Radiation Oncology treatment room design

Linear accelerator bunkers

McGill

MDPH 613 Fall 2004

Radiation Oncology

- Linear accelerator
- Brachytherapy
- CT simulator
- simulator

Basic shielding concepts

- Establish a target dose-rate at a certain point behind a barrier
- Calculate barrier thickness necessary to achieve the target dose rate

Shielding considerations

- Type of radiation
- Primary beam incidence
- Primary beam scatter
- Patient scatter
- Leakage radiation

Shielding considerations

- Type of space
  - Basement
  - Mountain
  - 3rd floor

- Space availability
  - New facility
  - Retro-fit

- Future workload
- Capital funding

Shielding considerations

- Machine workload
- Type of person to protect
  - NEW
  - Public
- Type of space to protect
  - Public access area
  - Restricted access

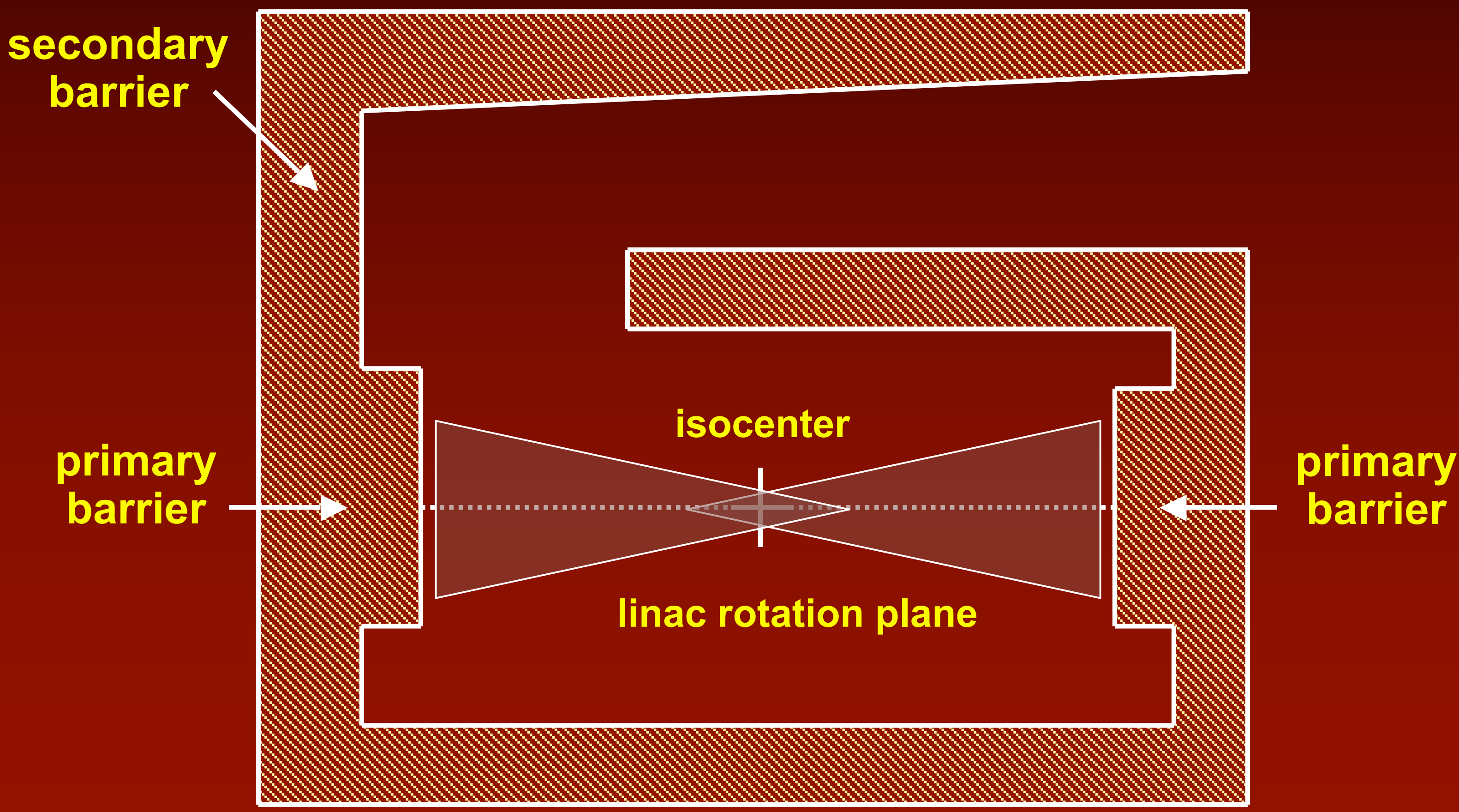
ALARA

- As Low As Reasonably Achievable
- ICRP 60 recommendations are limits
- Facilities should not be designed to the limits as they are not designed to be exceeded
- So ALARA factor of 10 - 20 can be applied

Types of barriers

- Primary barriers
  - Attenuate primary (direct) beam
  - Very thick (1.5-2.5m)
- Secondary barriers
  - Leakage
  - Patient scatter
  - Wall scatter

Treatment room

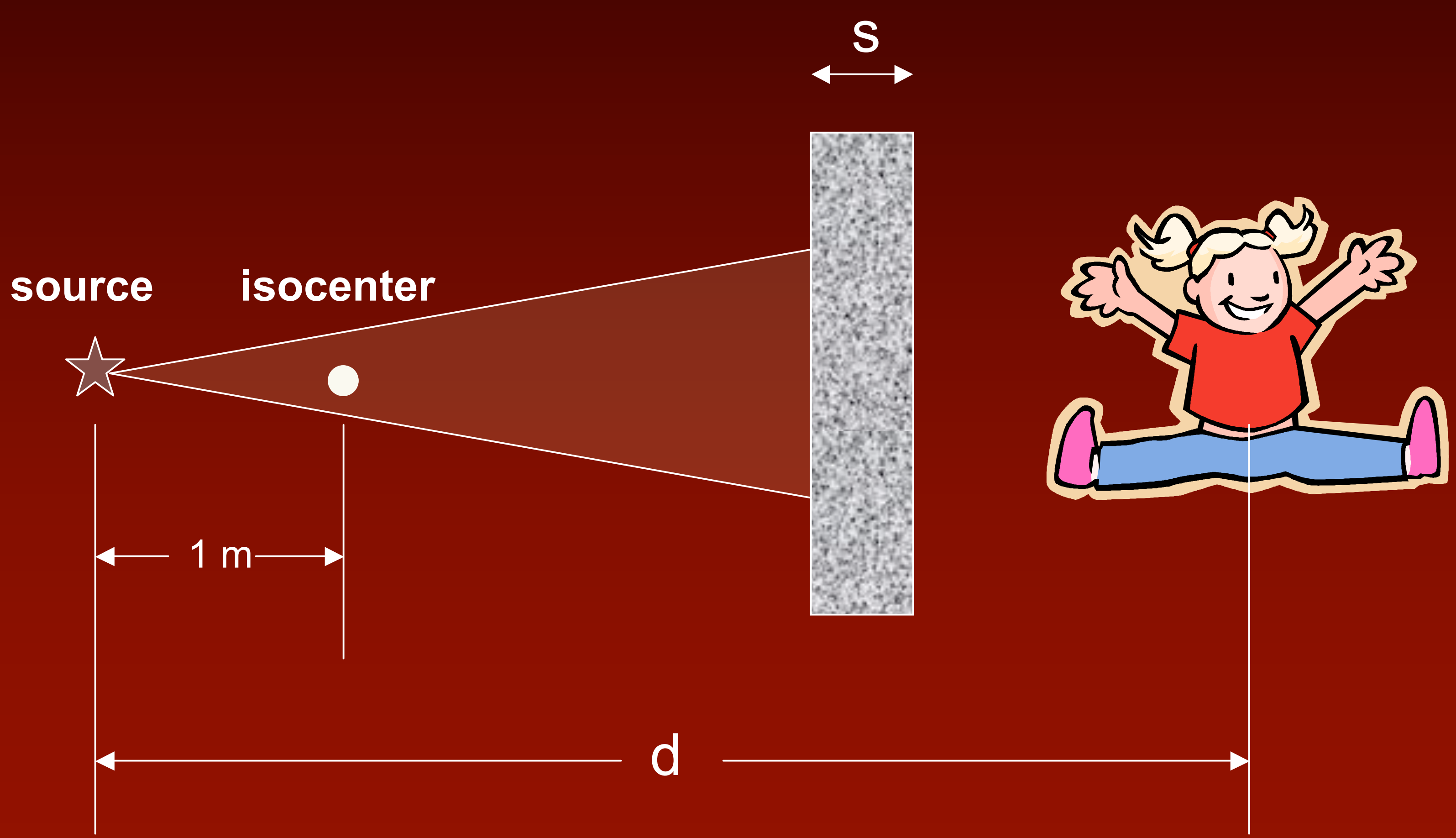


Primary beam

- Barrier thickness depends on:
  - Distance to POI from source (d)
  - Target dose rate (P)
  - Workload (W)
  - Occupancy (T)
  - Usage (U)

