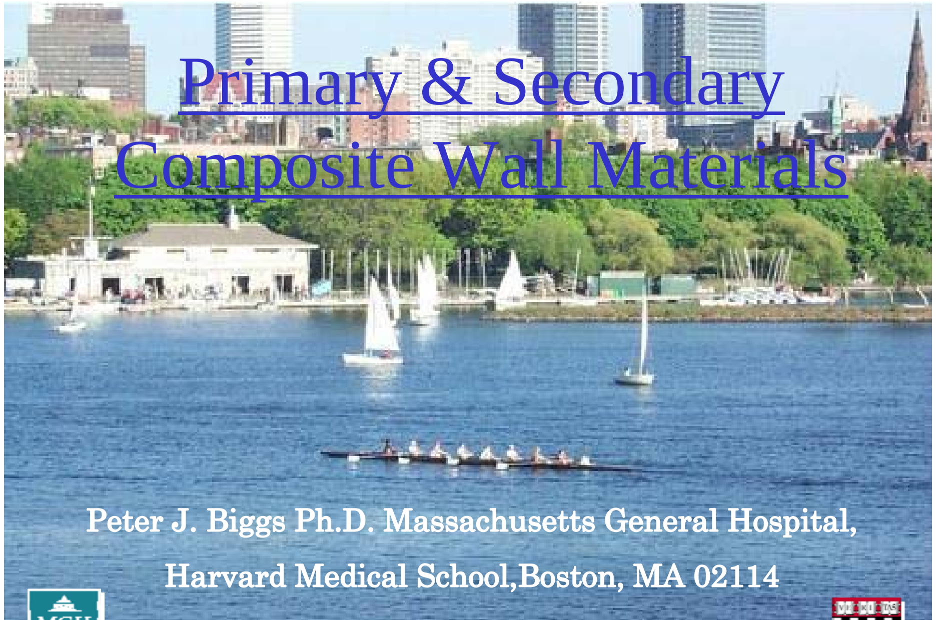

Primary & Secondary Composite Wall Materials

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Overview

- Review of shielding materials & their properties
- Lead/concrete primary barriers – low energy
- Lead/concrete primary barriers – high energy
- Secondary barriers
- Practical considerations
- Composite doors
- Escape hatch
- "Source constraints"

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
Earth	1.5	Cheap! Build underground
Brick	1.65 - 2.05	
Polyethylene; borated polyethylene	~1.0	Used to shield against neutrons in doors, ducts etc.

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	

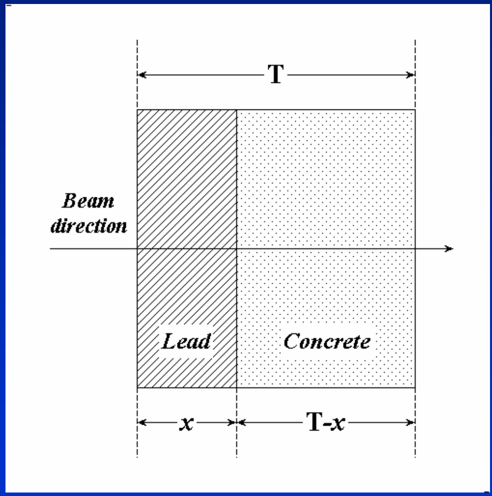
** First term is 1st TVL and term in brackets is for all other TVLs. Data from NCRP #151*

*** Data from McGinley*

Rationale for Laminated shielding

- upgrading existing facilities from low energy to high energy
- remodelling existing facilities where space is limited
- new facilities where space is limited
- requires high density, high-Z material
- photoneutron production, capture γ rays for high energy beams

Geometry for Laminate Problem



Laminated Barriers I: Low Energy

The general equations to determine the relative (optimal) thicknesses of lead and concrete for a single energy x-ray beam (no neutrons) for a fixed wall thickness are:

$$n_T = n_c + n_l$$

$$T = n_c TVL_c + n_l TVL_l$$

where n_T is the total number of TVLs, T is the overall thickness and c and l refer to concrete and lead respectively.

Laminated Barriers II

The solution to these equations is:

$$n_l = \frac{n_T TVL_c - T}{TVL_c - TVL_l}$$

$$n_c = n_T - n_l$$

Laminated Barriers II

However, life under NCRP #151 is not quite so simple since there are now two TVLs for concrete, so the equations become:

$$n_T = n_c + n_l$$
$$T = TVL_{c,1} + (n_c - 1)TVL_{c,e} + n_l TVL_l$$

where (c,1), is the first TVL and (c,e) are the subsequent TVLs for concrete.

Laminated Barriers III

The solution to these equations is:

$$n_c = \frac{n_T TVL_{c,e} - T + (TVL_{c,1} - TVL_{c,e})}{TVL_{c,e} - TVL_l}$$
$$n_l = n_T - n_c$$

Laminated Barriers IV

However, if lead is the first material in the beamline and the thickness is > 1 TVL, then only TVL $_{c,e}$ is needed and the equations become:

$$n_T = n_c + n_l$$
$$T = n_c TVL_{c,e} + n_l TVL_l$$

with the solution

$$n_l = \frac{n_T TVL_{c,e} - T}{TVL_{c,e} - TVL_l}$$

Example

- Assume that a maximum thickness of 122 cm (48”) is specified for the primary barrier thickness, that W=750 Gy/wk; d=7 m; U=0 .213; T=1; P=0.02 mSv/wk. One calculates n_T = 5.2.
- For a 15 MV x-ray beam: TVL $_{c,e}$ = 41 cm and TVL_l = 5.7 cm
- $\therefore n_l$ = 2.6, so t_l = 14.7 cm (5.8”)
- $\therefore n_c$ = 2.6, so t_c = 107.3 cm (42.2”)

Mixed Energy Beams I

- The majority of radiotherapy units sold today are dual energy machines
- Virtually all radiotherapy centers use a mix of photon energies
- If one uses 6 MV for IMRT, as many centers do, the majority of MU delivered could be at low energy
- Example: At MGH, 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%

Mixed Energy Beams II

- The equations now become more complicated (assuming lead is the first material and ignoring neutrons):

$$P_T = P_6 + P_{10} = \frac{UT}{d^2}\left(W_6 * 10^{-\frac{(T-x)}{TVL_{c,e,6}}} * 10^{-\frac{x}{TVL_{l,6}}} + W_{10} * 10^{-\frac{(T-x)}{TVL_{c,e,10}}} * 10^{-\frac{x}{TVL_{l,10}}} \right)$$

- This equation is solved using an iterative procedure or by solving separately for the two energies and making the usual comparison (<1TVL difference, add 1 HVL)

Mixed Energy Beams III

- One can take the alternative approach of using only the highest energy to calculate the primary and the mixed energies to calculate the leakage (90°) radiation.

