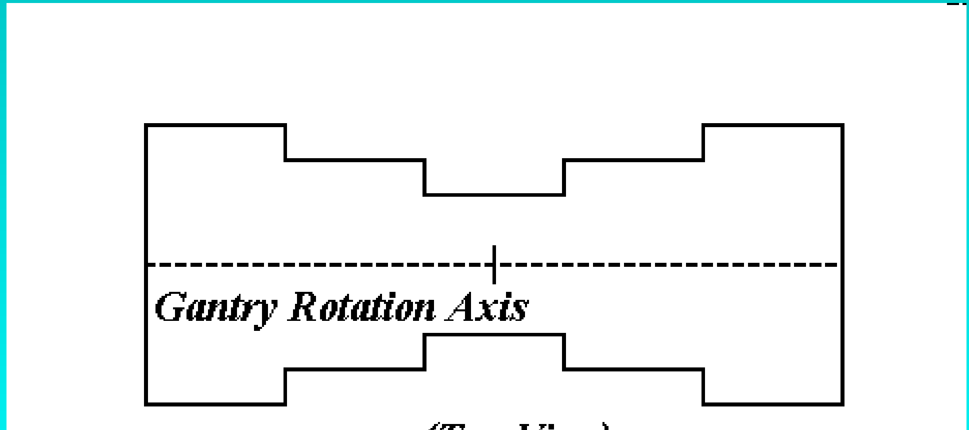


D

Contouring the Primary Shielding in the Ceiling

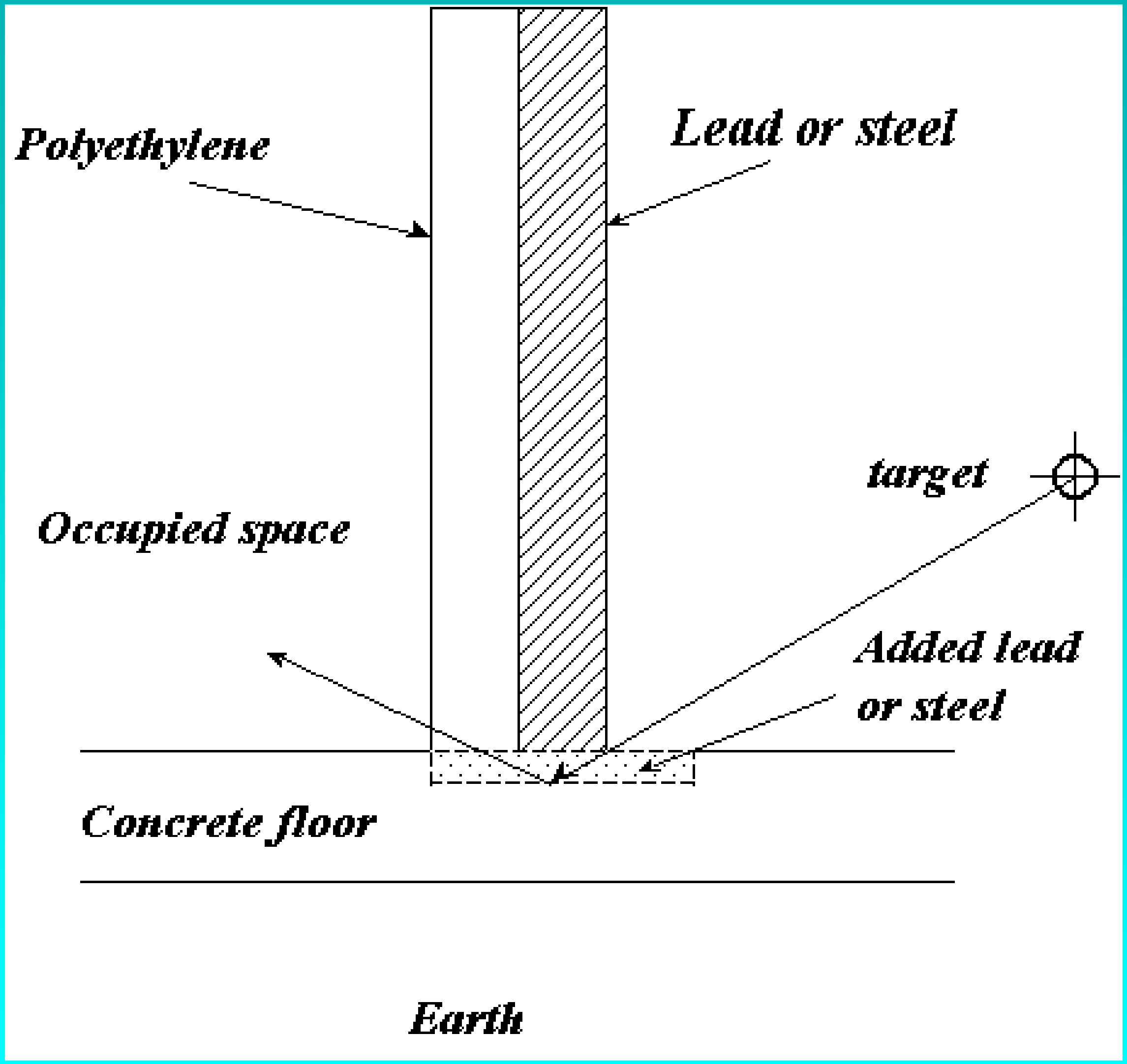


(Side View)



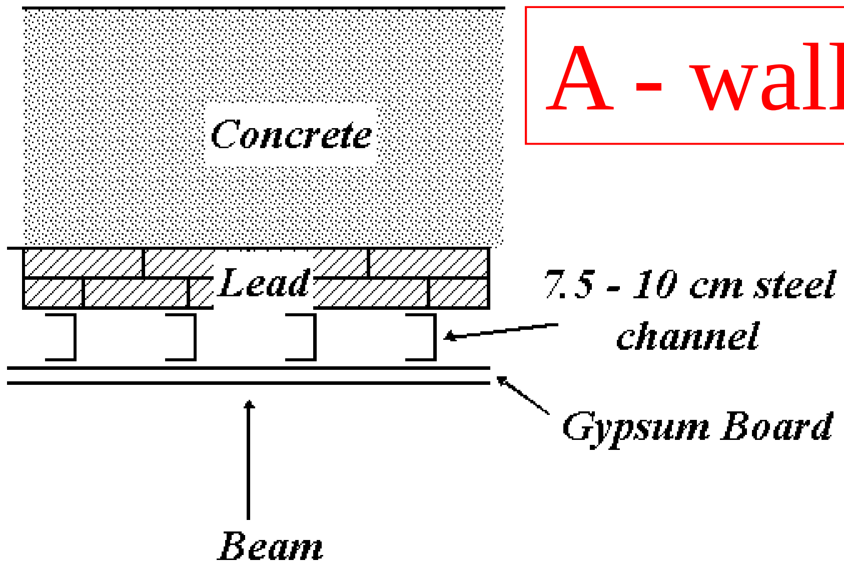
(Top View)