*Patient and table attenuation not taken into account

Basic situation



Reduction factor B

- **B** is the factor by which the intensity of radiation (P_o) must be reduced to achieve the target dose rate **P**

$$B = \frac{P}{P_o}$$

Transmission Curves

- NCRP 49, 51
- B as a function of material thickness

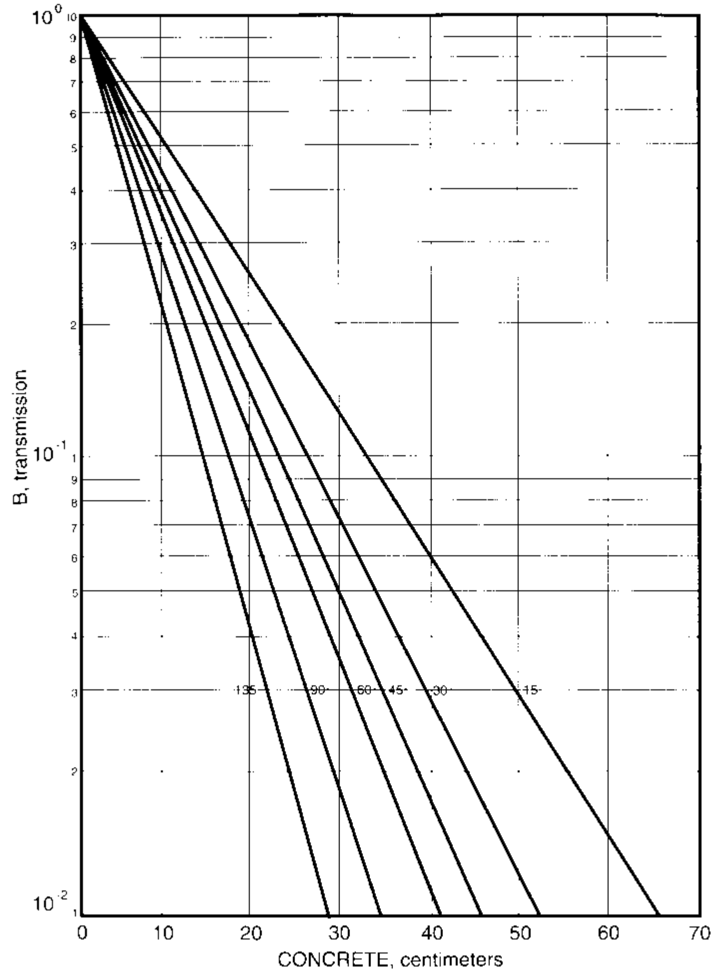


Figure 2-7. Transmission through concrete, density 2.35 g cm^{-3} (147 lb ft^{-3}), for 6 MV primary x-rays scattered at six different angles from a unit density phantom. From NCRP 1976 with permission.

TVL - Tenth Value Layer

$$n = \log\left(\frac{1}{B}\right)$$

$$S = TVL_1 + (n-1)TVL_e$$

TVL - Tenth Value Layer

- Thickness of material required to allow 10% transmission

- TVL depends on:
  - Photon beam energy
  - Barrier material
  - Barrier thickness

TVL - materials

Energy	Material	TVL_1 (m)	TVL_e (m)
6 MV	concrete	**0.350**	0.350
	steel	0.099	0.099
	lead	0.055	0.057
18 MV	concrete	**0.470**	0.430
	steel	0.108	0.108
	lead	-	-
24 MV	concrete	**0.510**	0.460
	steel	0.109	0.109
	lead	-	-

*values from NCRP 51

Shielding materials

material	density g/cm^3	Z	Relative cost	Tensile strength
concrete	2.3	11	1.0	500
heavy concrete	3.7-4.8	26	5.8	-
low C steel	7.87	26	2.2	40000
Pb	11.35	82	22.2	1900
dry packed earth	1.5	-	cheap	-

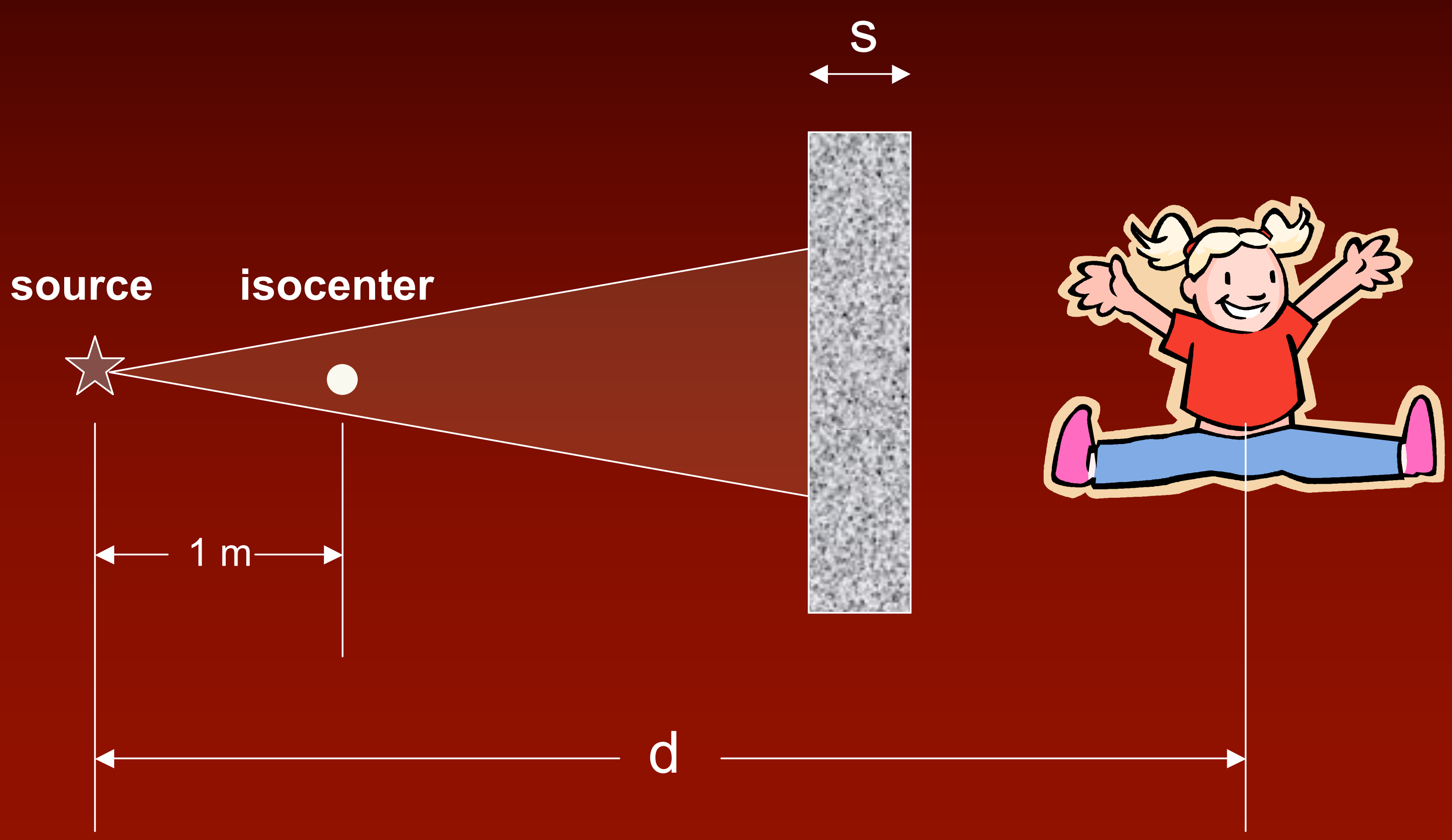
Primary beam

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

Distance

- d is the distance from the source to the point of interest (POI) in meters.
- The POI is located at least 30 cm from the surface of the outside of the barrier

Basic situation



Target dose rate P

Group	ICRP 60 Dose limit (mSv/y)	ALARA Target limit (mSv/y)	Maximum hourly dose rate* (μSv/hr)
NEW	20	2	10
Public	1	0.1	0.5

*1 year has 50 weeks of 40 hrs/week or 2000 hr/year

Workload W

- How much is the machine used
- Expressed in Gy/wk @ isocenter
- Good to overestimate

40 patients/day x 2 Gy/patient x 5 days/wk = 400 Gy/wk

- Typical values (NCRP 49, 51):
  - Low X machine (<10 MV) - 1000 Gy/wk
  - High X machine (> 10 MV) - 500 Gy/wk

Occupancy factor T

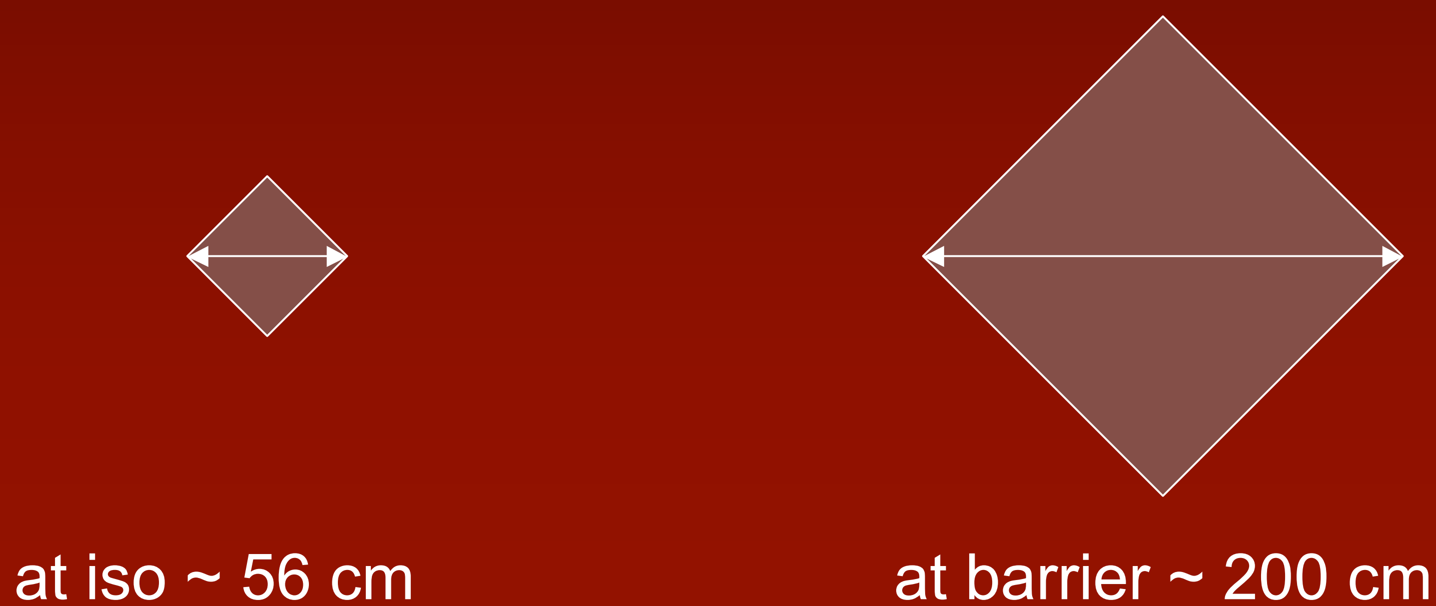
T	Type of area
1	Full Offices, shops, labs, living area
1/4	Partial Corridors, restrooms, parking
1/16	Occasional Waiting room, stairway, janitor closet