- The rationale is that this represents the worst case for both the primary (higher energy) and the leakage (higher MU)

Example

Assuming the same maximum thickness of 122 cm (48") for the primary barrier thickness, that W_{15}=225 Gy/wk;W_6=525 Gy; d=7 m; U=0 .213; T=1; P=0.02 mSv/wk.

- For a 15 MV x-ray beam: $TVL_{c,e}$ = 41 cm and TVL_l = 5.7 cm
- t_l = 12.7 cm (5")
- t_c = 109.2 cm (43")

Laminated Shielding for Secondary Barriers

Adjacent to primary:

- There are two TVLs for scattered radiation in lead
- The leakage TVLs are only for 90º
- There are no scatter TVLs for steel

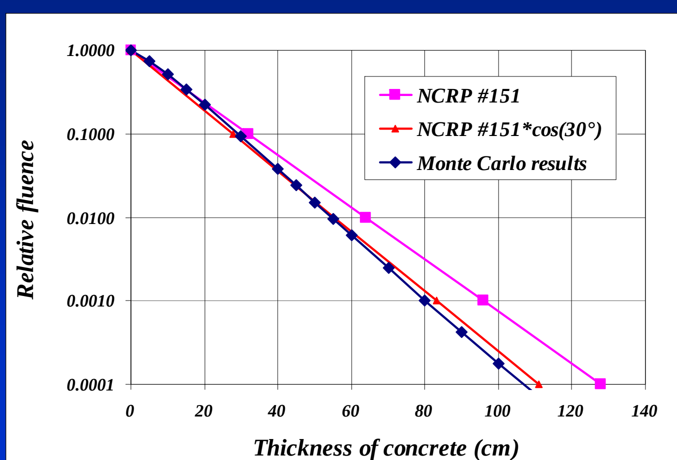
90º barrier:

- Only leakage is important, particularly if IMRT is a consideration

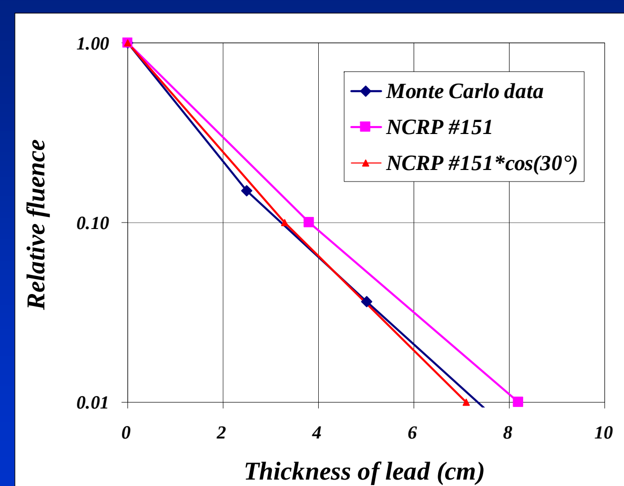
Does the Obliquity Fcator Apply to Scattered Radiation?

- Recommendations of NCRP #49 and NCRP #151
- Verify with Monte Carlo program
- Sheikh-Bagheri D. and Rogers DWO. "Monte Carlo calculation of nine megavoltage photon beam spectra using the BEAM code" *Med. Phys* 29: 391- 402; 2002

Obliquity Factor for 30° Scattered Radiation on Concrete: 18 MV



Obliquity Factor for 30° Scattered Radiation on Lead: 6 MV



Re-retrofit: A Case Study

- Treatment room began operating with a Co-60 unit (Theratron 780-with beam stopper)
- This unit was replaced with a 4 MV linac with no beam stopper
- It is now being replaced with a 6 MV machine
- The first room was all regular density concrete
- The first change added lead on 3 walls plus the ceiling (to be shown on later slides)
- The current change is to add additional lead
- Secondary barrier considerations

Laminated Barriers – High Energy

- *For high energy x-ray beams, neutrons have to be shielded against as well as photons*
- *For concrete-only walls, this generally presents no problem*
- *However, for laminated primary barriers, the sufficiency of the concrete barrier to protect against neutrons needs to be examined*

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Laminated shielding: Neutrons + Photons I

- The equations for determining the lead and concrete thicknesses are the same, with the constraint that the concrete is sufficient for the neutrons from the machine

$$n_\gamma = n_{\gamma,c} + n_{\gamma,l}$$
$$n_n = n_{n,c}$$
$$T = n_{\gamma,c} TVL_{c,e} + n_{\gamma,l} TVL_l$$
$$T_n = n_n TVL_{n,c}$$
$$\text{with } T_n \le n_{\gamma,c} TVL_{c,e}$$

- Ignore for the moment photoproduction of neutrons and subsequent generation of capture gamma rays

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Laminated shielding: Neutrons + Photons II

- If the concrete thickness is inadequate for neutrons, then polyethylene can partially be used, so we have a new set of equations

$$n_\gamma = n_{\gamma,c} + n_{\gamma,l}$$
$$n_n = n_{n,c} + n_{n,p}$$
$$T = n_{\gamma,c} TVL_{c,e} + n_{\gamma,l} TVL_l + n_{n,p} TVL_{n,p}$$
$$T_n = n_{n,c} TVL_{n,c} + n_{n,p} TVL_{n,p}$$
$$\text{with } n_{n,c} TVL_{n,c} \le n_{\gamma,c} TVL_{c,e}$$