Lead-Only Room: Groundshine

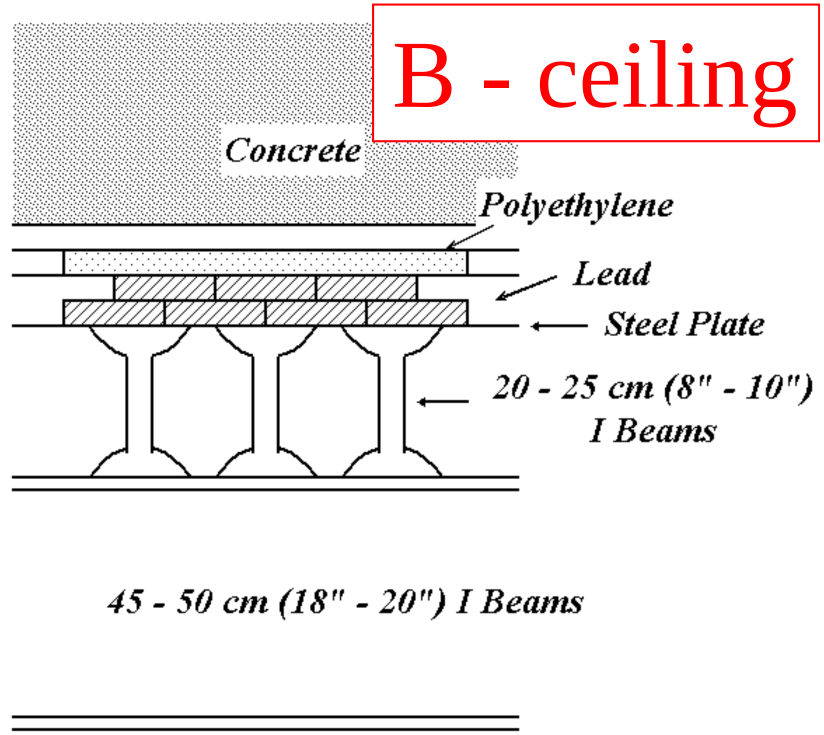


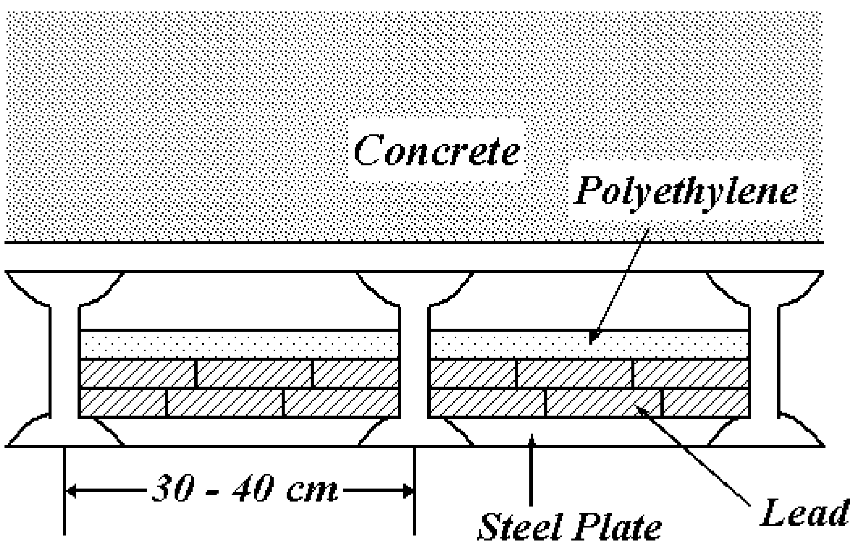
"McGinley" effect

A - wall



B - ceiling





C - ceiling

for primary barriers, laser support should be attached to the steel channel

Neutron Spectra from Medical Linacs

- *Neutrons produced in the head of the linac are first moderated by the x-ray shielding*
- *Neutrons are further moderated by scattering off the concrete walls of the therapy room*
- *Walls with only regular density concrete that are sufficient for x-ray protection will be adequate for neutrons.*

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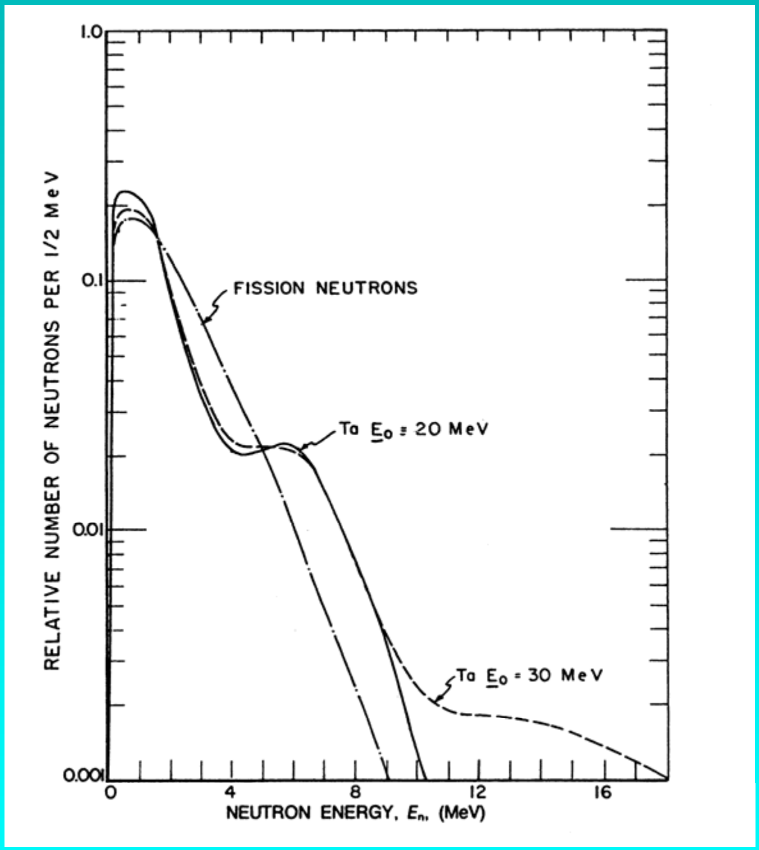
Neutron Spectra from Medical Linacs

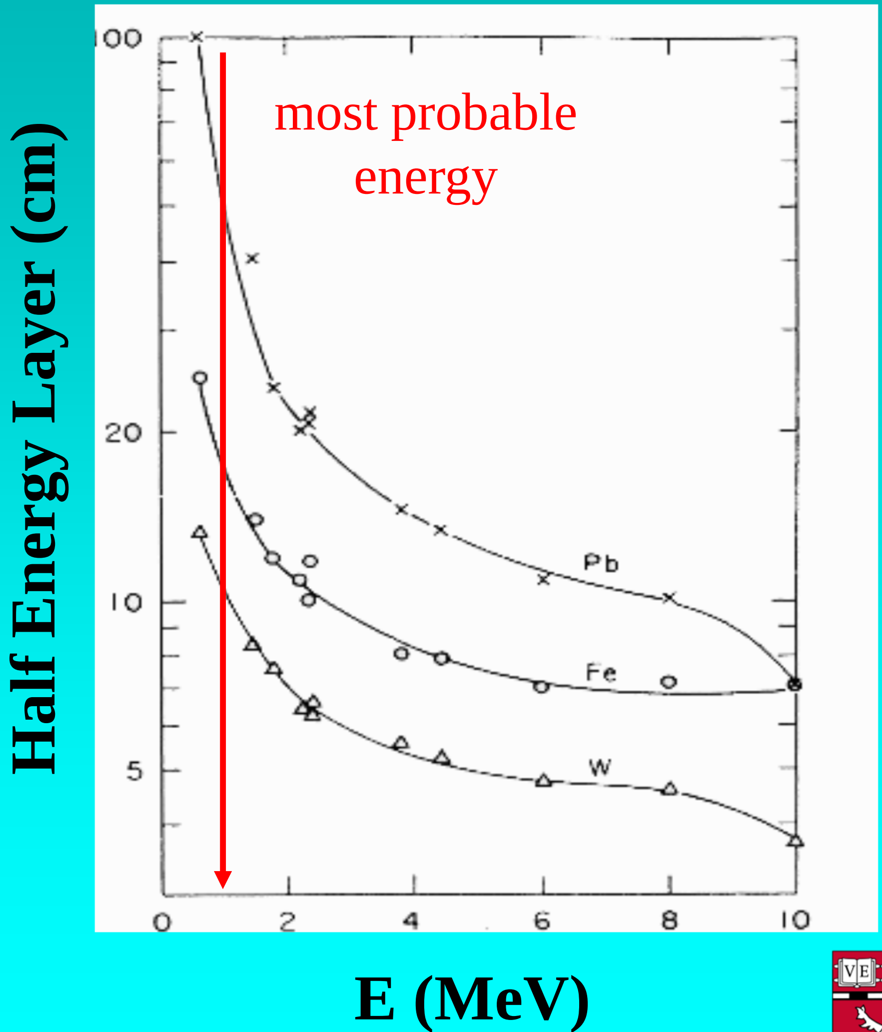
- *The total neutron fluence therefore consists of direct ('fast') neutrons, scattered neutrons and thermal neutrons*