Usage factor U

- Accounts for beam orientation
- Isocentric units have same usage for floors, ceiling, and walls.
- U = 0.25
- There are some exceptions
  - Dedicated rooms eg. TBI
  - Non-isocentric machines

Primary barrier

- At isocenter max FS is 40 x 40 cm^2
- Largest dimension is diagonal (56 cm)
- At barrier this will project to larger size



Primary barrier

- Primary barrier will be approximately 3X thicker than all other walls

- Max with of beam at barrier must be calculated

Primary beam: Example

- Calculate the **B** for a 6 MV photon facility primary barrier if:

  P = 0.1 mSv/year

  d = 4m

  W = 50 patients per day

  U = 0.25

  T = 1 (control area)

Primary beam: Example

- W = 50 pt/day x 2 Gy/pt x 270 day/y
- W = 27,000 Gy/y = 27,000,000 mSv/y

$$B = \frac{Pd^2}{WUT} = \frac{0.1 \text{ mSv/y} \times (4\text{m})^2}{27 \times 10^6 \text{ mSv/y} \times 0.25 \times 1}$$

$$B = 2.37 \times 10^{-7}$$

Primary beam: Example

- What would be the required thickness of concrete?

$$B = 2.37 \times 10^{-7}$$

$$n = \log\left(\frac{1}{B}\right) = \log\left(\frac{1}{2.37 \times 10^{-7}}\right) = 6.62 \text{ TVL}$$

Primary beam: Example

- 6.62 TVL are required

$$S = TVL_1 + (n-1)TVL_e$$

$$S = 0.35 + (6.62-1)\ 0.35 = 2.32m$$

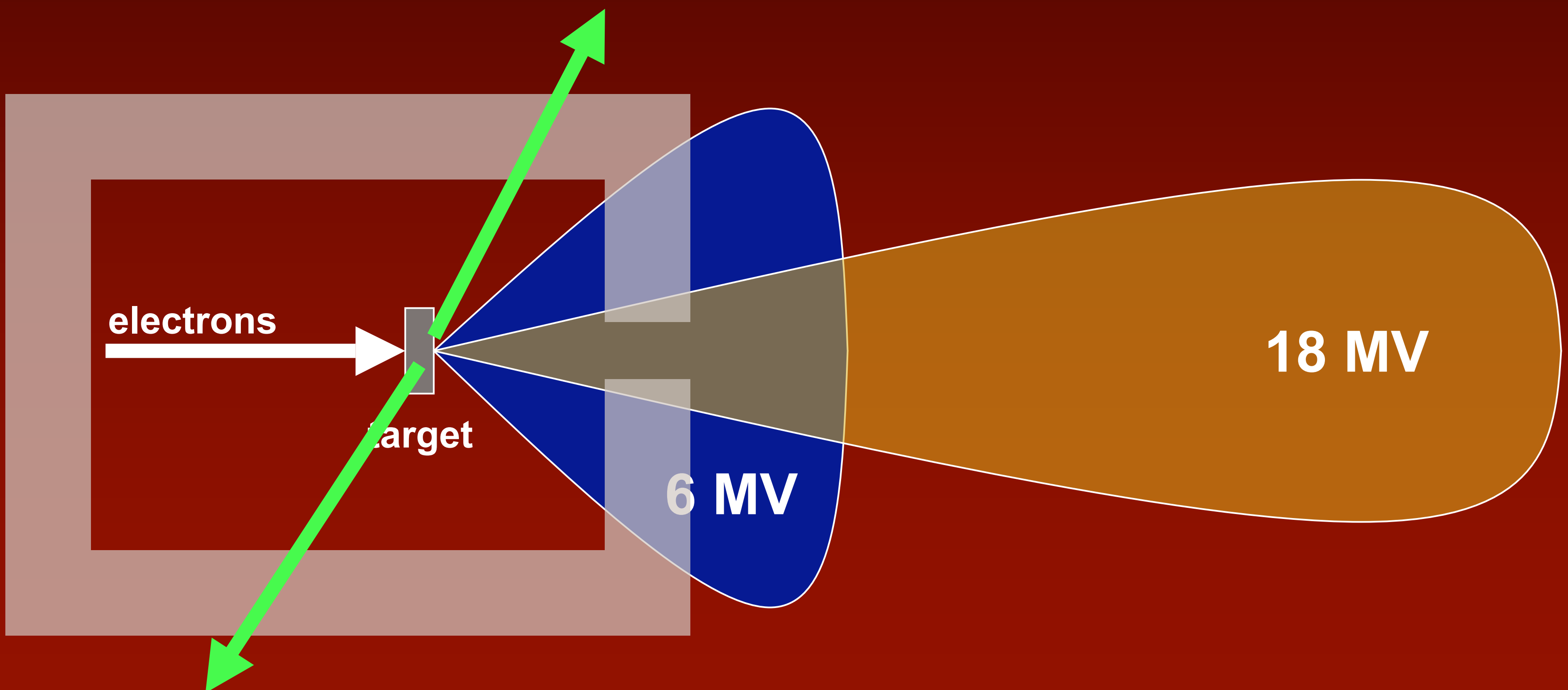
Secondary barriers

- Head leakage
- Patient scatter
- Wall scatter

- For energy > 10 MV head leakage is dominant

Leakage radiation

- Photon beam produced in many directions



Leakage radiation

- Head shielding designed to reduce intensity by factor of 1000
- d is distance from target to POI
- Leakage assumed to be isotropic: U = 1

$$B = \frac{1000\ Pd^2}{WT}$$

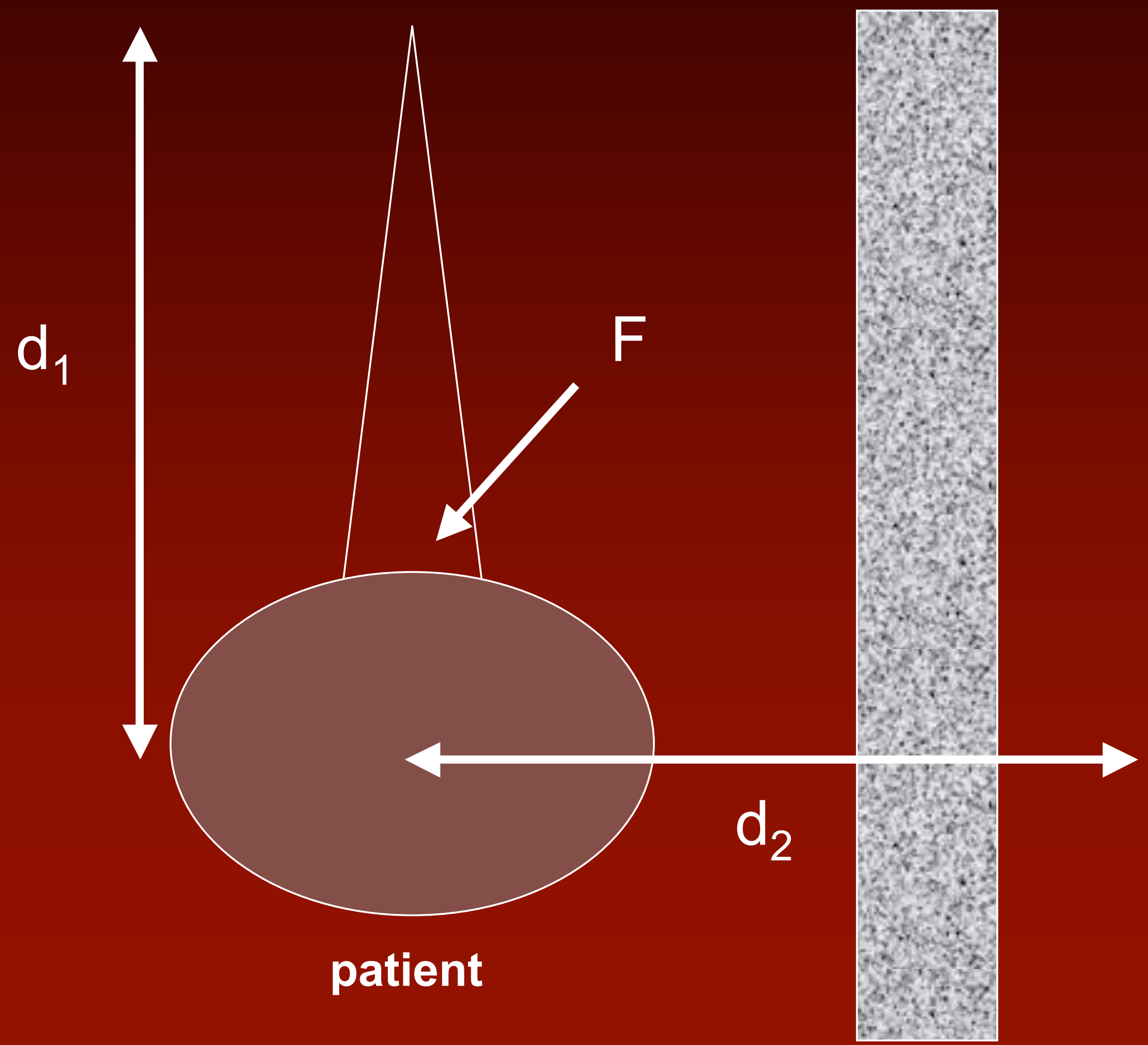
Patient scatter

$$B = \frac{P\, d_1^2\, d_2^2 \quad 400}{a\, W\, T \qquad F}$$

Patient scatter

$$B = \frac{P\, d_1^2 d_2^2\ 400}{a\, W\, T\, F}$$

F is the incident field size on the patient



Patient scatter

- **a** is the scatter fraction
- Ratio of scattered radiation at a point 1m from the patient to the primary beam dose rate at isocenter
  - Taylor and Rodgers, 1999
  - Rule of thumb 0.1-0.2%