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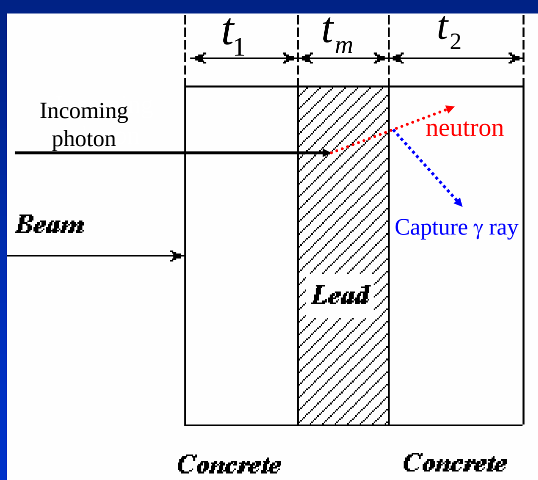
Laminated Barriers – High Energy

- In addition, photoneutron production in the lead and subsequent production of capture gamma rays needs to addressed
- The greater the thickness of lead required, the greater the neutron fluence and production of capture gamma rays will be
- The magnitude of this effect will also depend how much concrete is placed after the lead

Laminated Barriers – High Energy

- For walls, it is easy to install the lead on the upstream side of the beam since the lead can be installed in a self-supporting manner
- This is not true for shielding in the ceiling where a base support for the lead of approximately 18” concrete is required
- It also does not apply to the situation where there are two adjacent high-energy rooms facing each other where the high Z material should be centered in the concrete

Production of Neutrons by Primary Beam in a Laminated Barrier



Production of Neutrons by Primary Beam in a Laminated Barrier

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

P. McGinley

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

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

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)

Production of Neutrons by Primary Beam in a Laminated Barrier

Note that the value of H in McGinley's equation is a balance between attenuation of the incoming photons (1st exponential term) and the attenuation of the photoproduced neutrons (2nd exponential term)

Capture Gamma Rays

To account for capture gamma rays, NCRP recommends using a factor of 2.7 for the photon component:

$$H_{Tot} = H_n + H_{photon} = H_n + 2.7 * H_{tr}$$

Solution to the Laminated Barrier Problem for High Energies: Two Solutions

1 Successive approximation:

- Calculate lead and concrete thicknesses required for stopping photons and concrete for neutrons separately.
- Determine dose equivalent for photoneutrons.
- Determine overall photon dose from "2.7" factor
- Scale the total dose to 0.02 mSv/wk and start again with the first step using the reduced MPD

2 Optimization

Cost Effectiveness of Laminated Barriers

- Newman and Asadi-Zeydabadi* have used a linear programming technique to optimize the cost of laminated shielding, subject to dose and/or thickness constraints
- They found that steel was a cheaper laminate than lead, contrary to popular construction techniques

** AAPM 2007; SS-FF-T-16*

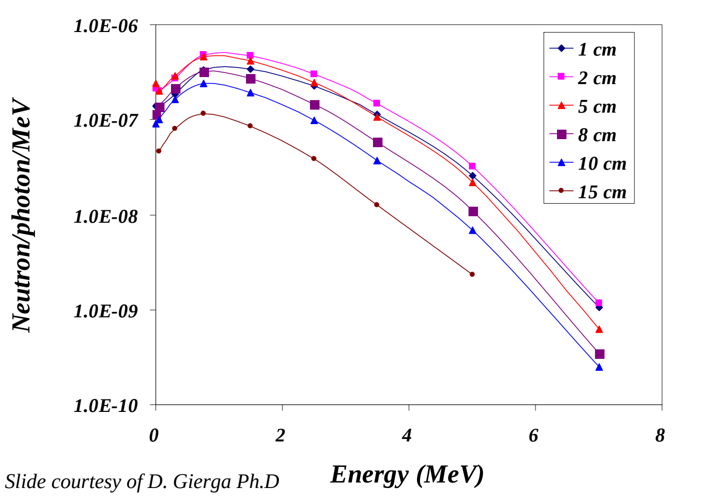
Optimization: The Cost of Lead

- Until a few weeks ago, the cost of lead was ~$0.70/lb
- More recently it has climbed to >$1.75/lb
- Shortage is due to major mine closure in Australia and redued exports from China

Thresholds for Photonuclear Reactions

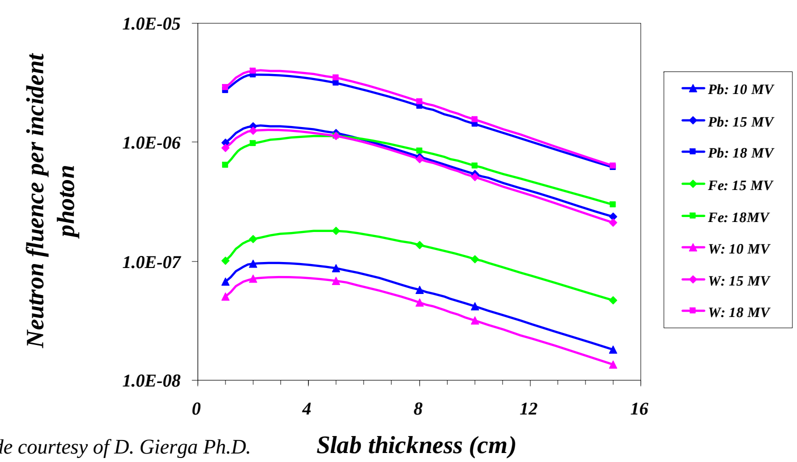
Reaction	Threshold (MeV)
$\gamma + Fe \rightarrow n + ...$	11.2 (92%)
$\gamma + {}^{206}Pb \rightarrow n + ...$	8.1
$\gamma + {}^{207}Pb \rightarrow n + ...$	6.7
$\gamma + {}^{208}Pb \rightarrow n + ...$	7.4