$$\boxed{\Phi_{total} = \Phi_{dir} + \Phi_{sca} + \Phi_{th}}$$

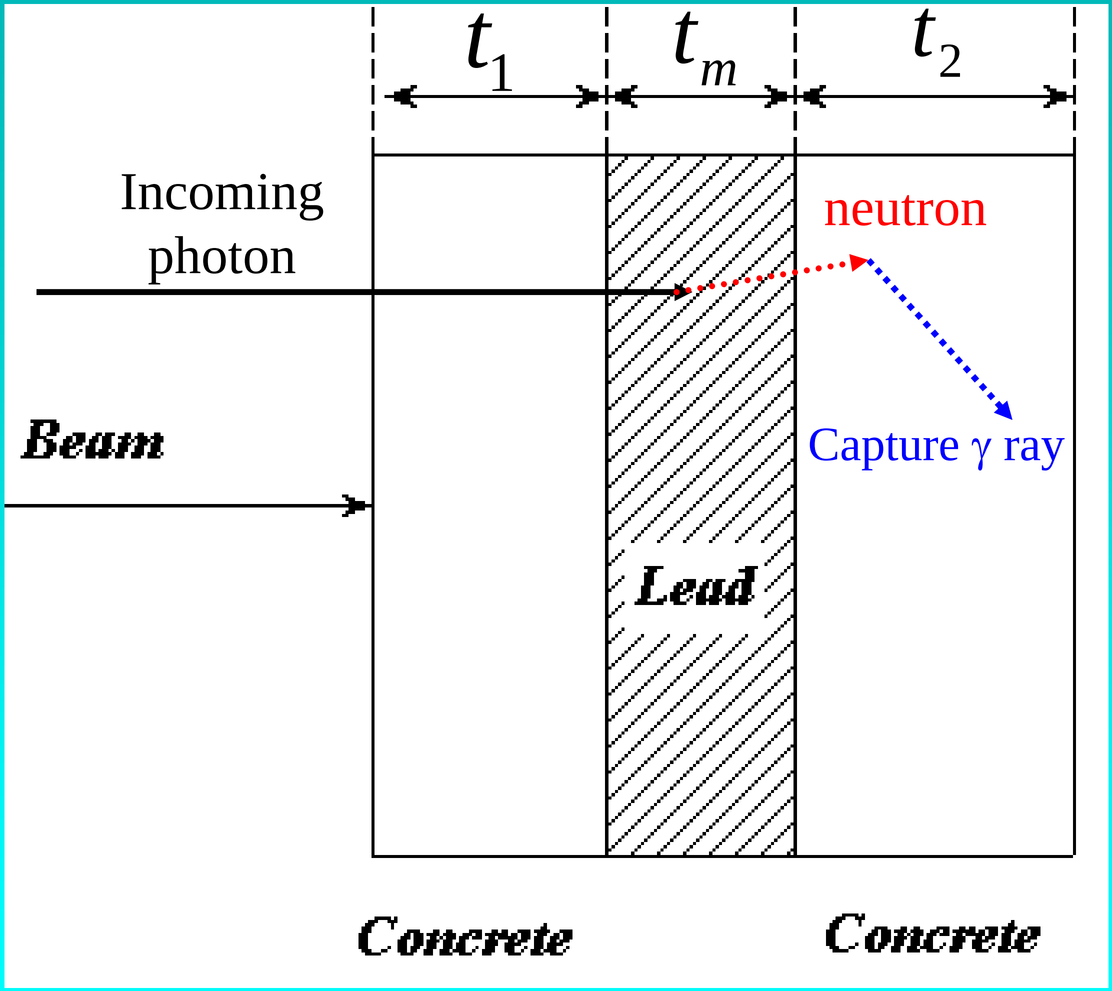
- *Fast neutrons obey the inverse law, but scattered and thermal neutrons are isotropically distributed; hence the neutron fluence drops off less fast than inverse square*

Shielding Thickness Required to Halve the Average Neutron Energy





Production of Neutrons by Primary Beam in a Laminated Barrier



For high energy x-ray beams, the x-ray dose is enhanced by a factor of 2.7 to be conservative

Production of Neutrons by Primary Beam in a Laminated Barrier

$$H = \frac{D_0 R\, F_{\max}}{\left(\frac{t_m}{2} + t_2 + 0.3\right)} * 10^{-t_1/TVL_x} * 10^{-t_2/TVL_n}$$

where H is the neutron dose equiv.($\mu Sv\ wk^{-1}$)

D_0 is the x-ray dose at isocenter (cGy wk^{-1})

R is the neutron prod^n. rate ($\mu Sv\ cGy^{-1}\ m^{-2}$)

and F_{max} is the max. beam area at isocenter (m^2)

Total Dose Behind a Laminated Barrier

$$H_{tot} = H_n + H_{ph} = H_n + 2.7 * H_{tr}$$

The 2.7 factor accounts for the production of capture gamma rays by the photo-produced neutrons. This is an conservative, empirical figure given by McGinley

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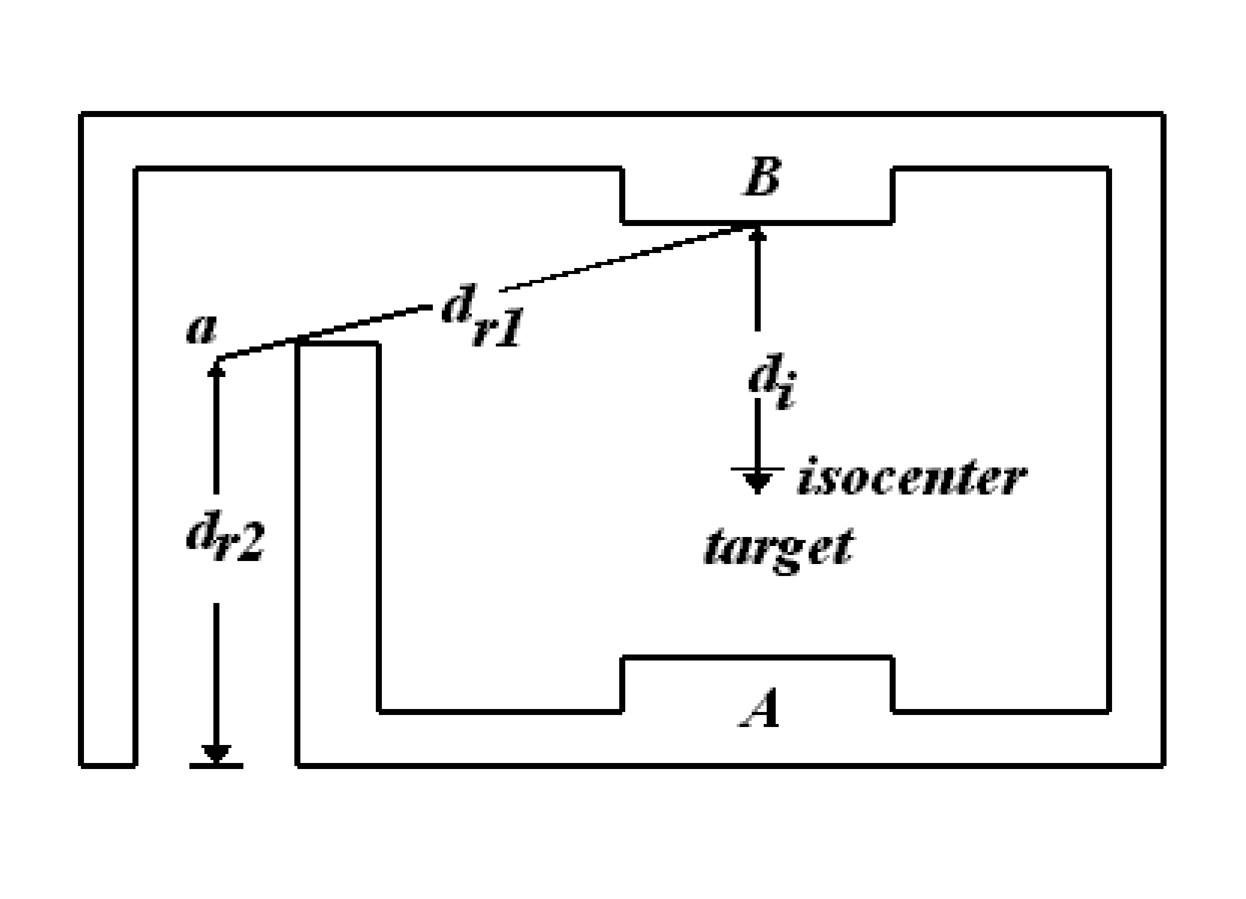
Contributions to the Dose at the End of a Maze

1. Primary scatter
2. Patient scatter
3. Leakage along maze
4. Leakage through maze wall

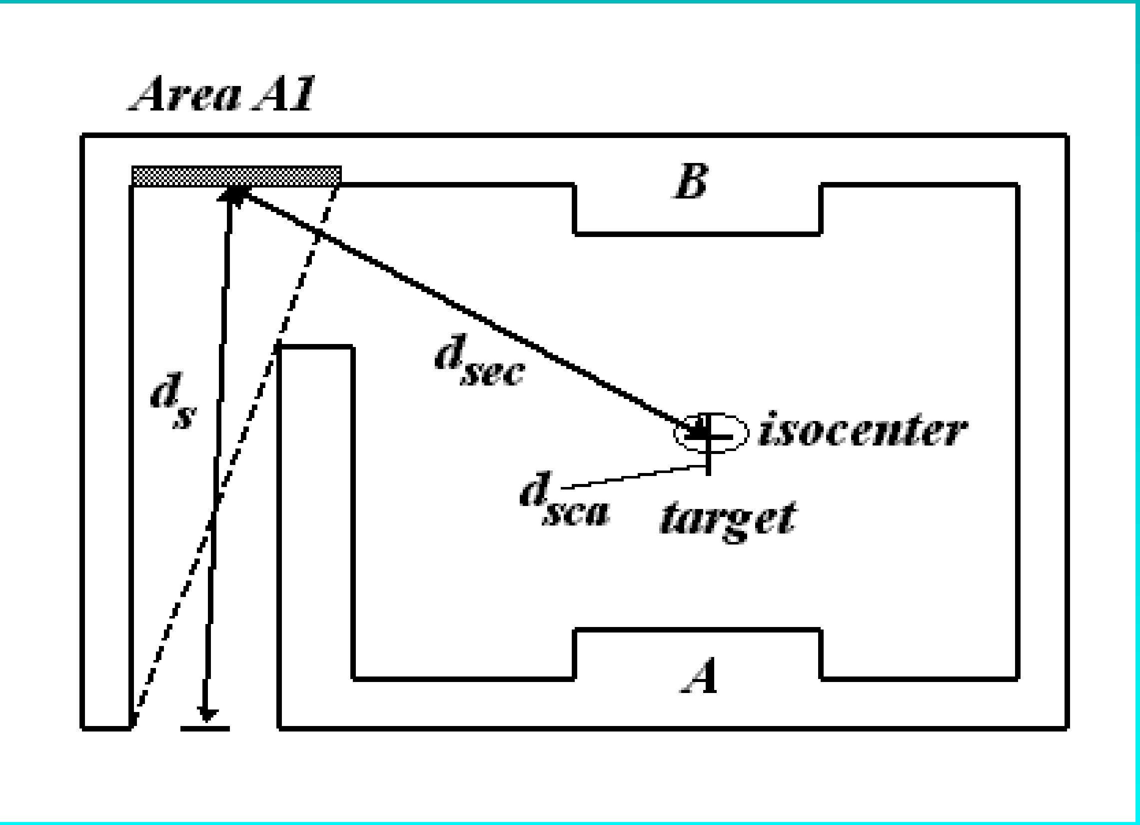
Secondary Radiation at Door due to Wall Scatter of Primary Beam

