Linac Room Design

Dose Equivalent

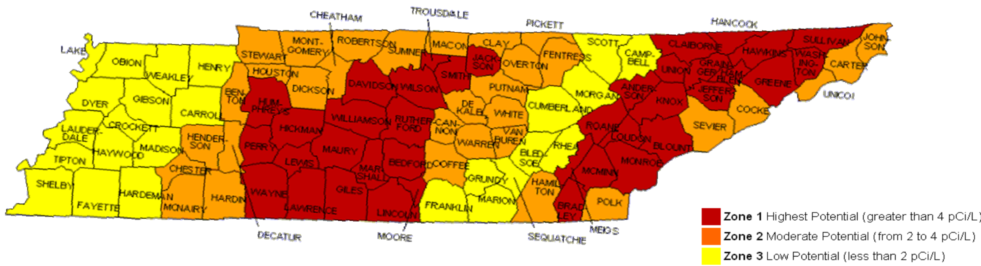
The biological effects of radiation depend on the dose and the type of radiation

- Types of radiation with a high kinetic energy transfer (*LET*) produce the greatest damage
- The dose equivalent (*H*) is defines as $H = D \cdot Q$, where *D* is the absorbed dose and *Q* is a quality factor for the type of radiation
- The SI unit for dose equivalent is the sievert (*Sv*), and is defined as 1 J/kg
- The old unit for dose equivalent was the rem, which is equal to 10^{-2} Sv

Background Radiation

Background radiation consists principally of three sources: *Terrestrial*, Cosmic, and Internal

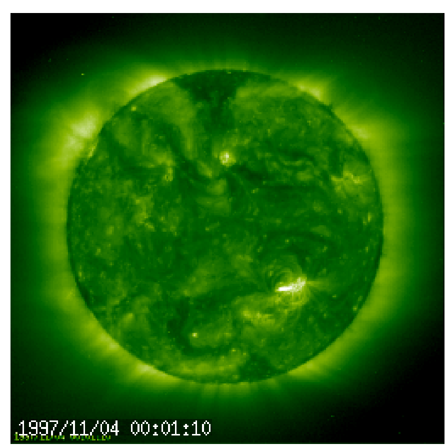
- Terrestrial radiation varies over the earth because of differences in the composition of the earth's crust
- In addition, many buildings may incorporate radioactive materials
- It is estimated that the average annual dose to the bronchial epithelium from radon decay is 24 mSv (*2.4 rem*)



Background Radiation

Background radiation consists principally of three sources: Terrestrial, *Cosmic*, and Internal

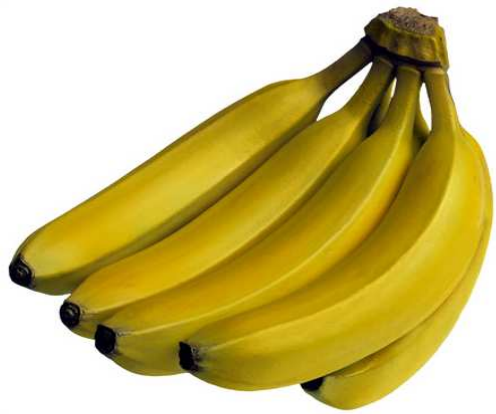
- Cosmic radiation comes from the cosmic background radiation and from solar activity
- Cosmic radiation levels change with elevation
- Air travel exposes individuals to increased dose level because of the decreased in shielding from the atmosphere
- It is estimated that the dose equivalent at 30,000 is about 0.5 mrem per hour



Background Radiation

Background radiation consists principally of three sources: Terrestrial, Cosmic, and *Internal*

- Internal radiation comes from the decay of ^{40}K in our body, which emits β and γ decay for a total of 1.1 mSv (*0.1 rem*) to the bone
- Potassium is needed for proper nerve and muscle function
- It helps regulate the water balance and electrolyte balance of the body.
- Many foods are rich in potassium, including scallops, potatoes, figs, bananas, prune juice, orange juice, and squash.