Neutron Yield vs. Lead Thickness: 18 MV



Slide courtesy of D. Gierga Ph.D

Photoneutron Production vs. Thickness

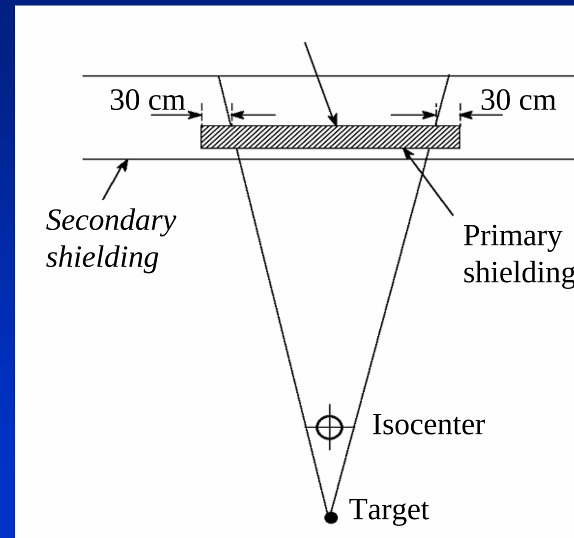


Slide courtesy of D. Gierga Ph.D.

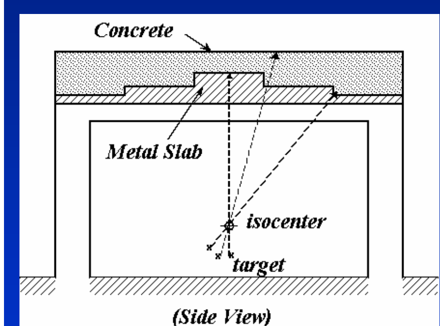
Photoneutron Ratios

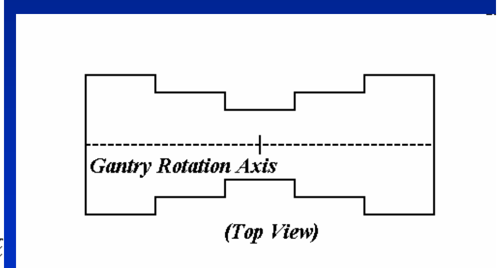
NCRP #151	$mSv\ cGy^{-1}\ m^{-2}$	
Pb 18 MV	19	
Fe 18 MV	1.7	
Pb 15 MV	3.5	
Ratios:	NCRP #151 (dose)	Monte Carlo (fluence)
18 MV (Pb/Fe)	11.2	4.5
Pb (18 MV/15 MV	5.4	2.5

Width of Primary Barrier



Contouring the Primary Shielding in the Ceiling



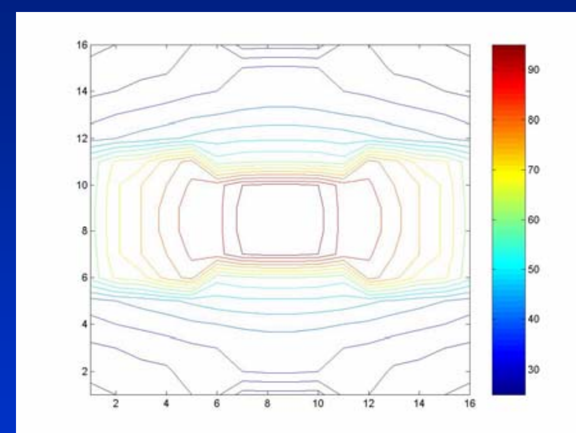


Diagrams courtesy of P. McGinley

Primary Ceiling Isodose Contours

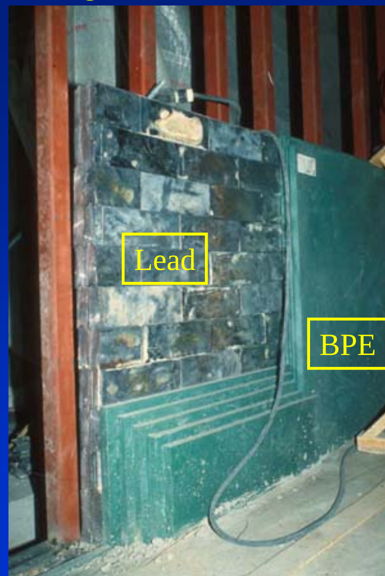
Programs can help to make the process of determining the isodose curves and, hence the lead "steps", easier

-Biggs.P. Health Physics, 43:601-607, 1982.

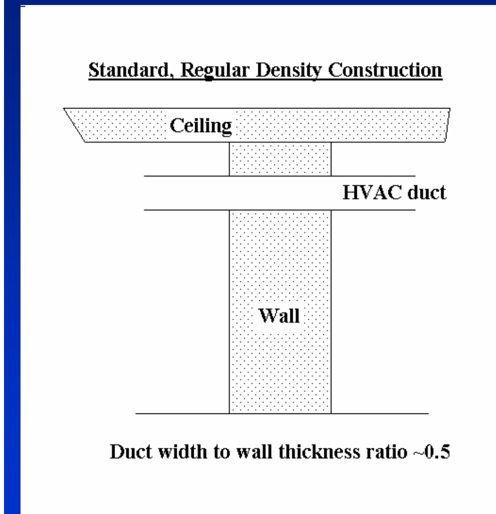


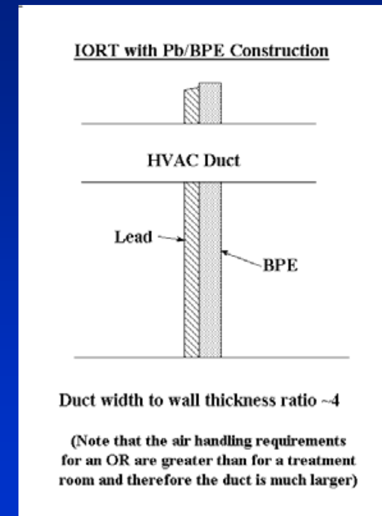
What About Concrete-Free Barriers?