$$S_s = \frac{W\,U_B \alpha_1 A_1 \alpha_2 A_2}{\left(d_i d_{r1} d_{r2}\right)^2}$$



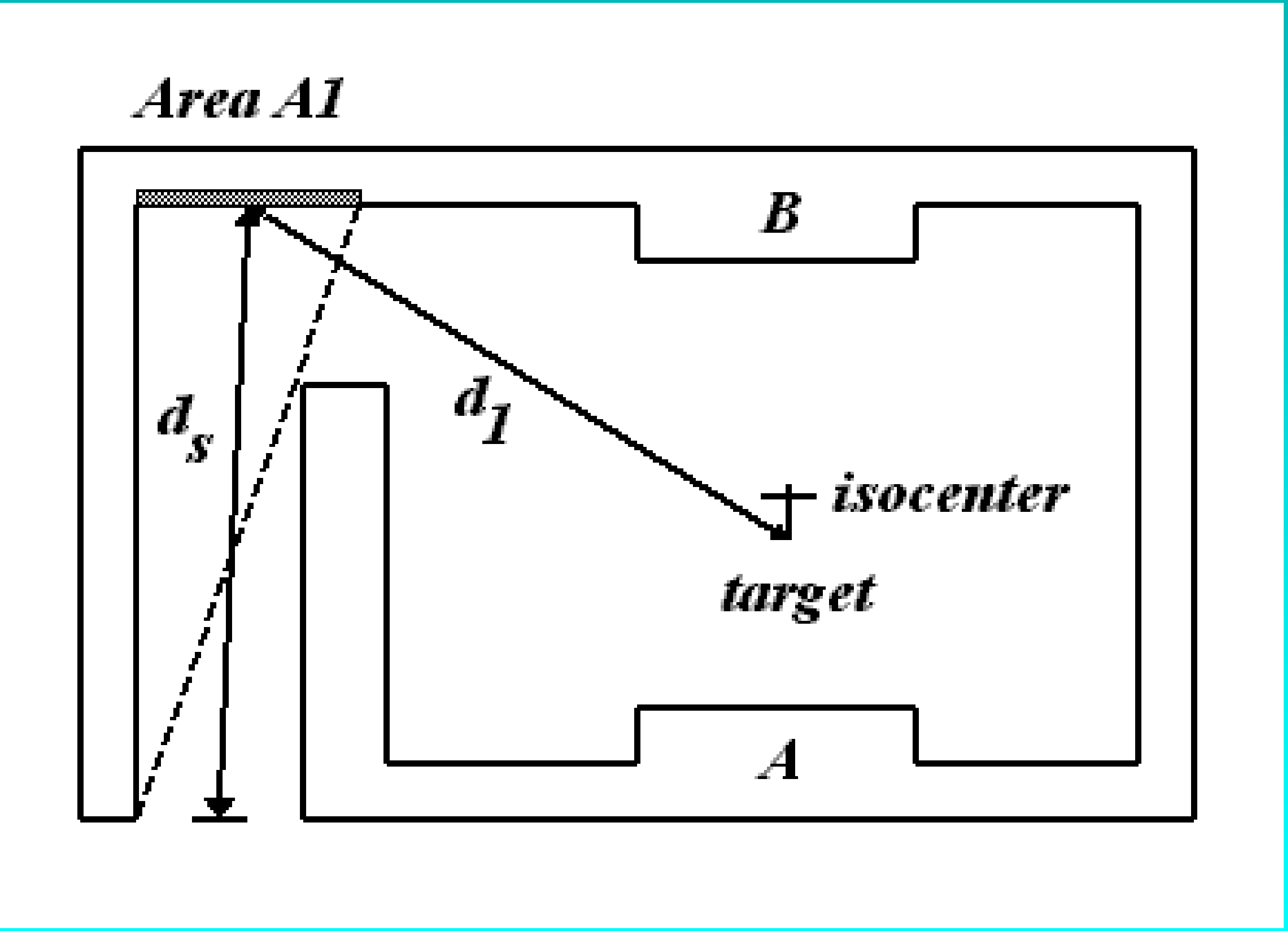
Secondary Radiation at Door due to Patient Scatter

$$S_p = \frac{aW\,U_B\left(F/400\right)\alpha_1 A_1}{\left(d_{sca}d_{\sec}d_s\right)^2}$$



Secondary Radiation at Door due to Leakage

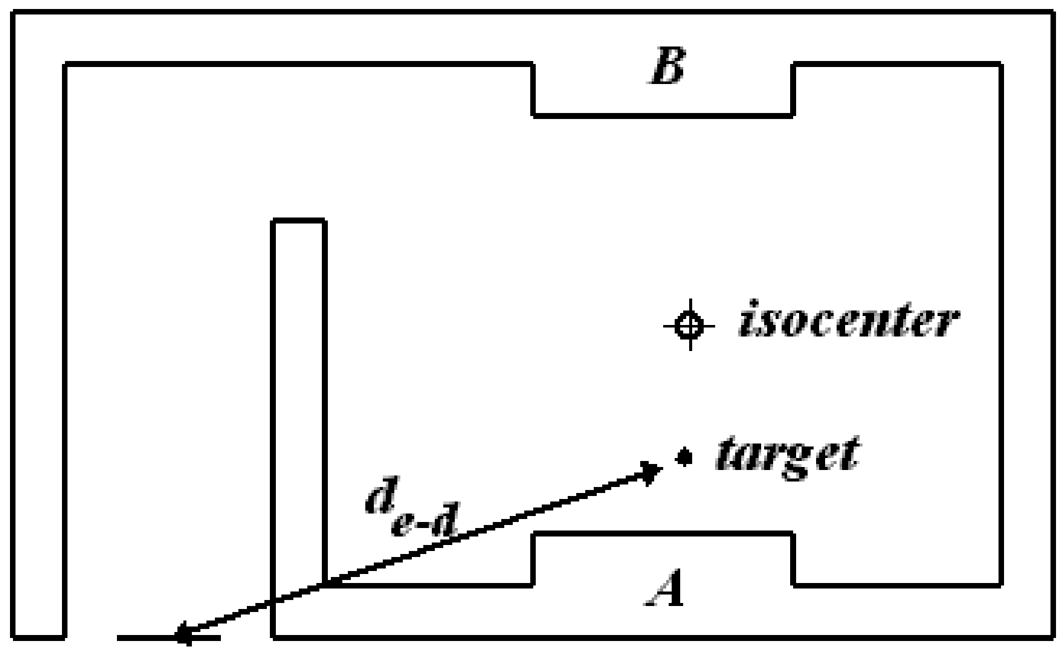
$$L = \frac{L_0\, W\, U_B\, \alpha_1 A_1}{(d_s d_1)^2}$$