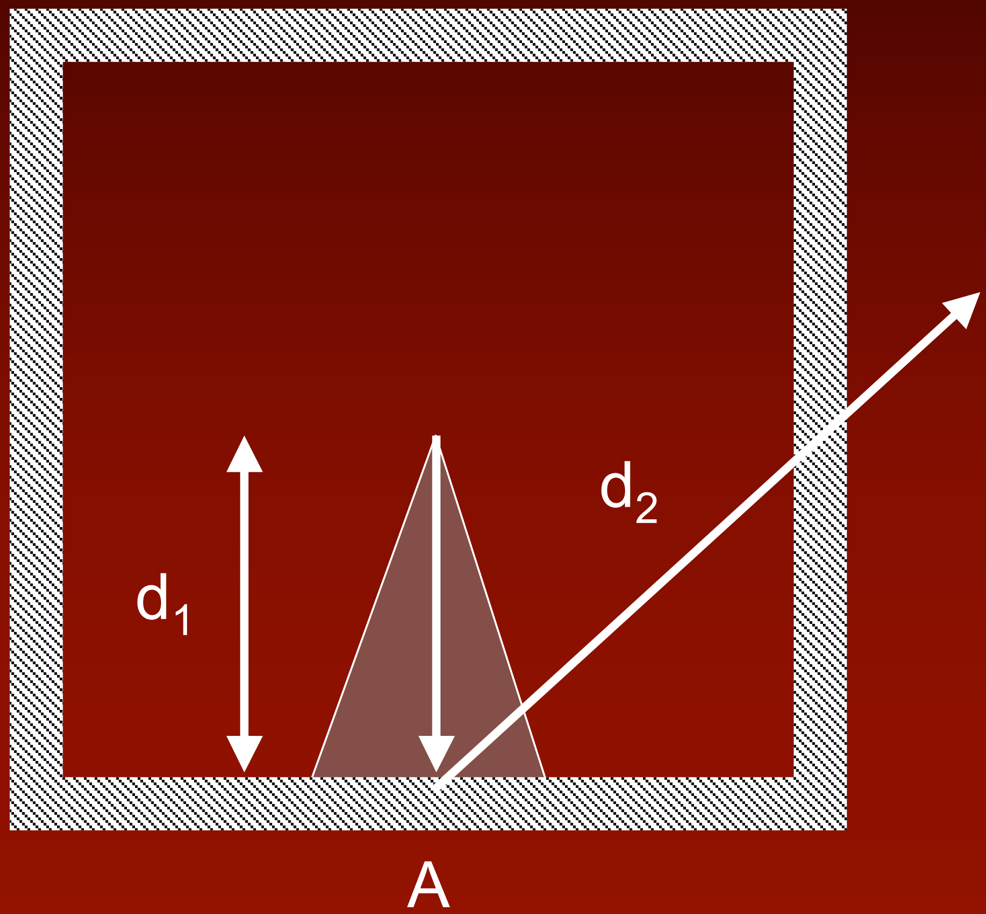
Angle (deg)	6 MV	10 MV	18 MV	24 MV
10	1.04×10^{-2}	1.66×10^{-2}	1.42×10^{-2}	1.78×10^{-2}
20	6.73×10^{-3}	5.79×10^{-3}	5.39×10^{-3}	6.32×10^{-3}
30	2.77×10^{-3}	3.18×10^{-3}	2.53×10^{-3}	2.74×10^{-3}
45	1.39×10^{-3}	1.35×10^{-3}	8.64×10^{-4}	8.30×10^{-4}
60	8.24×10^{-4}	7.46×10^{-4}	4.24×10^{-4}	3.86×10^{-4}
90	4.26×10^{-4}	3.81×10^{-4}	1.89×10^{-4}	1.74×10^{-4}
135	3.00×10^{-4}	3.02×10^{-4}	1.24×10^{-4}	1.20×10^{-4}
150	2.87×10^{-4}	2.74×10^{-4}	1.20×10^{-4}	1.13×10^{-4}

Wall scatter

$$B = \frac{P\, d_1^2 d_2^2}{\alpha\, A\, W\, T\, U}$$

Wall scatter

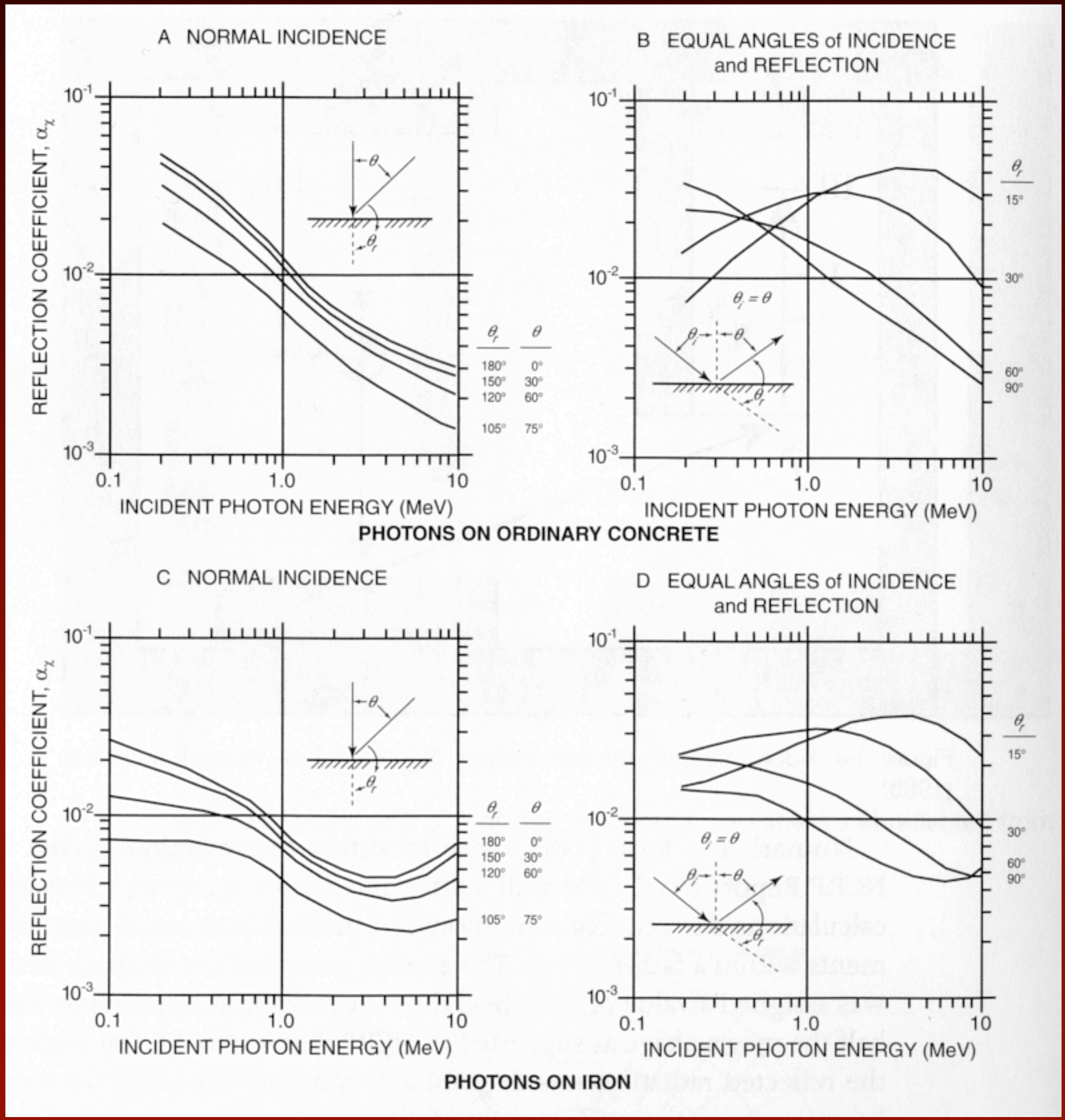
$$B = \frac{P\, d_1^2 d_2^2}{\alpha\, A\, W\, T\, U}$$



Wall scatter

- α is the reflection coefficient
- Function of material, energy, and angle of incidence
- Generally between 0.001-0.1