Shielding for 3rd floor IORT machine



Problem of HVAC Ducts





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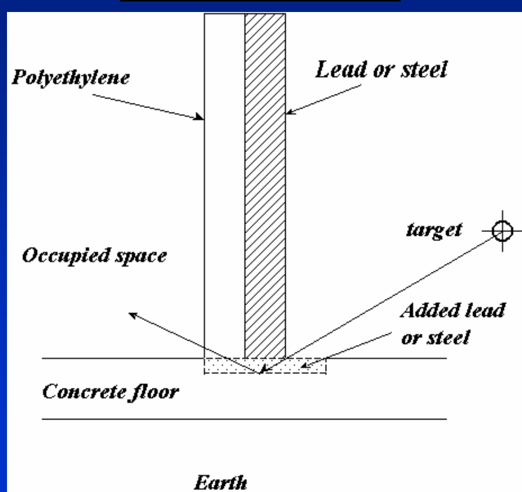
Lead-Only Room (Photons) : Groundshine



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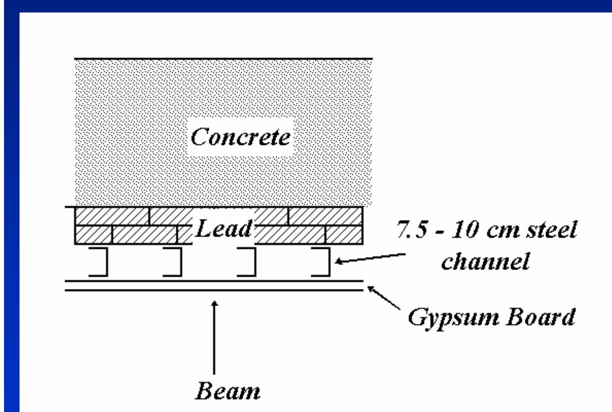
Upgrading to a High Energy Linac - Wall (1)



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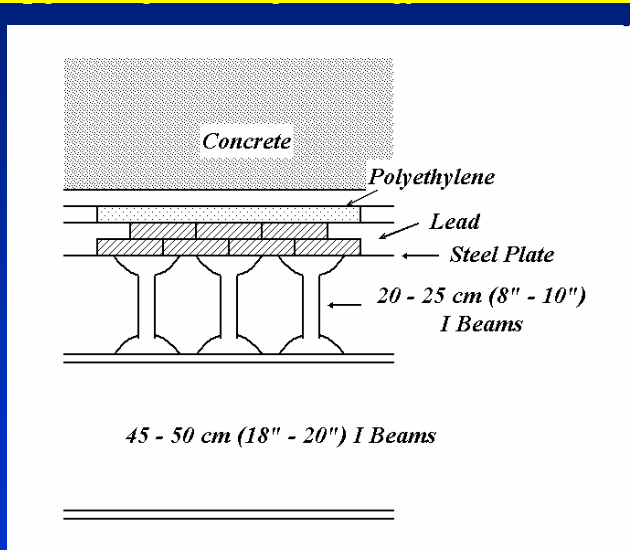
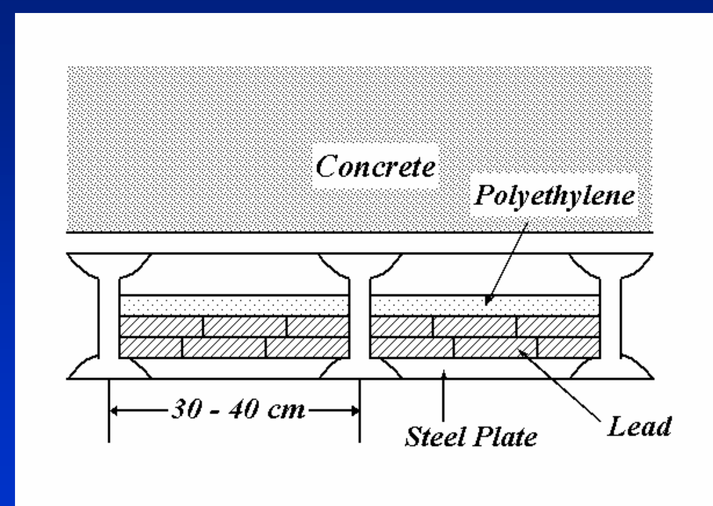
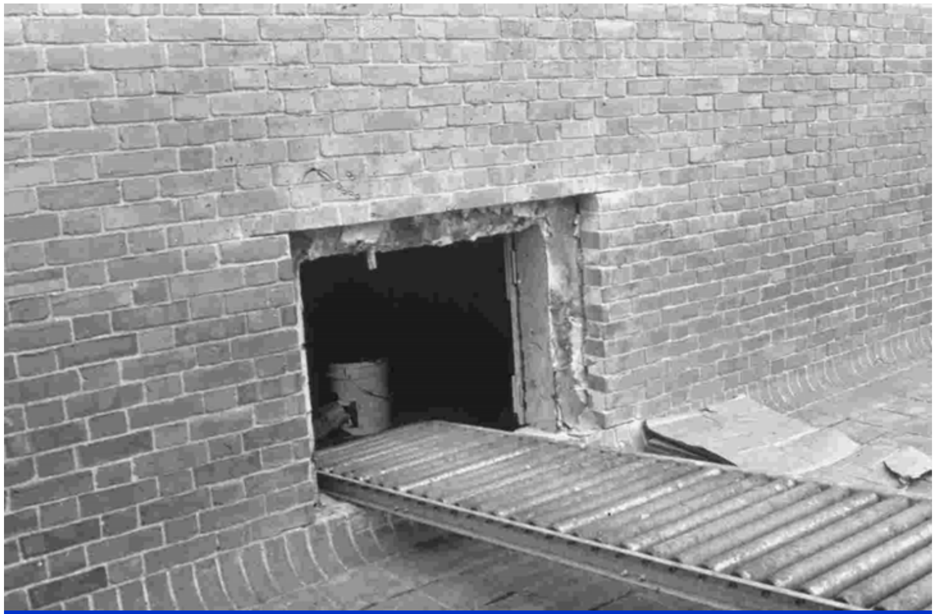
Upgrading to a High Energy Linac - Ceiling (1)