Secondary Radiation at Door due to Leakage Through Maze Wall

$$L_d = \frac{L_0 \, W \, U_B 10^{-(t/TVL)}}{\left(d_{l-d}\right)^2}$$

Note that this radiation is more energetic than radiation along the maze



Mazes

The total dose when the beam is directed towards the wall is the sum of the four components:

$$D_t = f{*}S_s + S_p + L + L_d$$

Note that the S_s component is reduced by a factor "f" to account for patient attenuation. Assuming use factors of ¼ for the 4 gantry angles, McGinley gives an average total dose of:

$$D_T = 2.64\ D_t$$

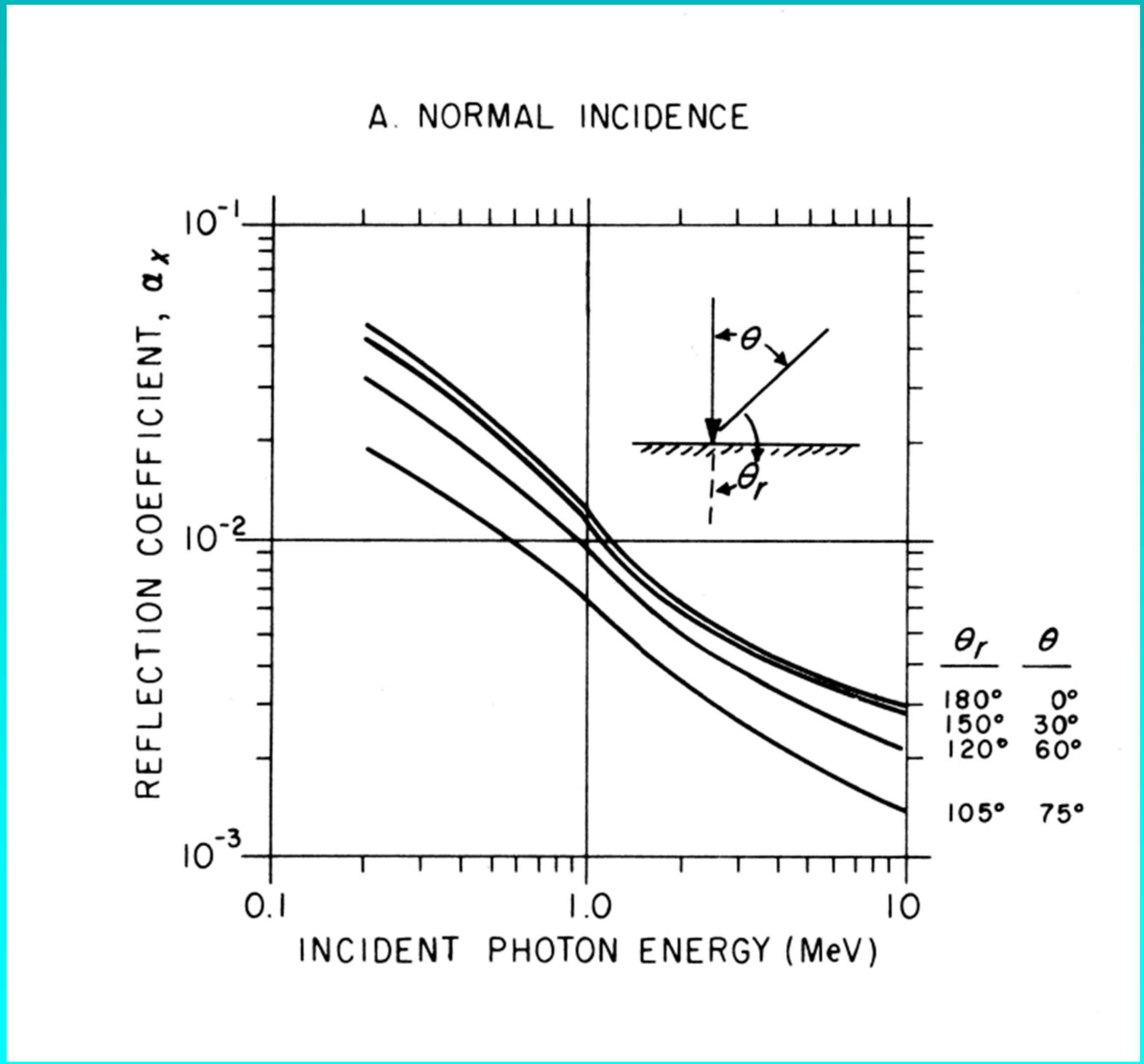
Comments on NCRP Formalism

- *Several authors[†] have noted that the foregoing formalism underestimates the true dose at the door.*

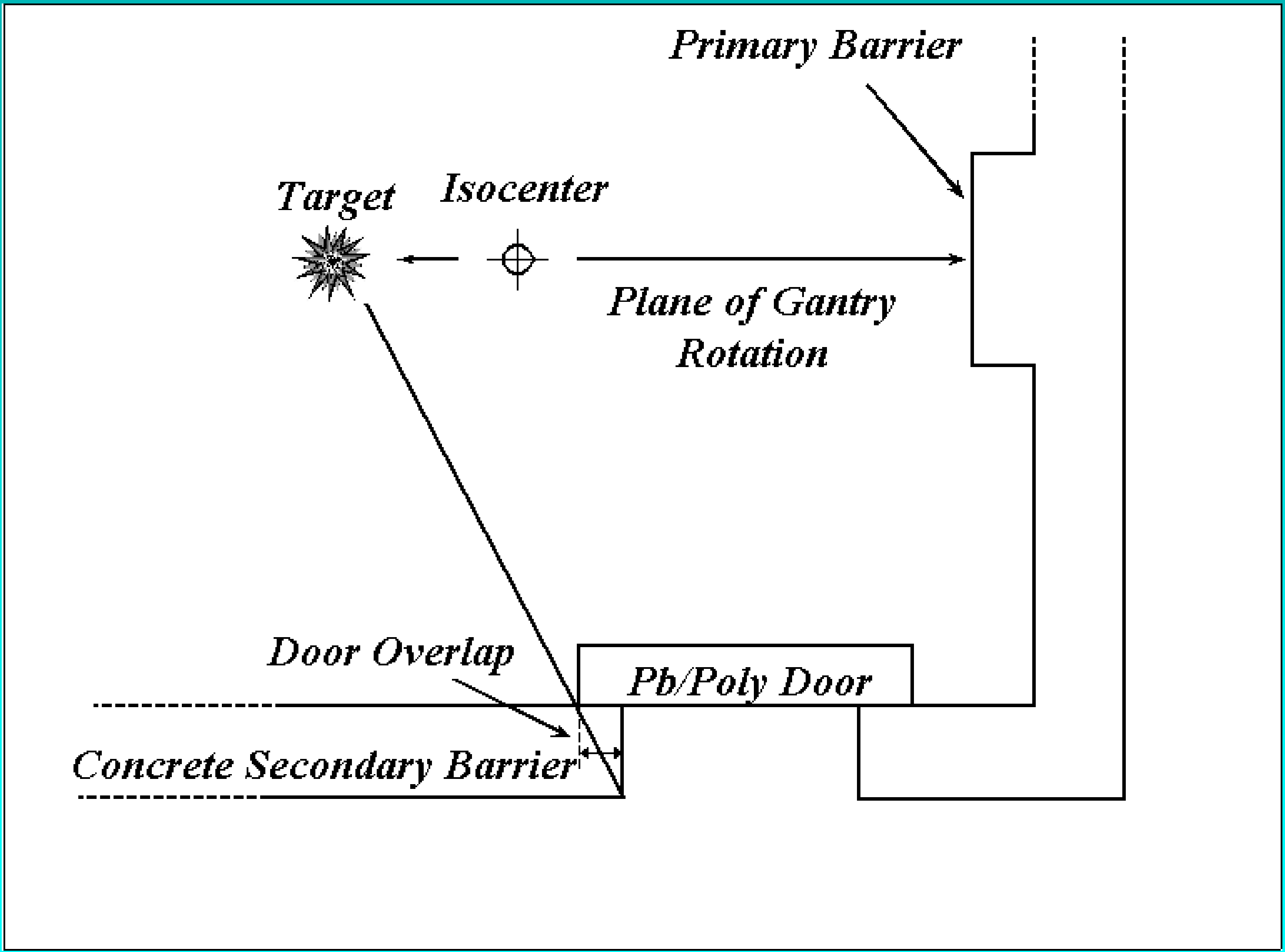
- *This problem has been partly rectified by redefining the geometry of the scatter and assuming lower energies for the scattered radiation which, in turn, increase the scatter coefficients*