Reflection coefficients



Rule of thumb

- 6 TVL required for primary barrier
- 3 TVL required for secondary barrier

Room Mazes

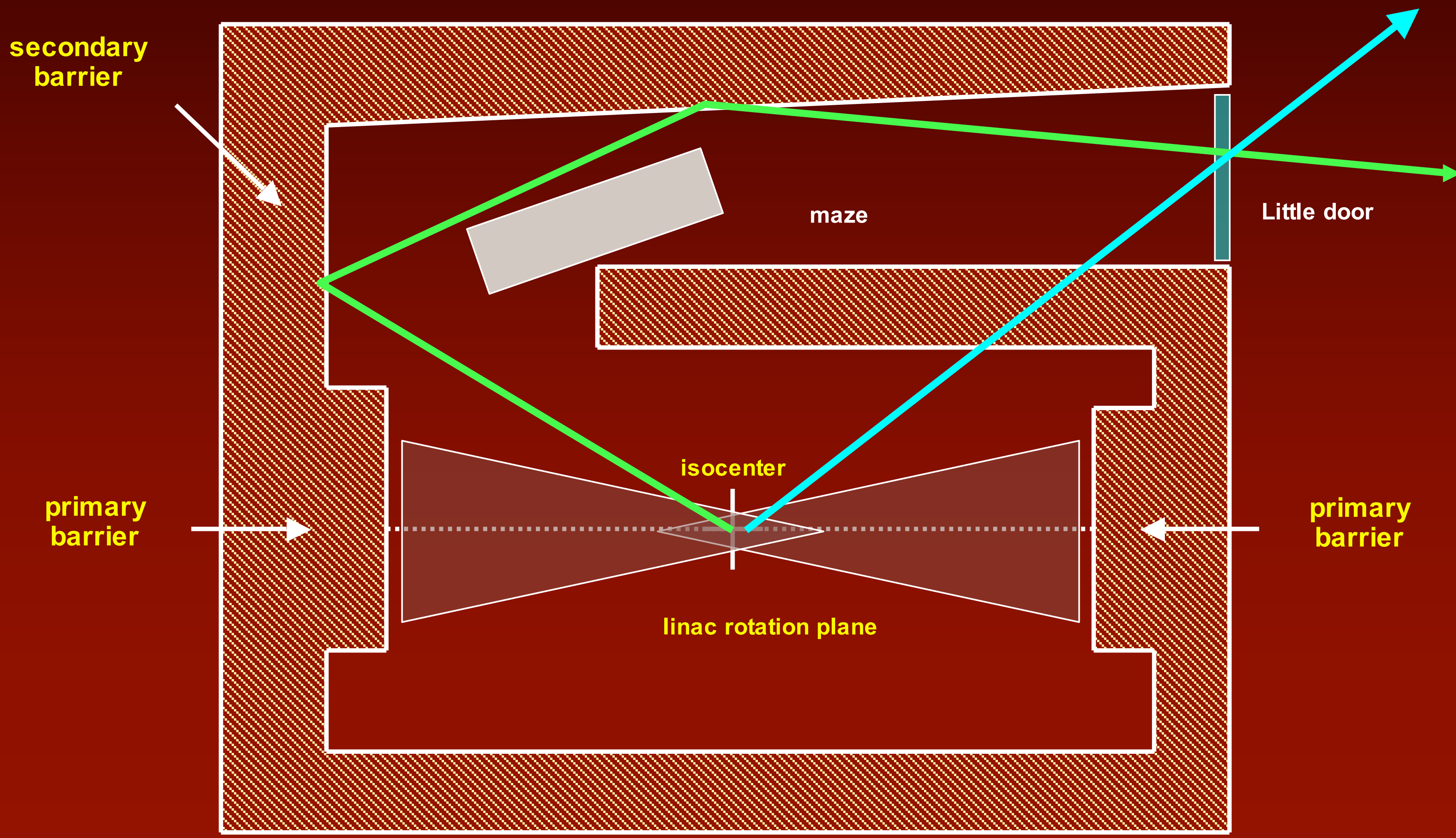
- Mazes used to reduce door size
- Disadvantage is that the maze takes up considerable space
- Remember to build maze wide enough to pass equipment and patients on stretchers

Room Mazes

- Radiation reaching the maze door is from the scattering from room surface and the patient, and leakage transmission through the maze.

- maze + wall thickness is at least calculated secondary barrier thickness

Low energy < 10 MV



Room mazes

- Scatter is comprised of 3 components:
  - Scattered primary beam from room surfaces (S_s)
  - Head leakage photons scatted (L)
  - Primary scatter from patient (S_p)

  - Scattered photon energy ~ 0.2-0.3 MeV

Dose at room door

$$D_c = f\,S_{prim} + S_{pat} + L + T$$

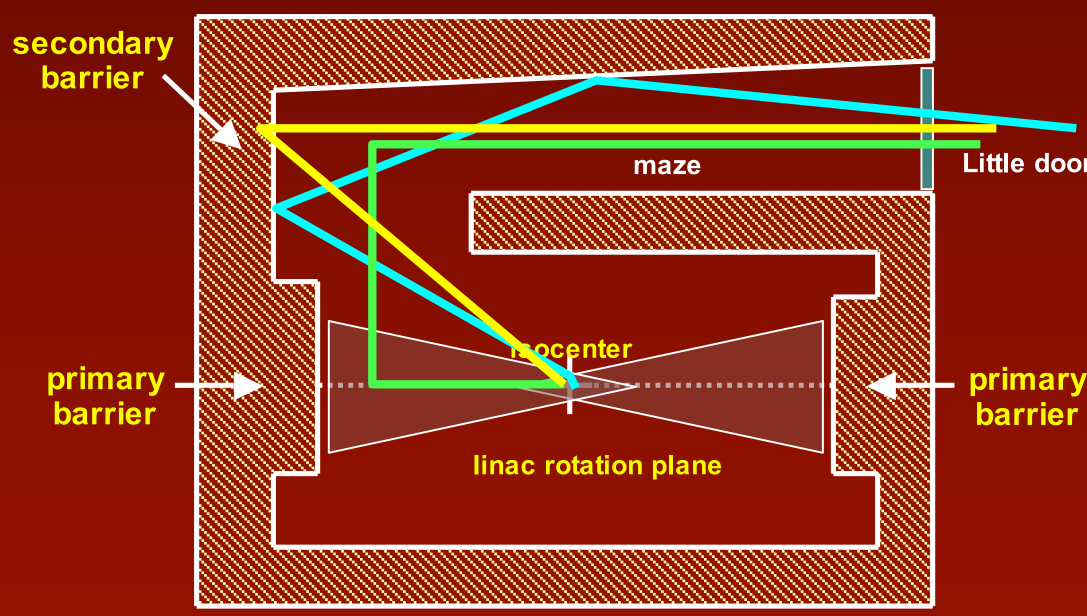
- ***f*** fraction of scattered photons transmitted through patient (0.25)
- S_{prim} dose from scattered primary beam
- S_{pat} dose from scattered patient scatter
- **L** scattered leakage dose
- **T** transmitted leakage dose

Equations for the door

$$S_{prim} = \frac{D_o \alpha_1 A_1 \alpha_2 A_2}{(d_1 d_{r1} d_{r2})^2}$$

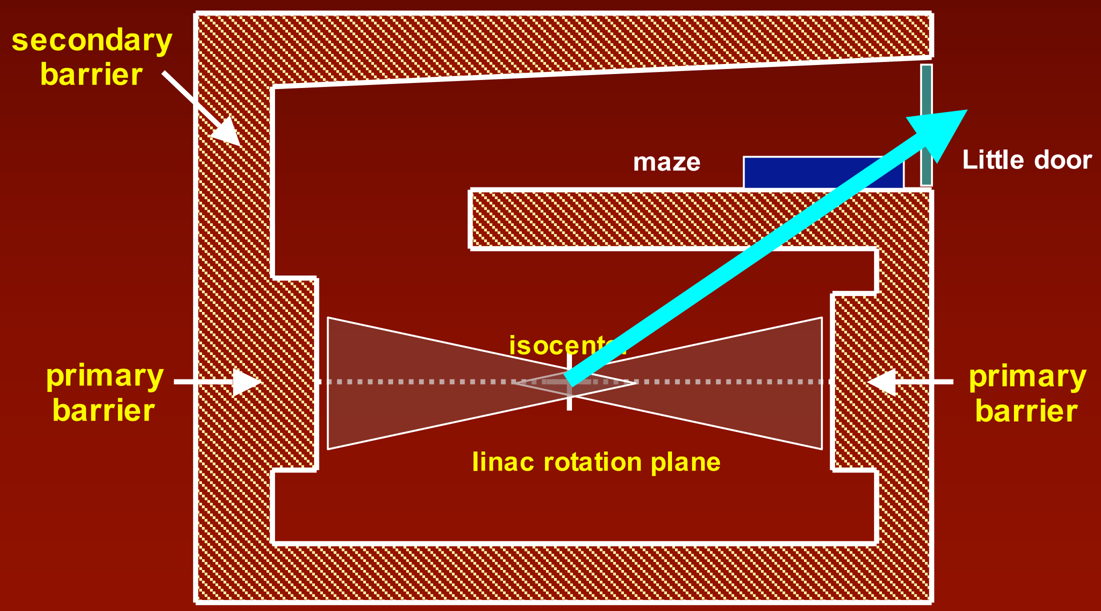
$$S_{pat} = \frac{a D_o \alpha_1 A_1 (F/400)}{(d_1 d_2 d_{rl})^2}$$

$$L = \frac{D_o\, L_o \alpha_1 A_1}{(d_1 d_s)^2}$$



Leakage photons

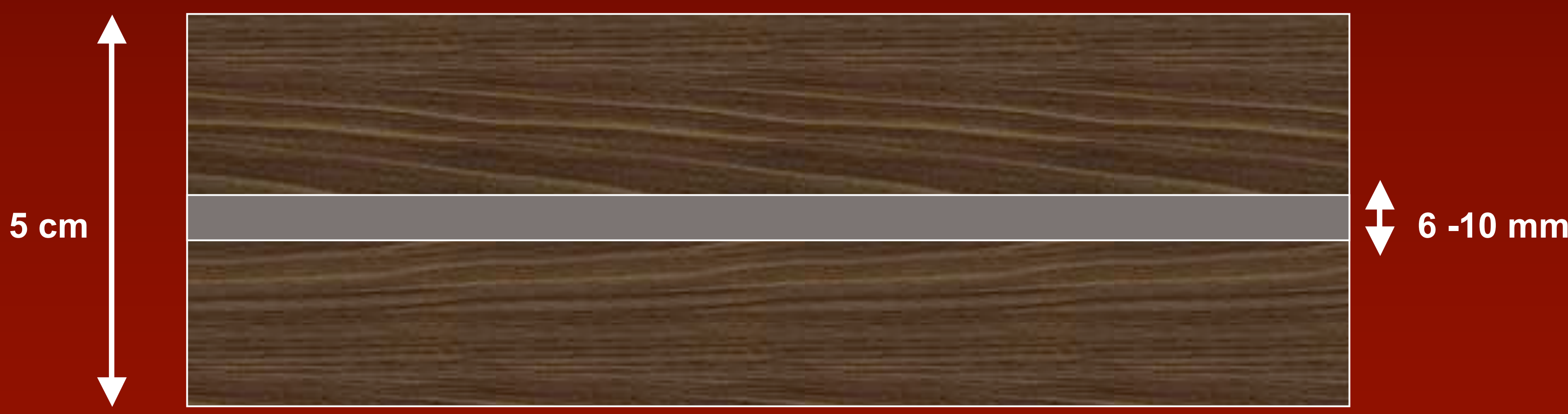
- Care must be taken to shield non-scattered leakage photons



$$T = \frac{D_o L_o B}{d^2}$$

Doors and mazes: Low X

- Typical door size is 6-10 mm Pb in 5 cm of wood



High energy installations

- Energy > 10 MV
- Photo-neutrons
- Neutron capture (activation)