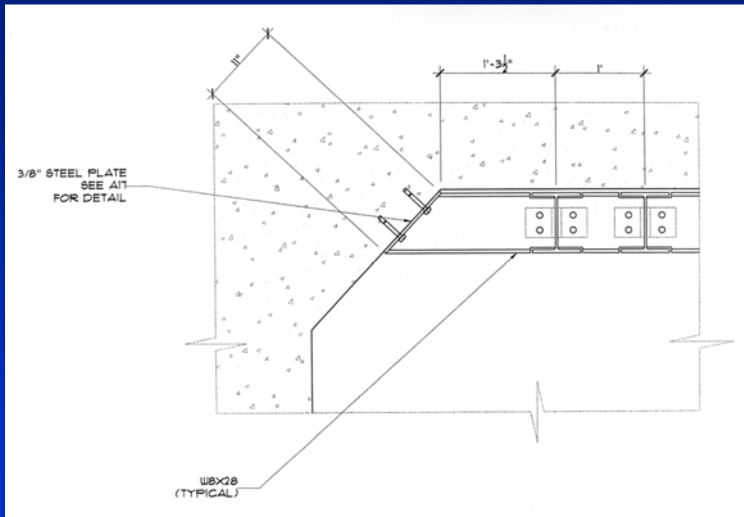


Upgrading to a High Energy Linac - Ceiling (2)





Upgrading to a High Energy Linac - Ceiling

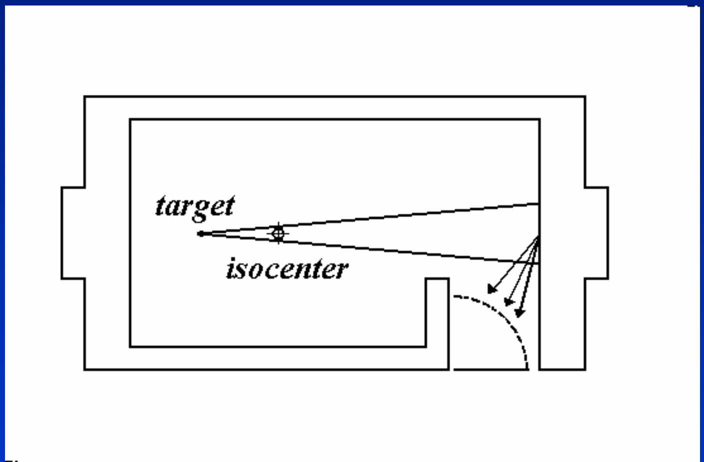


I-Beam Support

Maze Doors

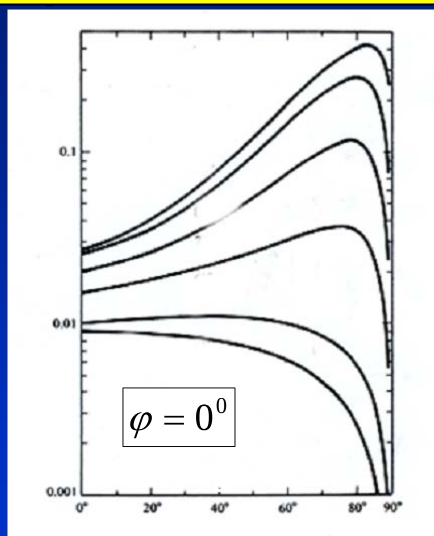
- For low energy machines, maze doors are constructed solely of lead and steel/or wood
- For high energy machines, in addition to lead, neutrons have to be considered and polyethylene/borated polyethylene is the material of choice.