† *Numark & Kase; Al-Affan; McGinley & James*

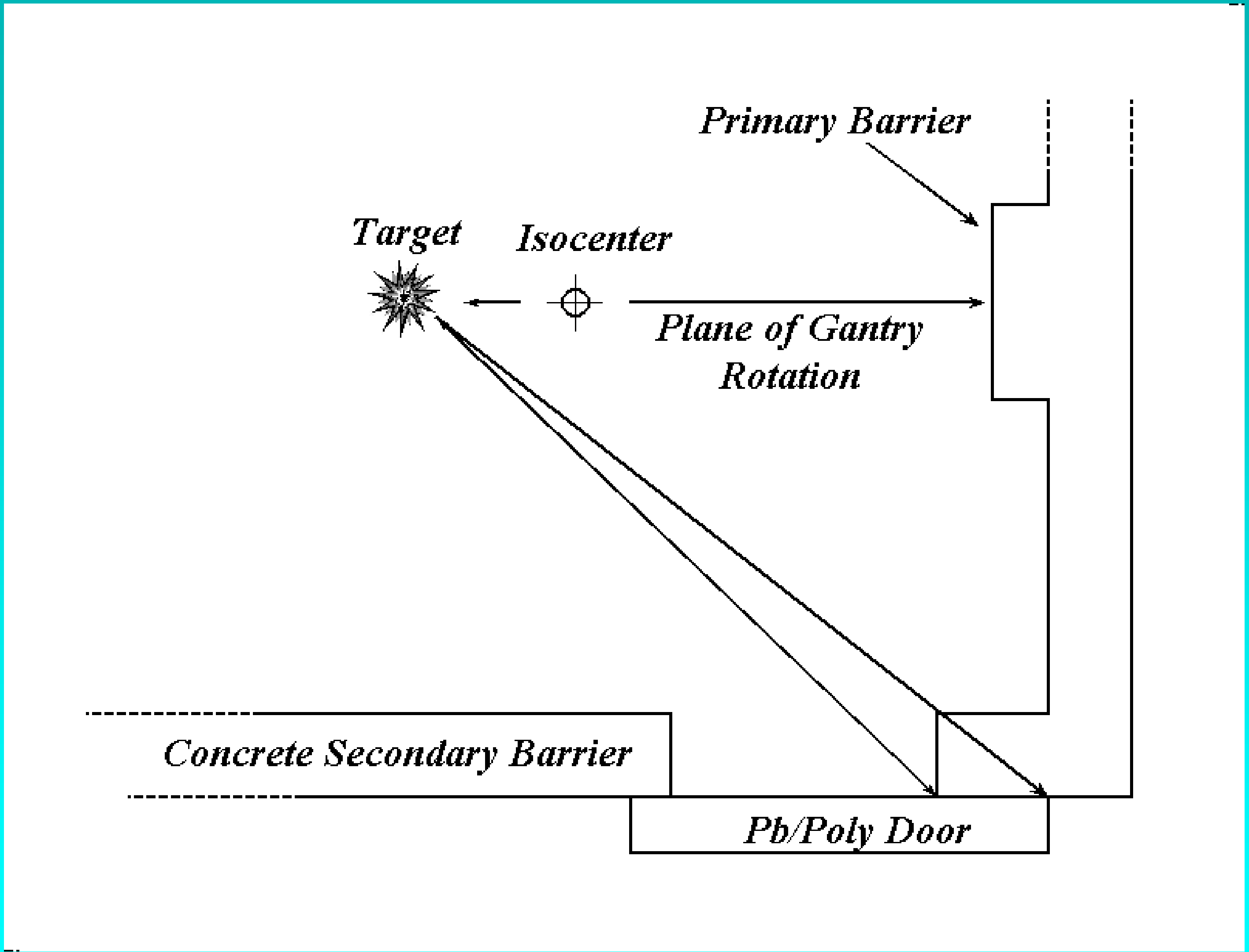
Reflection Coefficients for Monoenergetic X-Rays on Concrete