Photo-neutrons

- Photo-nuclear interactions can result in the production of neutrons

$$^{A}X(\gamma,n)^{A-1}X$$

- Neutrons can be created from the heavy metal components in the head of the LINAC
- Electrons make photons that make neutrons

Photo-neutrons

Relative yield of photo-neutrons as a function of incident electron energy. Values normalized to W at 25 MeV. (NCRP, 1984)

		Electron energy (MeV)			
Element	Threshold (MeV)	10	15	20	25
Al	13.1	0	0	0	0.03
Cu	9.91	0	0	0.11	0.25
Fe	13.4	0	0	0.07	0.17
Pb	6.74	0	0.25	0.7	0.93
W	6.19	0	0.25	0.7	1.0

Neutron activation

- (n,γ) reactions can activate heavy metal components of LINAC head

Reaction	Decay mode	Half life	Photon energy
$^{27}Al(n,\gamma)\ ^{28}Al$	β-	2.3min	1.78
$^{63}Cu(\gamma,n)\ ^{62}Cu$	β+	9.7min	0.511
$^{55}Mn(n,\gamma)\ ^{56}Mn$	β-	2.6min	0.847
$^{63}Cu(n,\gamma)\ ^{64}Cu$	β+ β-	12.7hr	1.346
$^{65}Cu(\gamma,n)\ ^{64}Cu$	β+ β-	12.7hr	1.346
$^{186}W(n,\gamma)\ ^{187}W$	β-	23.9hr	0.479/0.686
$^{58}Ni(\gamma,n)\ ^{57}Ni$	β+	36hr	1.387/1.920

Neutron activation

- Average neutron E is 2 MeV (fast)
- ~ 15% are attenuated or scattered in linac head (~ 7 cm Pb)
- Average neutron E leaving linac head is ~1.7 MeV
- Room scattered neutron E is ~ 0.5 MeV
- There is also a thermal neutron energy group present (~ 0.025 eV)

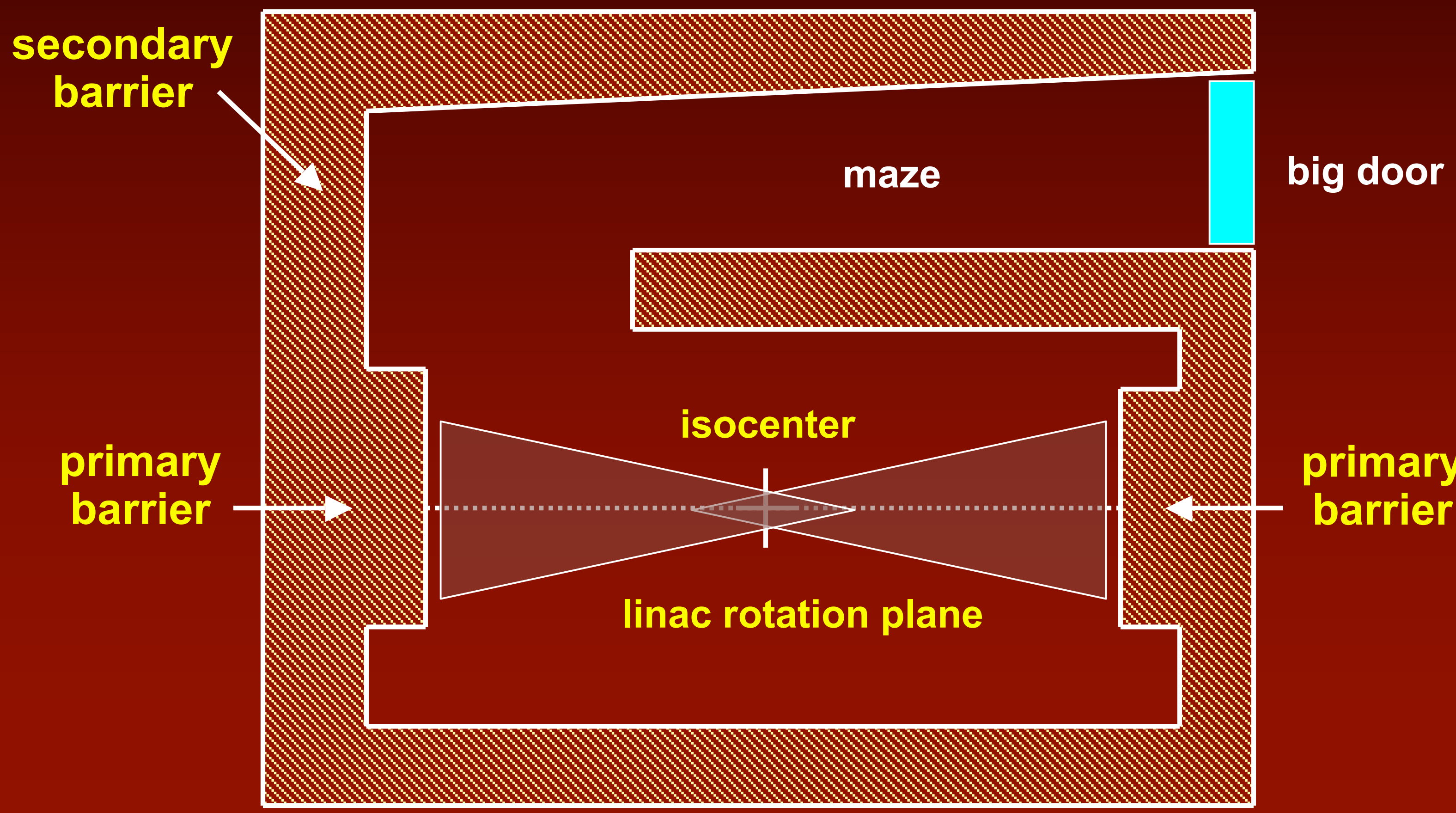
Neutron shielding

- Fast neutrons are efficiently attenuated by materials rich in Hydrogen (concrete)
- TVL_n in concrete is 22 cm
- TVL_{18MV} in concrete 44 cm
- Fast neutrons are adequately shielded by room shielding

Neutron shielding

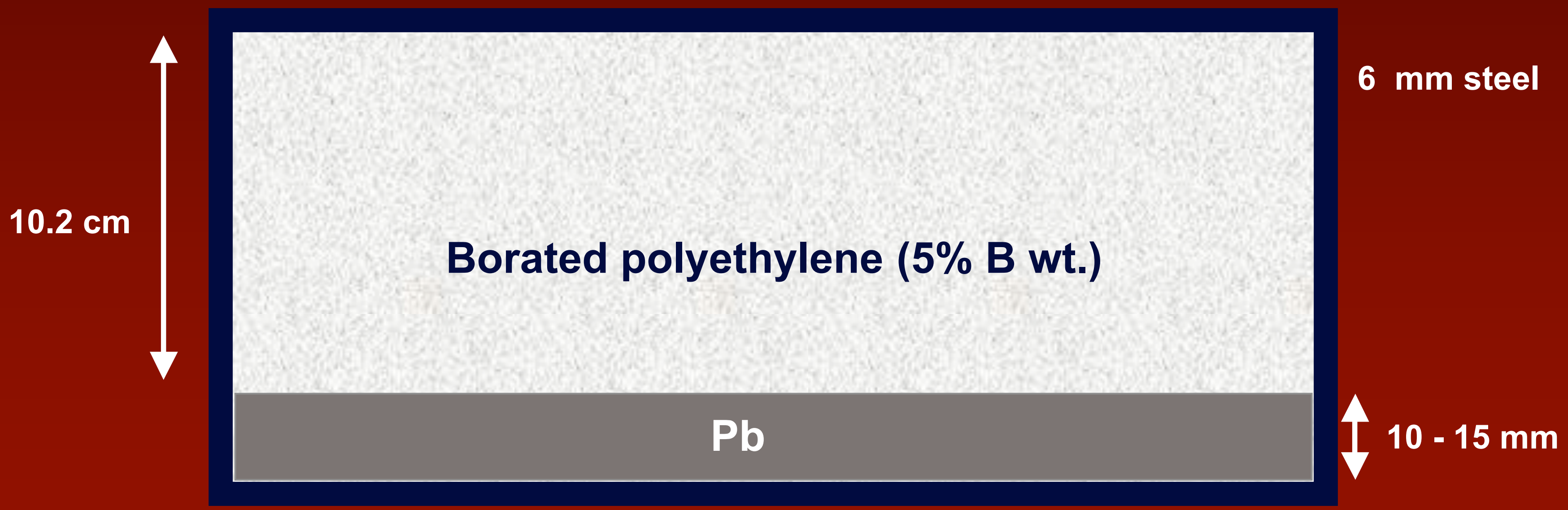
- Fast neutrons are moderated by hydrogen collisions and become slow neutrons
- Capture reactions with slow neutrons can yield high energy γ
  - $E\gamma_{ave}$ = 3.6 MeV
  - $E\gamma_{max}$ > 8,0 MeV
- Boron moderates slow neutrons effectively (few mm)
- Slow neutron capture results in 0.478 MeV γ–emission