Primary Beam Incident on Outer Maze Wall

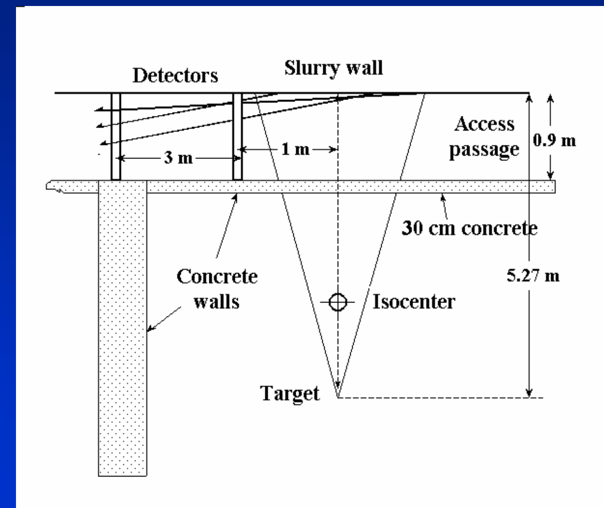


Albedos for In-Plane Scattering

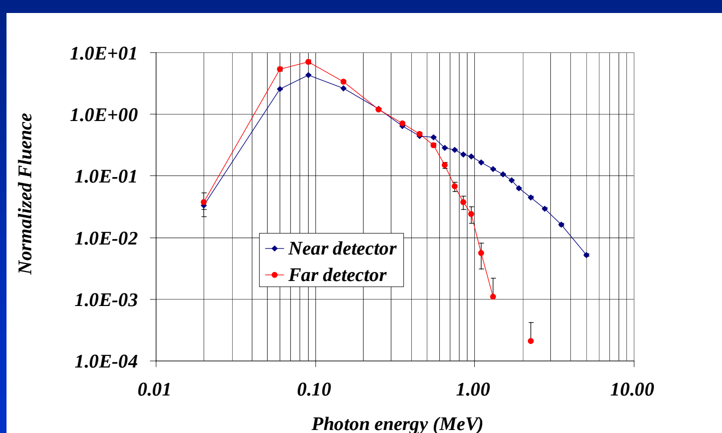
E_0 =1.25 MeV
concrete



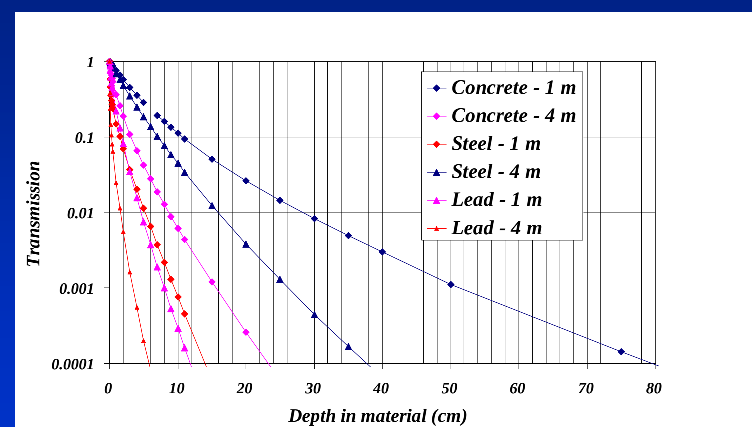
X-ray spectrum from Primary Scattered at ~90°



Spectrum of 90° Scattered Primary Radiation



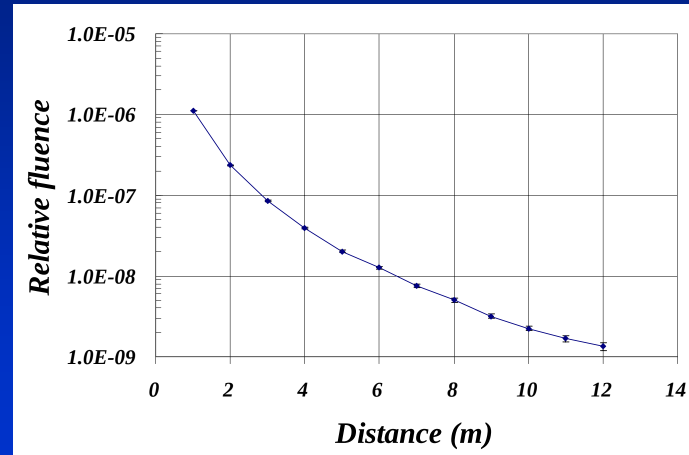
Attenuation of 90° Scattered Radiation by Various Materials



Material Thickness Required to Reduce Fluence by 10^{-4}

Material Distance (m)	Concrete (cm)	Steel (cm)	Lead (cm)
1	79.3	23.2	14.0
4	37.6	11.8	5.8

Attenuation of 90° Scattered Primary Radiation



Doors for High Energy Mazes

- In addition to the scatter and leakage components noted earlier, additional components due to neutrons come into play at high energies (≥ 10 MV)
- These components dominate over the wall-scattered x-ray components
- They consist of neutrons and capture gamma rays from neutron interactions

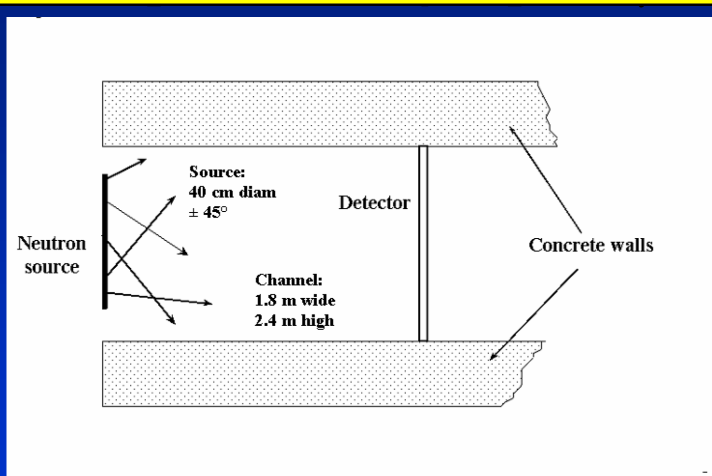
Combined Dose at Maze Door

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:

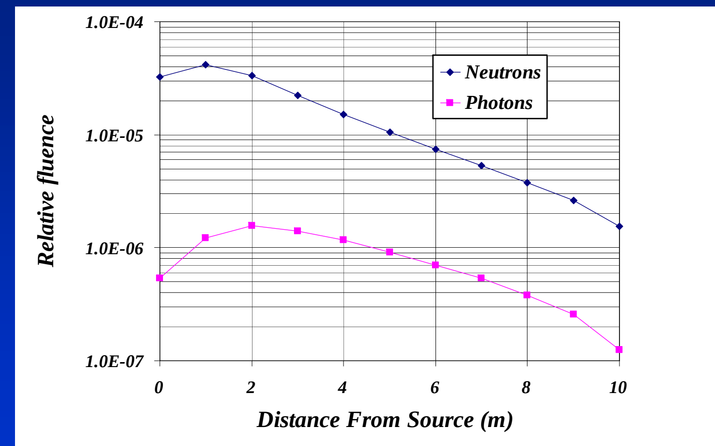
neutrons (100 keV) - 4.5 cm polyethylene

capture γ rays - 6.1 cm lead

Neutron production of Capture γ Rays



Photon, Neutron Fluence vs. Distance



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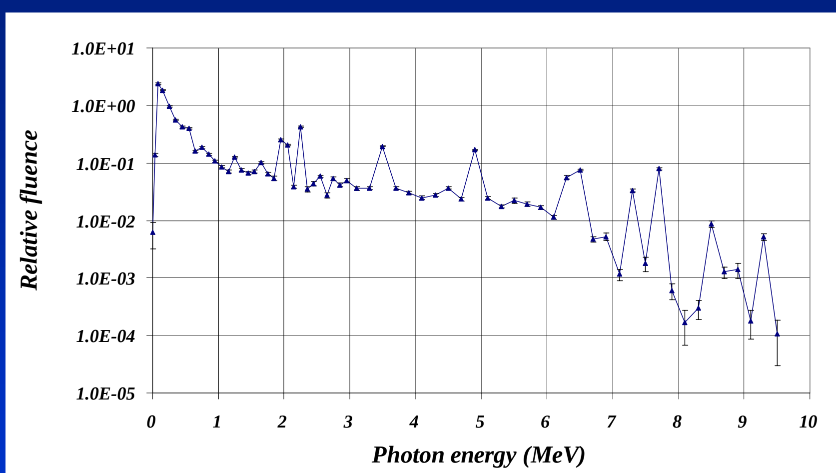
Capture γ Ray Spectrum