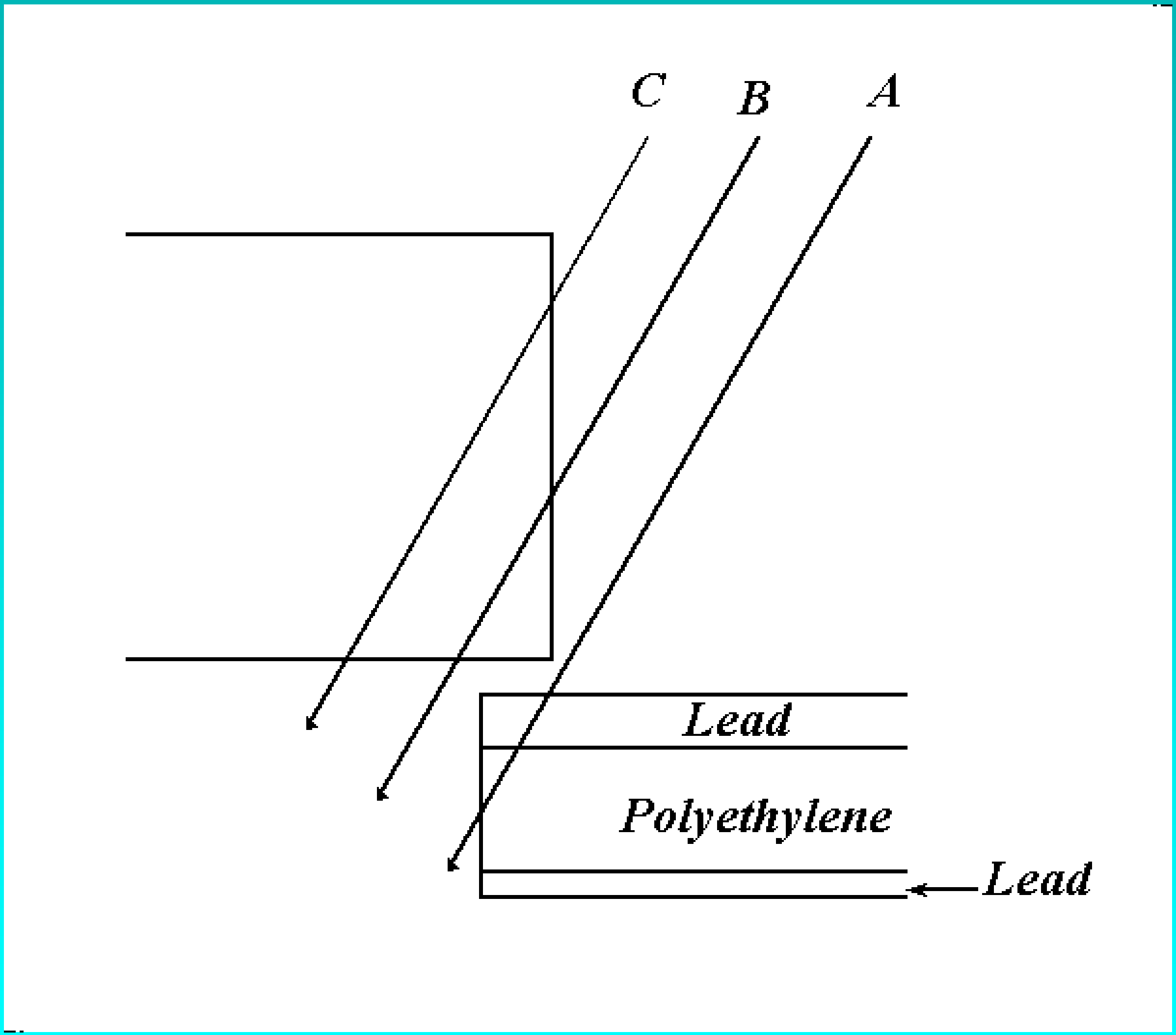
Door Inside Room



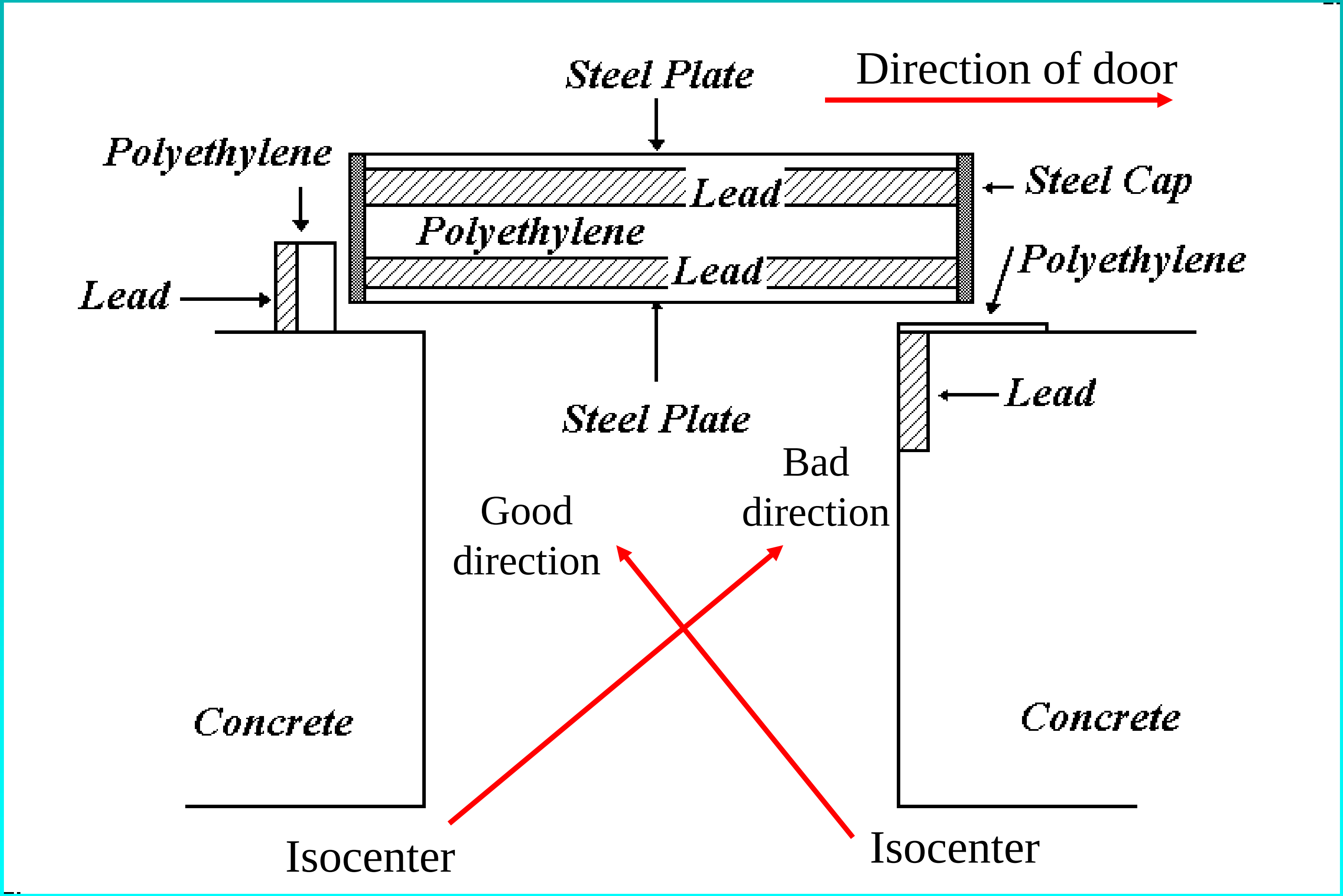
Door Outside Room



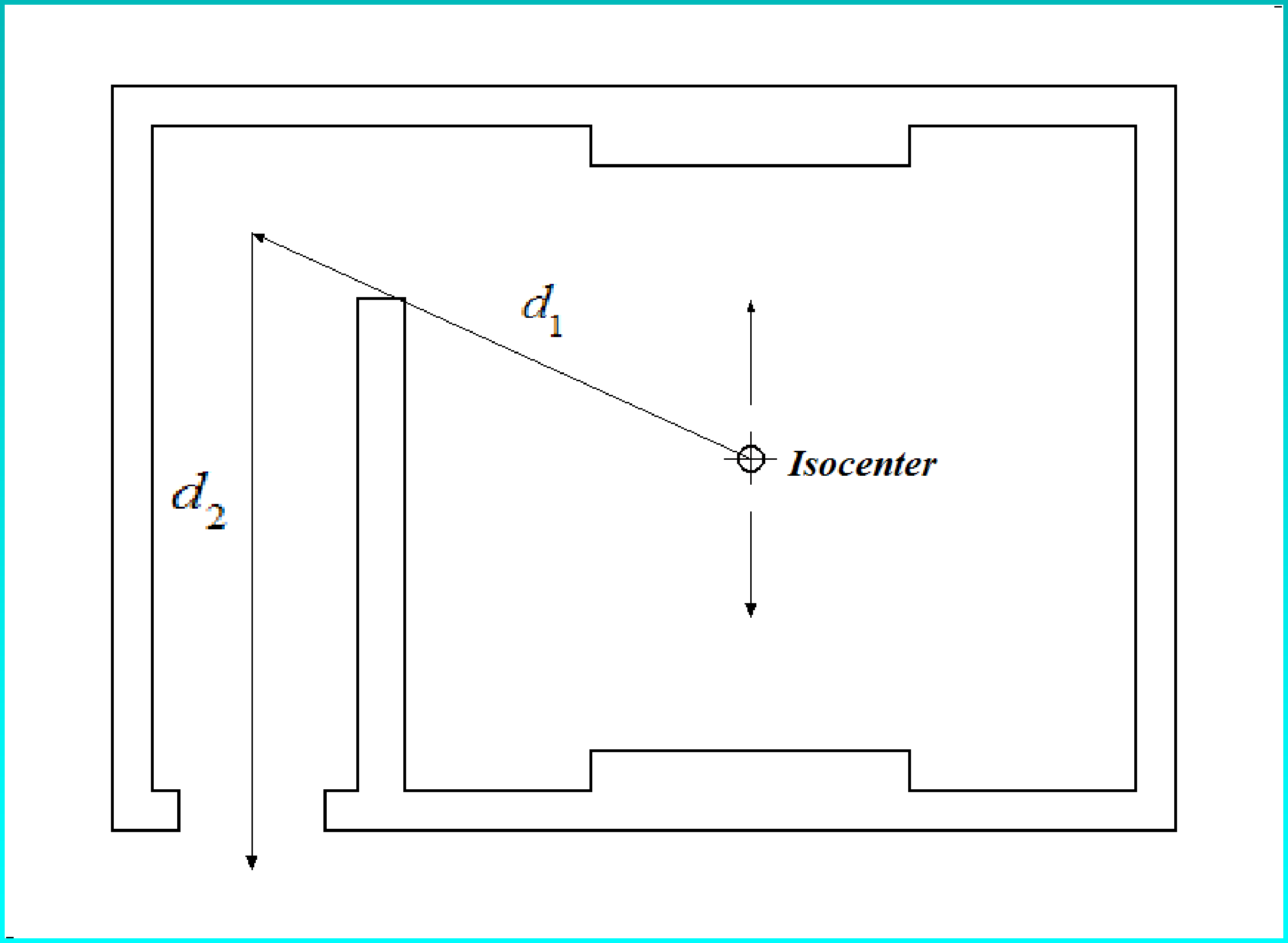
Edge Effect for Direct Shielded Doors



High Energy


Steel Plate
Direction of door
Polyethylene
Lead
Steel Cap
Polyethylene
Lead
Polyethylene
Lead
Lead
Steel Plate
Bad
direction
Good
direction
Concrete
Concrete
Isocenter
Isocenter

Parameters for Calculation of Neutron Dose at Door



Neutron Fluence Entering the Maze

The total neutron fluence is given by (McCall et. al, 1999)

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

The addition of (2π) in the scattered and thermal terms accounts for the directionality of the neutrons and Q_n is the #neutrons/photon Gy

Neutron Dose at Door of Maze

Kersey formula:

$$H = H_0 \frac{S_0}{S} \frac{1}{d_1^{\,2} 10^{-d_2/5}}$$

where H_0 is the total neutron head leakage at 1.4 m from the target, d_1 is the distance from the target to the maze entrance and d_2 is the length of the maze. S_0/S is the ratio of the inner to outer maze areas (rationale for lintel). The TVL for neutrons along the maze is 5 m.

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Modified Kersey Formula

Wu & McGinley's formula:

$$H_{n,D} = 2.4x10^{-15}\varphi_A\sqrt{\frac{S_0}{S_1}}\left[1.64x10^{-\left(\frac{d_2}{1.9}\right)} + 10^{-\left(\frac{d_2}{TVD}\right)}\right]$$

is a modification of McGinley's 2-component model and is based on an analysis of a number of facilities.

Dose at Maze Door due to Capture γ Rays

Capture rays follow the same formalism for photoneutron attenuation in the maze. For mazes >3 m, the first term disappears and a single exponential term is left.