High energy > 10 MV

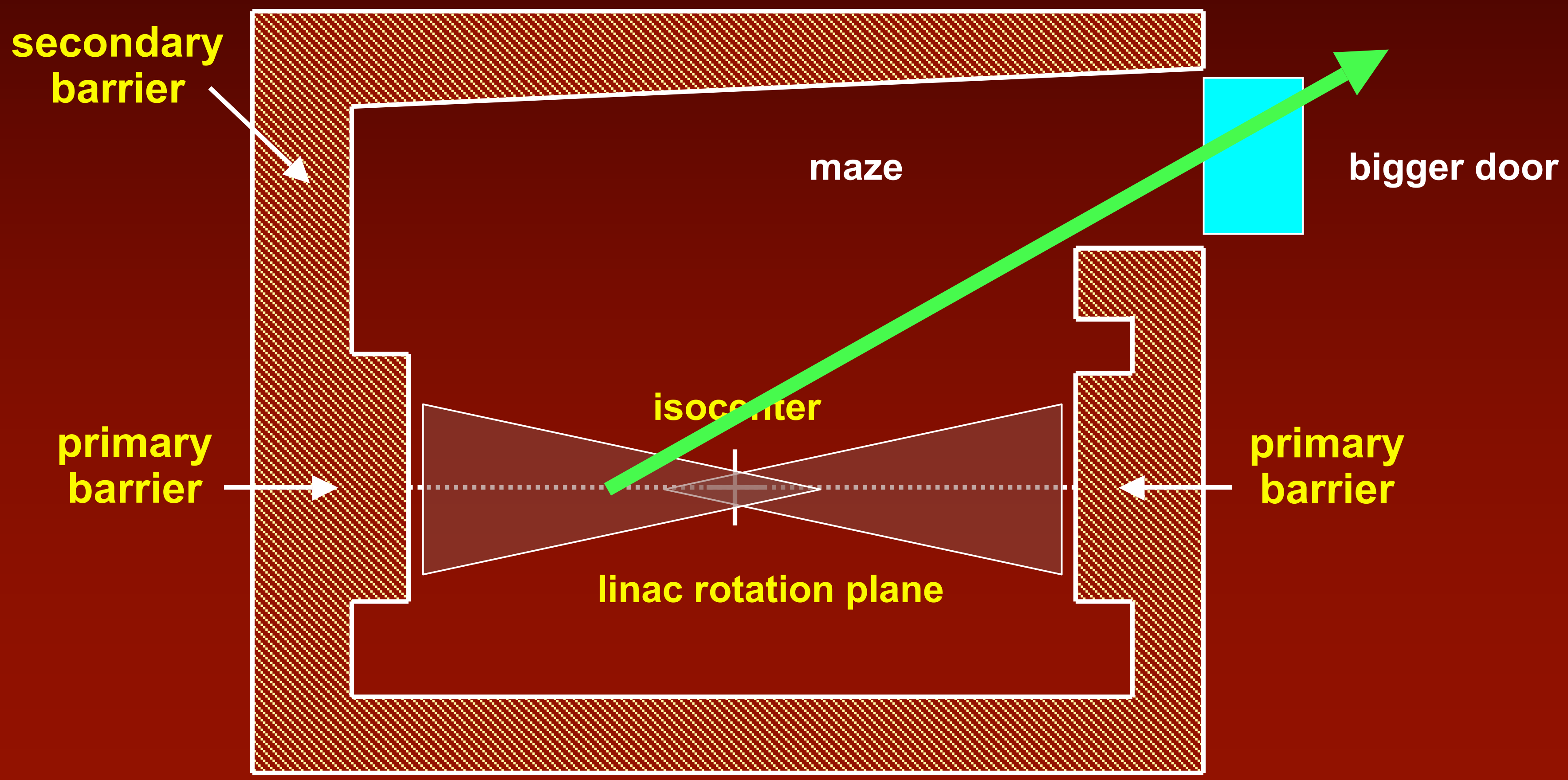


Doors and mazes: High X

- Door has to stop neutrons, scatter photons, and, activation gammas.

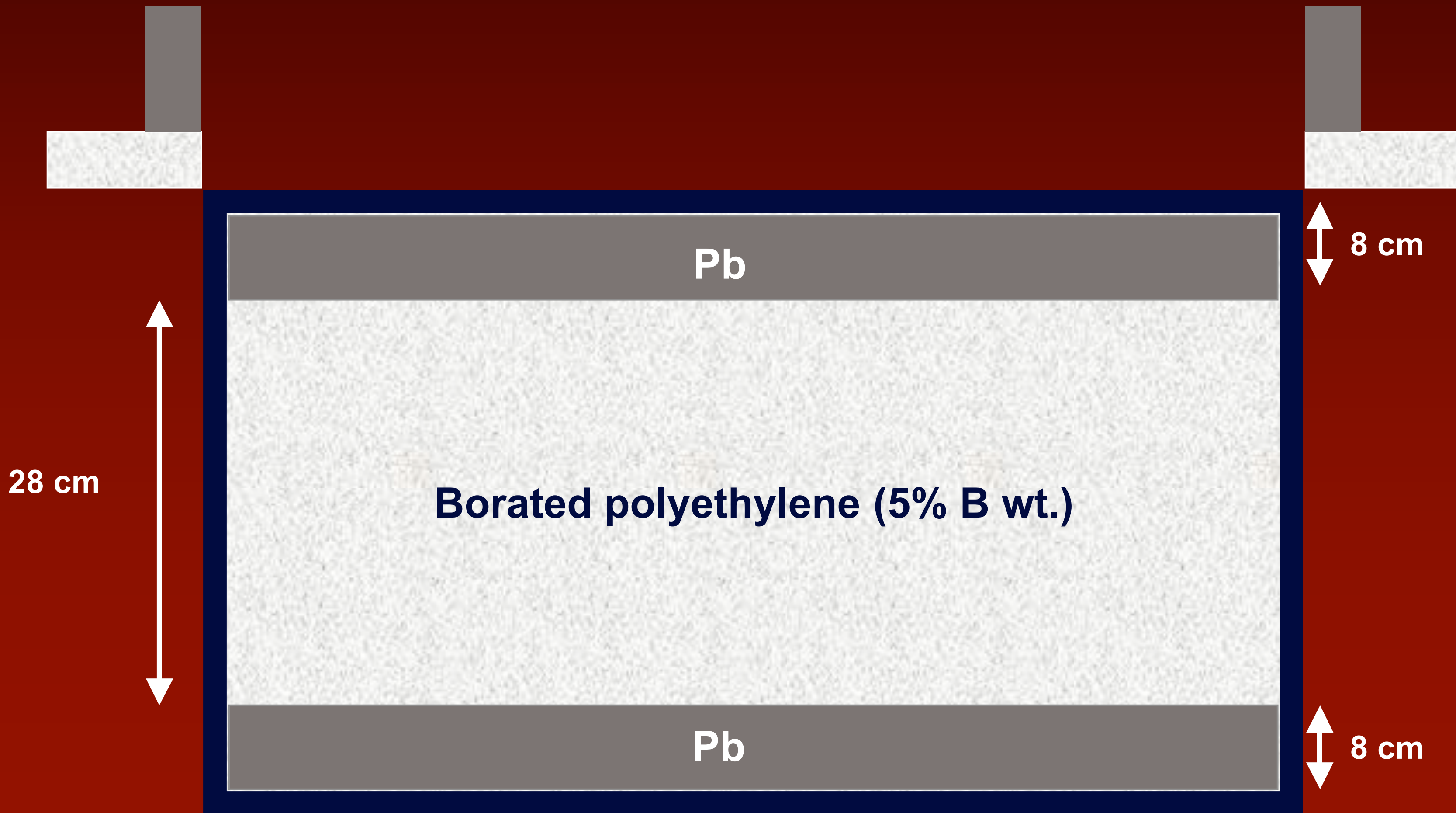


High energy > 10 MV



Doors and no maze: High X

- Direct shielded door



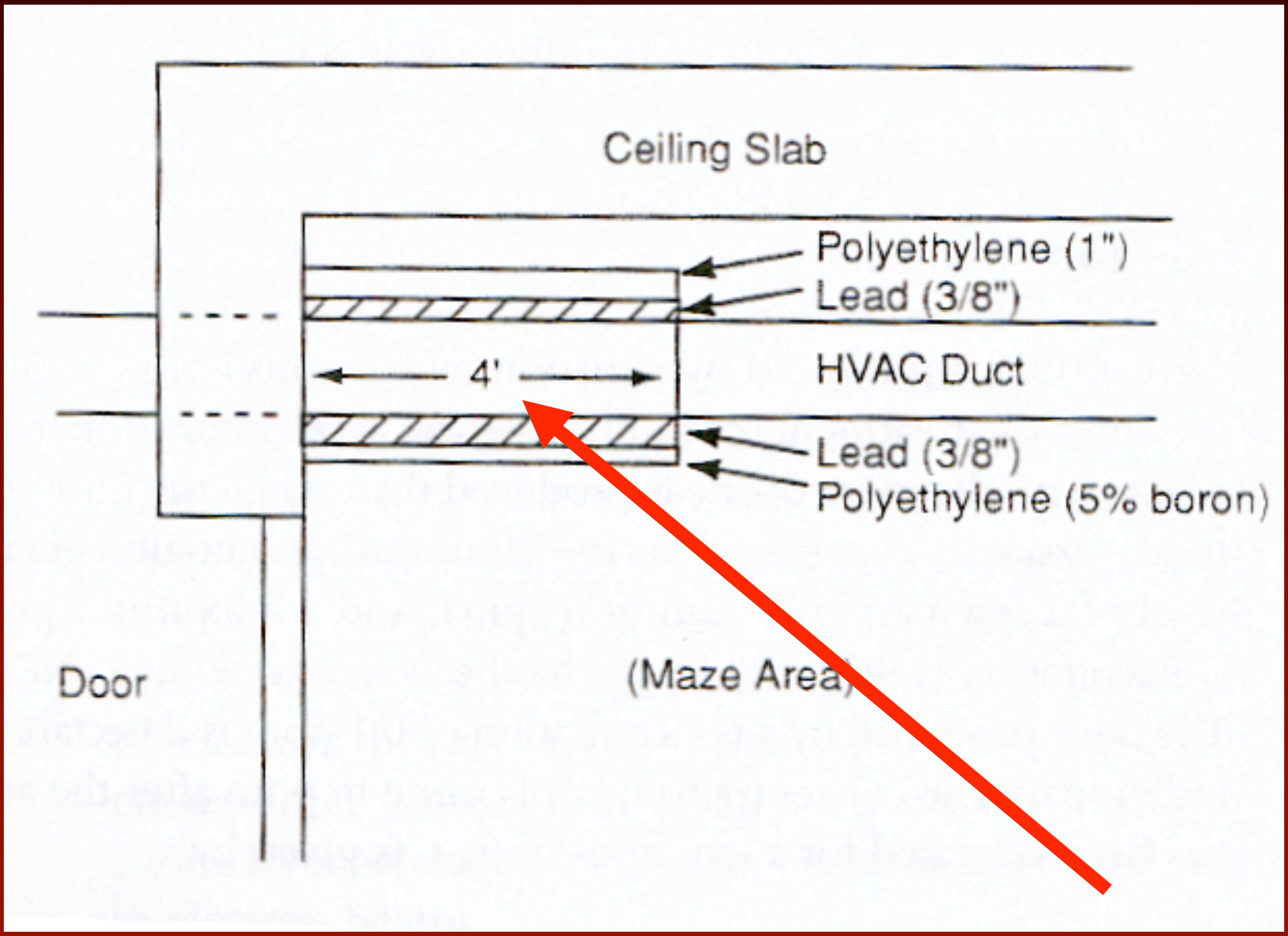
Surveys

- A complete survey of the facility should be carried out immediately following the installation of the linear accelerator
- The survey should be encompass all primary and secondary barriers as well as above the ceiling
- If a high energy Linac is involved, a complete neutron survey must be carried out