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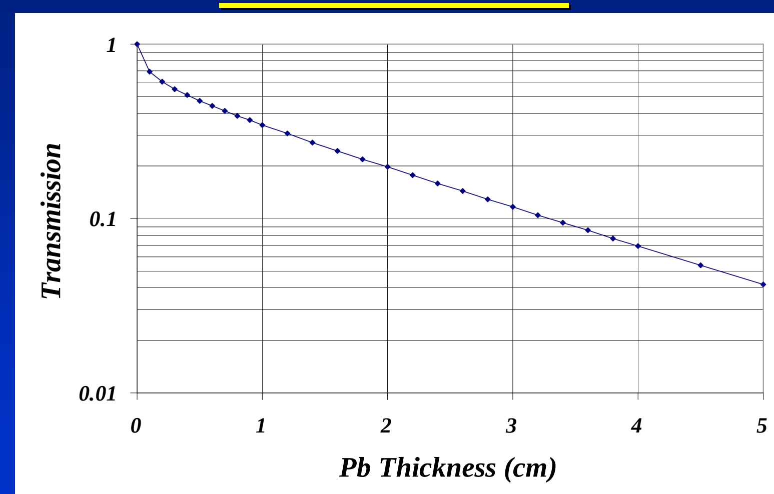
Attenuation of Neutron-generated Photons in Lead



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High Energy

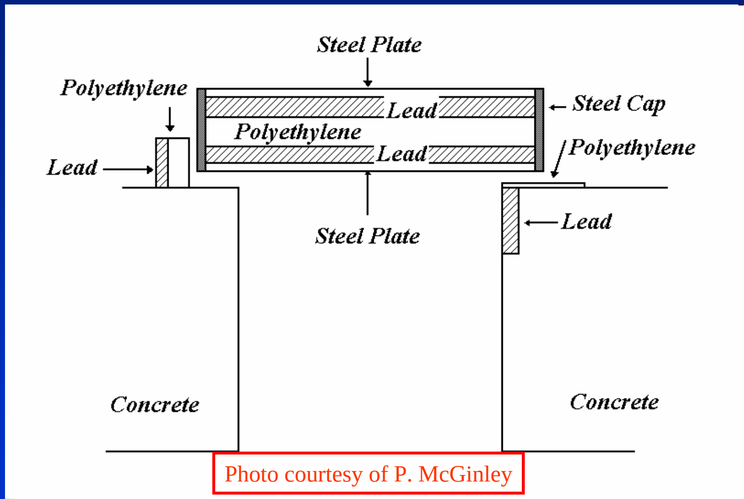


Photo courtesy of P. McGinley

Heavy Door Requirements

- All electrical/electronic equipment should be outside the room for ready access
- A come-along should be available to open the door mechanically; this requires a bolt hole in the door and in the wall.

If the Door Does Not Move: Escape Hatch

- What is its purpose?

  If a heavy sliding door fails in the closed position with a patient on the table, there needs to be emergency access. If the problem is not electrical and the come-along does not work, another method of entry is required.

- But is it needed?

  The design of current heavy door support systems (overhead rail) minimizes mechanical failure with the door touching the floor. However, …

Equipment Needed in Case of Electrical or Mechanical Failure

Escape Hatch Shielding Requirements

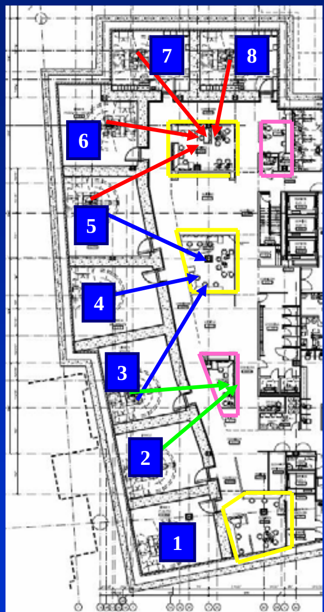
- For low energy rooms, lead only, can use two doors, total thickness equivalent to local wall thickness
- For high energy rooms, need lead and polyethylene, total thickness equivalent to local wall thickness for photons and neutrons
- Doors must be linked to the general door interlock chain to ensure that, if opened, the beam will be cut off

Escape Hatch

Escape Hatch

And now for something completely different …

- In the talk on Report #147 yesterday, we heard how the issue of “source constraints” was overcome
- We also heard from the PET talks where the need to consider multiple sources was required to compute the dose in various adjacent areas
- In RT, the need sometimes arises to consider the same situation ….



New Radiation Therapy Department at MGH

Consideration of the impact of multiple sources on maximum permissible doses in RT

Therapists Receive Dose Inside the Room!

Summary

- Laminated barriers are commonly used to upgrade old Rx rooms and also in new construction where space is limited
- The methodology for handling laminated barriers is straightforward at low energies, but requires careful consideration of neutrons and capture γ rays for high energies and involves iterative calculations

Acknowledgements

Finally, I would like to thank my colleagues David Gierga, Elizabeth Crowley, Kevin Beaudette and Cynthia Pope for their assistance and advice in preparing this lecture and to John Styczynski for his help with the Monte Carlo programming

Thank you for your attention!

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