$$D = K\Phi_{total}10^{-d_2/TVD}$$

where K is the γ dose/n fluence ratio at the maze entrance

Φ is the neutron fluence at the maze entrance

d_2 is the distance along the maze

and TVD is the TVL for γ's down the maze

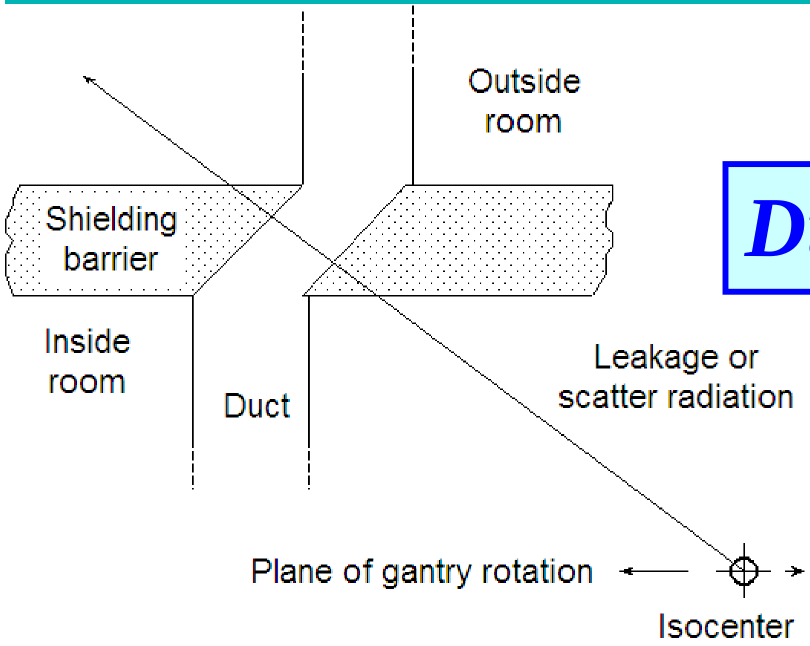
Combined Dose at Maze Door

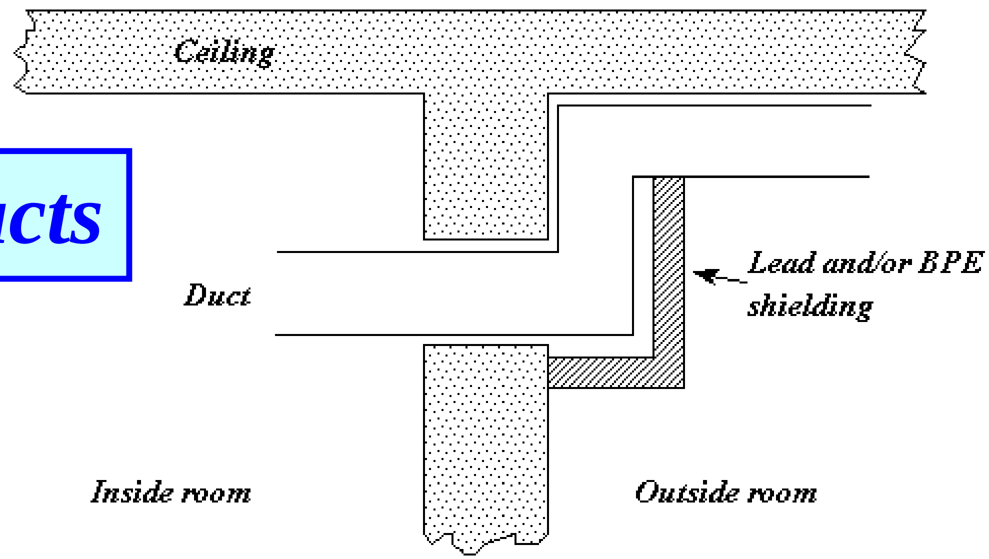
The neutron and capture γ ray components are calculated and shielding thicknesses to meet the required effective dose equivalent are derived using the following TVLs:

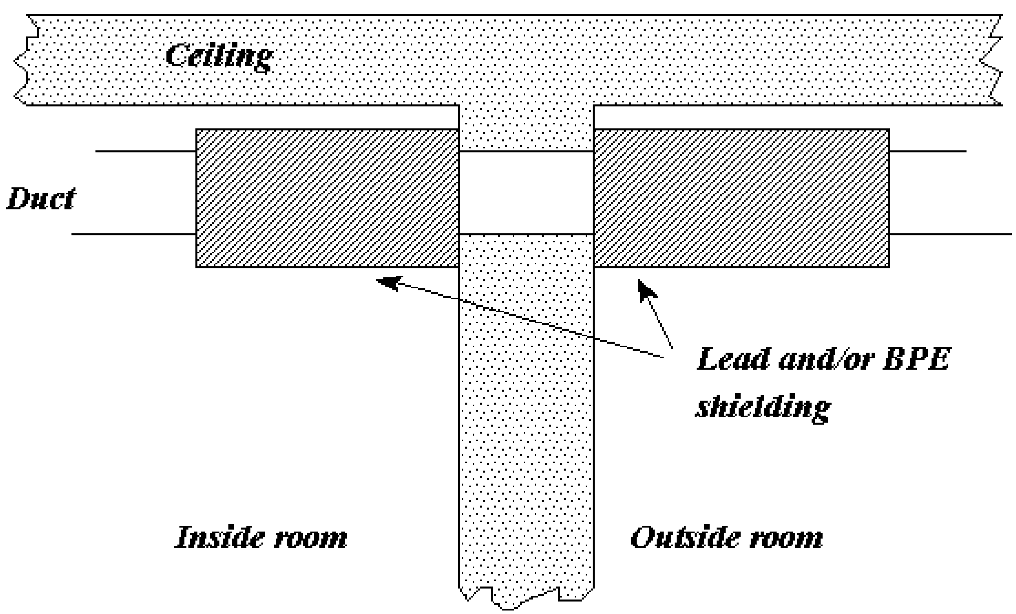
neutrons (100 keV) - 4.5 cm polyethylene
capture γ rays - 6.1 cm lead

As a rule, for high energy machines only these components and the photon leakage components need be considered. Generally, for 15 & 18 MV photons, $D_n > D_{capture\ \gamma\ rays}$

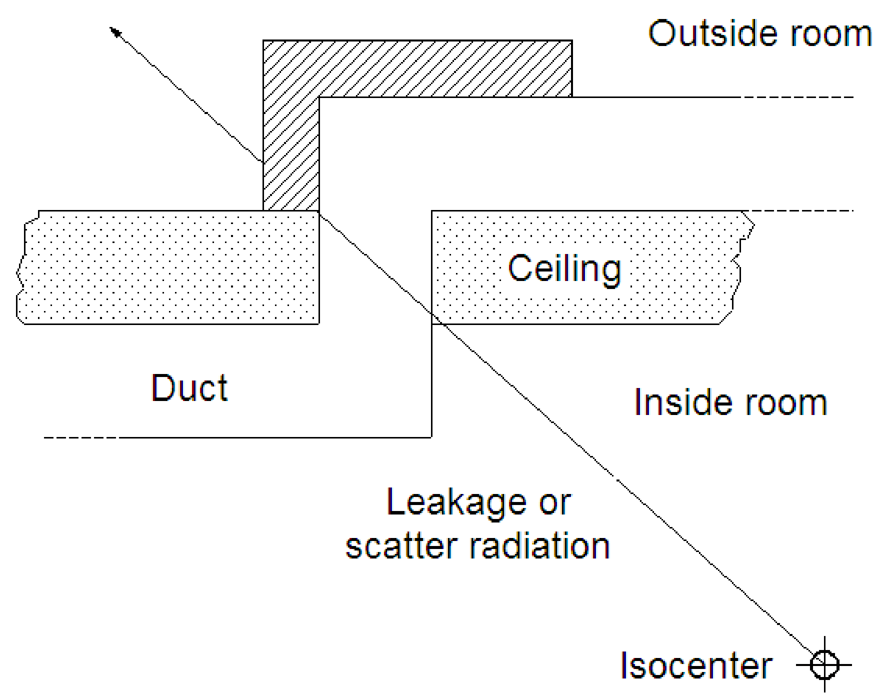
Ducts







Additional shielding



Practical Problems with NCRP #151

- Use of dual energy workloads, dual TVLs, laminated barriers creates confusion in the calculations

- Use of the obliquity factor for scattered radiation (not leakage) is unclear – two examples in the text give opposing views. Experts are divided on this issue, but it can be used, but with caution!

Handling Dual Energies in NCRP #151

- A dual energy machine having say 6 and 18 MV will have different workloads for (P,S) and L radiation for 3D CRT and IMRT (6 MV assumed). In general, a conservative approach assumes:

- use of the maximum energy in a full 3D CRT environment for the primary and …

- the IMRT workload for the secondary barrier orthogonal to the plane of gantry rotation

Handling Dual Energies in NCRP #151

- in the secondary barrier region adjacent to the primary, the dominance of 3D CRT vs 3D CRT+IMRT depends on the explicit workloads and room geometry

- one should be careful to consider 20° scatter radiation for laminated barriers since the primary beam angle is only 14° (exclusive of extra 2' barrier width recommended by NCRP)

Handling Dual Energies in NCRP #151

- In that same angular zone in the secondary barrier, there will be be TVLs for two energies for scattered and leakage radiation
- Rule is that:
- scatter should be added to scatter to determine if an extra HVL is required
- leakage should be added to leakage to determine if an extra HVL is required
- Scatter is then compared to leakage to determine if an additional HVL is required

Handling Dual Energies in NCRP #151

- To recap:

  (i) $S1 + S2 \rightarrow S$

  (ii) $L1 + L2 \rightarrow L$

  (iii) $S + L \rightarrow$ Total secondary thickness

- Question remains as to which of the TVLs to use; higher or lower for L (ii); S or L for (iii)
- However, because of these multiple additions, this may overestimate the required shielding

Example: Barrier Adjacent to Primary

Energy	Radiation	Workload (Gy)	Thickness	Comment
15 MV	Leakage	225	36.1”	
6 MV	Leakage	1775	42.9”	
Combined 6 +15 MV	Leakage	2000	47.2”	Use TVL_1 for 15 MV
15 MV	Scatter	225	45.6”	
6 MV	Scatter	525	42.0”	
Combined 6 +15 MV	Scatter	750	49.3”	Use TVL_{sca} for 15 MV
Combined 6 + 15 MV	Leakage + scatter		53.3”	Use TVL_1 for 15 MV

N

Note: … and only one shielding material is used!

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Example: Barrier Orthogonal to Gantry Rotation Plane

Energy	Radiation	Workload (Gy)	Thickness	Comment
15 MV	Leakage	225	37.3”	
6 MV	Leakage	1775	43.9”	
Combined 6 +15 MV	Leakage	2000	47.8”	Use TVL_1 for 15 MV
15 MV	Scatter	225	19.8”	
6 MV	Scatter	525	22.6”	
Combined 6 +15 MV	Scatter	750	24.7”	Use TVL_{sca} for 15 MV
Combined 6 + 15 MV	Leakage + scatter		47.8”	Use TVL_1 for 15 MV

Thank you for your attention!

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