miscellaneous

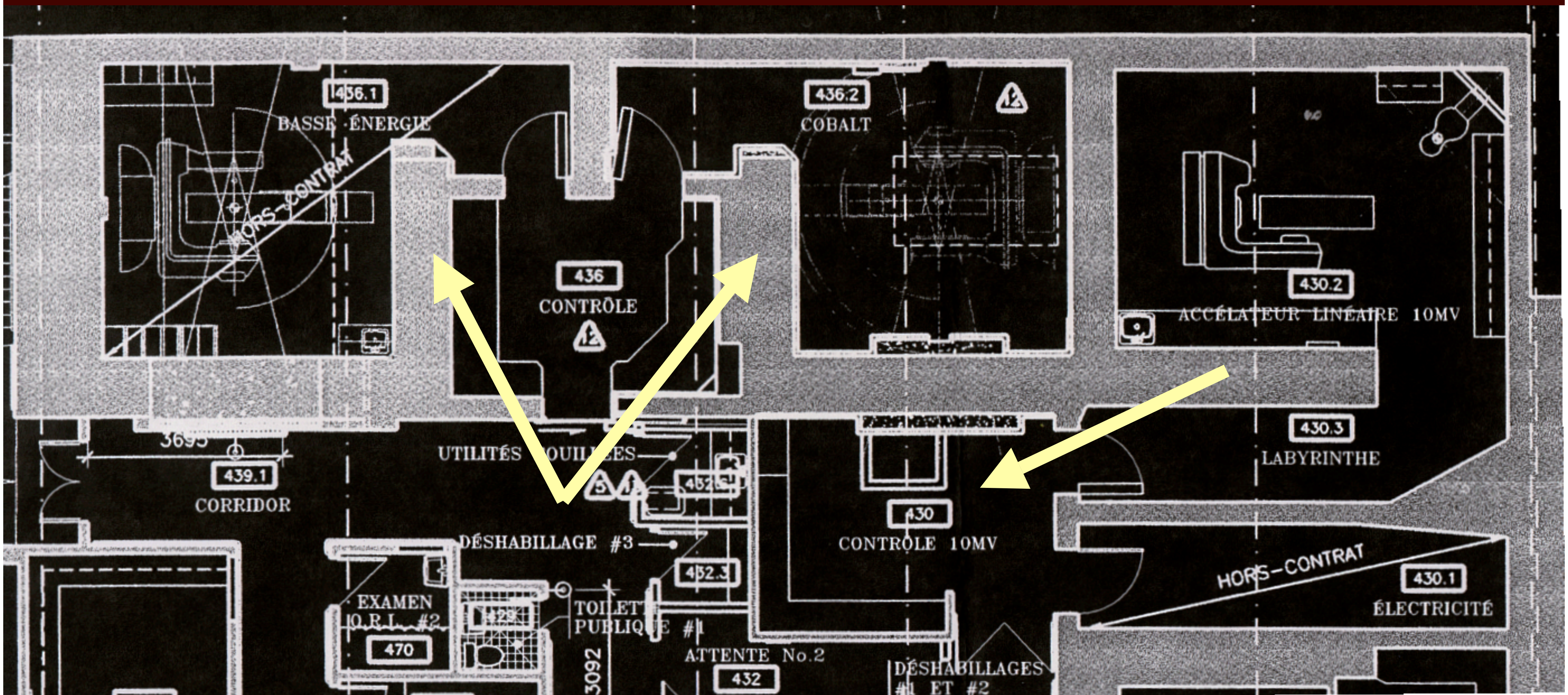
- High energy machines can create ozone
- The requirement is for 6 complete air exchanges per hour
- HVAC holes are large and must be constructed in such a way as to not compromise the shielding. (are usually located above the door)

ducting



Ceiling Slab
Polyethylene (1")
Lead (3/8")
HVAC Duct
4'
Lead (3/8")
Polyethylene (5% boron)
Door
(Maze Area)

CL6EX-A/B and CL18



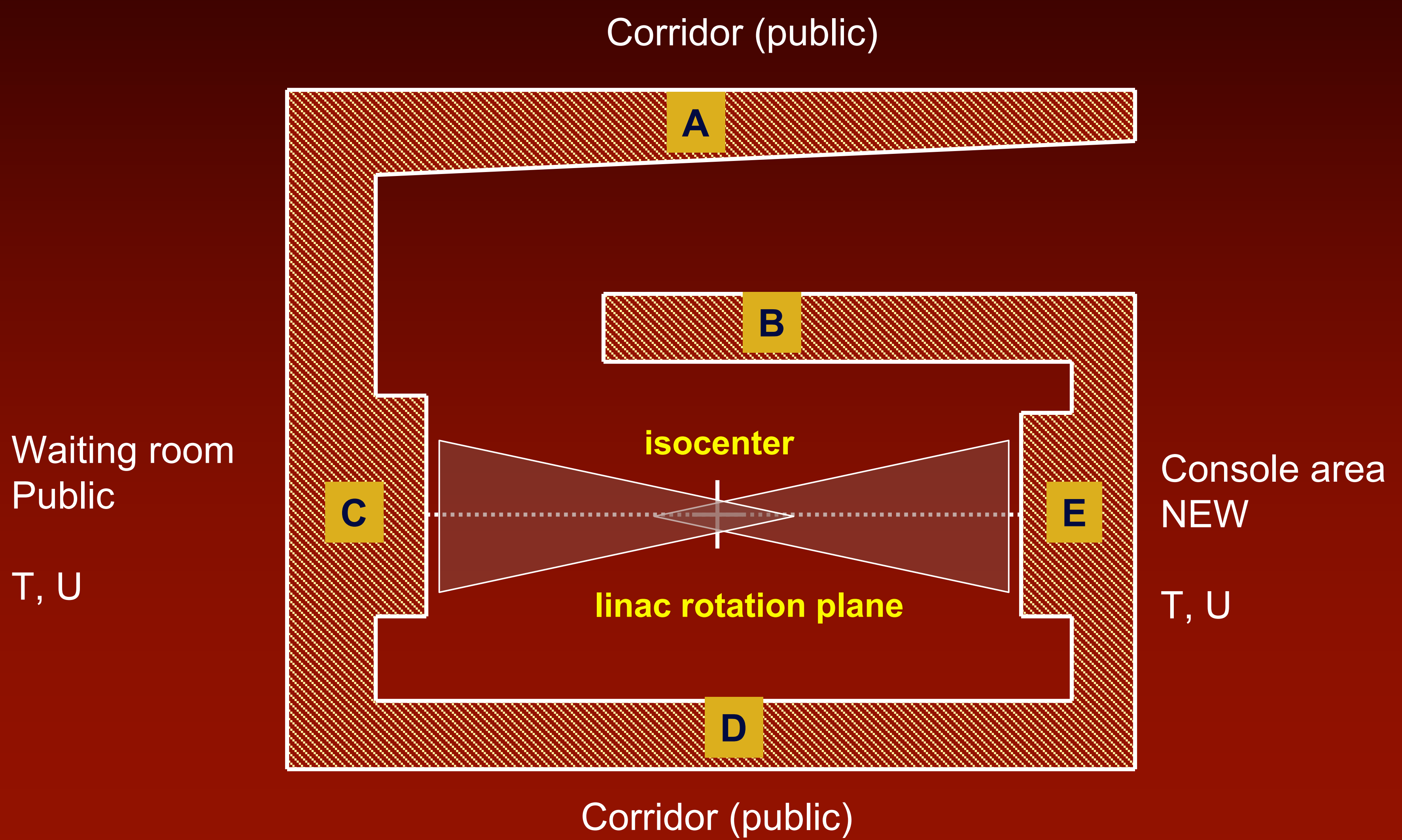
CL21EX-B

RANGEMENT PRODUITS
RADIOACTIFS
242
EL
49 800
120.59
LABYRINTHE
233.3
NOUVEL
ACCÉLÉRATEUR
23MV
233.4
AIRE DE
SERVICE
233.5
BETON
HAUTE DENSITÉ
HAUTE DENSITÉ
CHAMBRE
NOIRE
232
CONTRÔLE
23 MV
233
233.1
233.2
CONTRÔLE
23MV
231
4
13
DÉSHABILLAGES
AIRE D'ATTENTE No.3

Let’s design a room

- Inside 8 x 8 m^2
- High energy - 6/18 MV
- Concrete and high density concrete available
- Design with maze
- Max f/s @ iso is 40 x 40 cm^2
- Max dose rate at isocenter is 500 cGy/min

Let's design a room



Let’s design a room

- What is the workload of the linac?
- What is the target dose-rate?
- What are the relevant factors? (U,T,d)
- What is the B?
- What barrier thickness is required?
- Maze and door (neutrons)?