Shielding Design

- **NCRP Report 49**
  - Primary and secondary barrier calculation methodology for ^{60}Co and linacs up to 10 MV
- **NCRP Report 51**
  - Extended NCRP 49 methodology up to 100 MV and added empirical shielding requirements for maze doors
- **NCRP Report 79**
  - Improved the neutron shielding methodology
- **NCRP Report 151**
  - Update of NCRP 51 that is primarily aimed at radiation therapy facilities

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

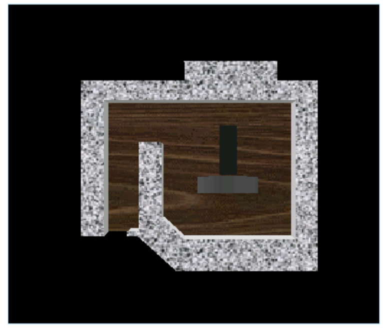
Where:

B = barrier transmission
P = weekly allowable exposure rate
W = workload
U = use factor
T = occupancy
d = distance from radiation source
m = correction factors for secondary barriers

Barrier Transmission

- The barrier transmission is the calculated dose rate at a defined distance from the source without attenuating material
- The dose equivalent contribution is calculated for primary, scattered, and leakage radiation
- The number of Tenth Value Layers (*TVL's*) are then calculated in order to reduce the radiation levels to the legal dose constraints (*occupational or public)*

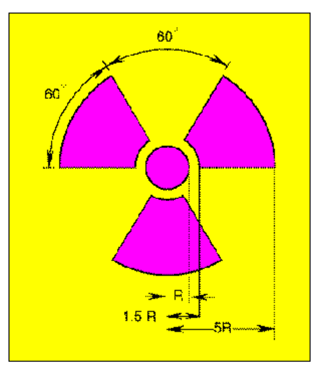
$$B = \frac{Pd^2}{WUT} \cdot M$$



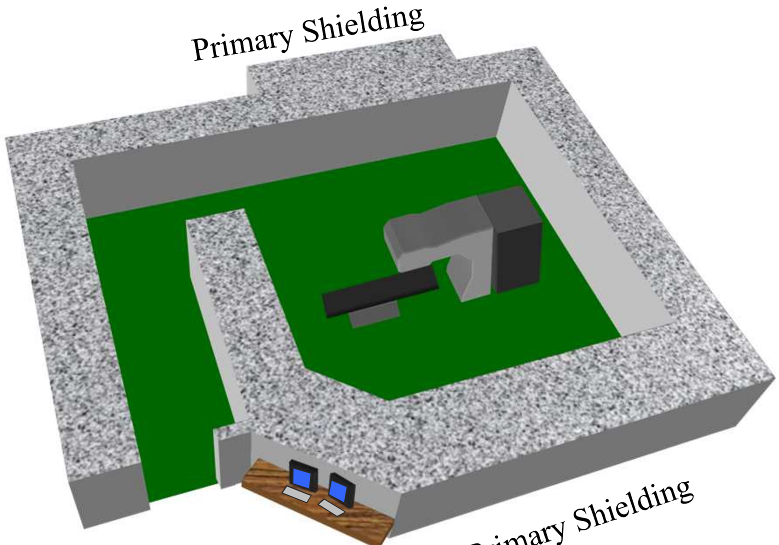
Radiation Protection Limits

- The purpose of shielding is to limit the dose equivalent to people
  - Exposure must not exceed a specific dose equivalent limit
  - As Low as Reasonably Achievable (*ALARA*)
- The limits are legally binding and defined by the NRC or an Agreement State
- Typical design dose limits (*P*)
  - 0.40 to 0.10 mSv/week for occupational
  - < 0.02 mSv/week for the general public

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



Treatment Vault Design



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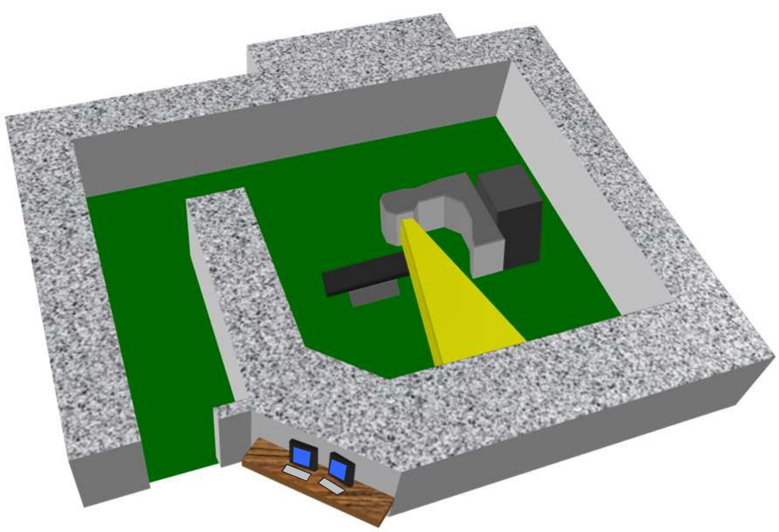
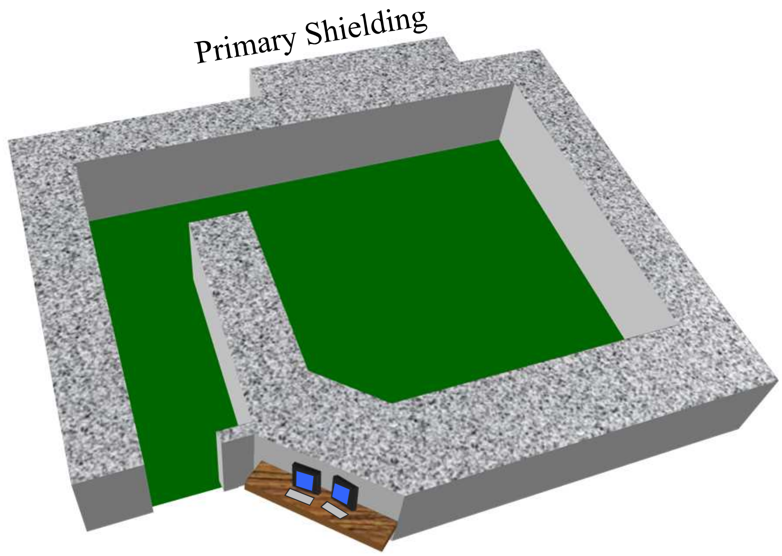
Treatment Vault Design



Treatment Vault Design



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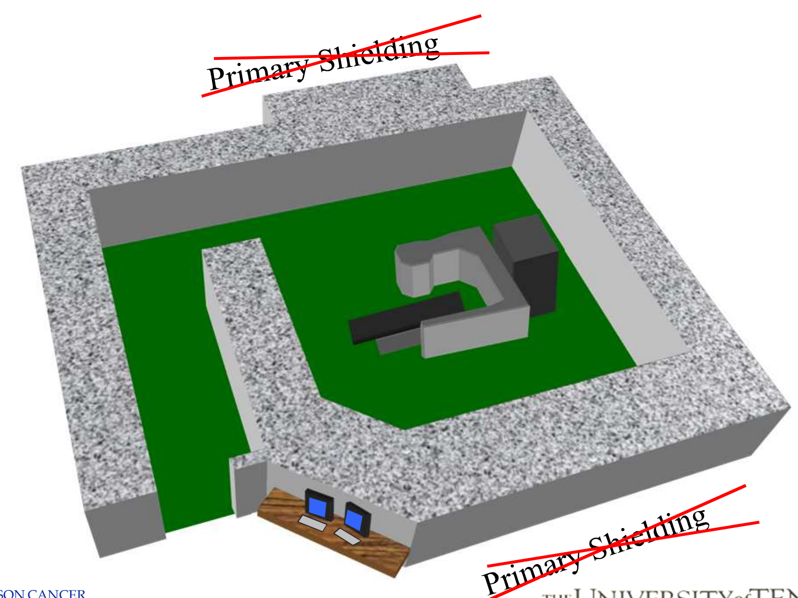
Treatment Vault Design



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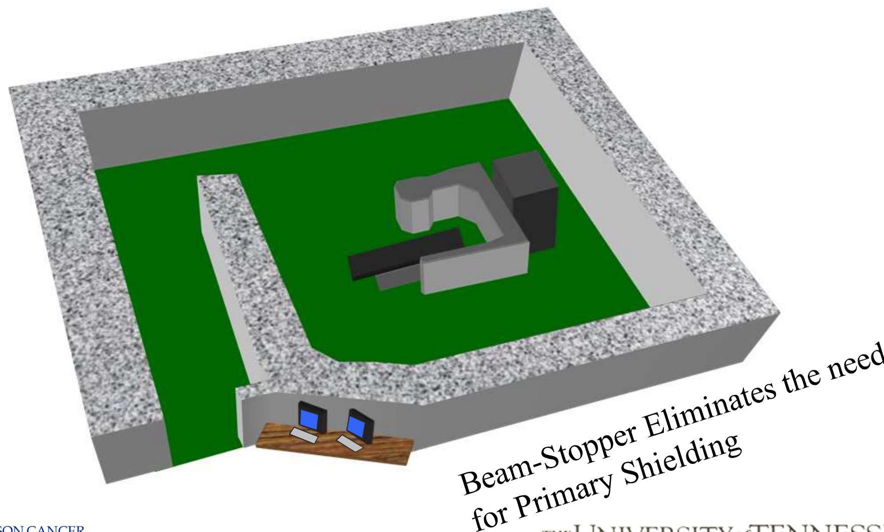
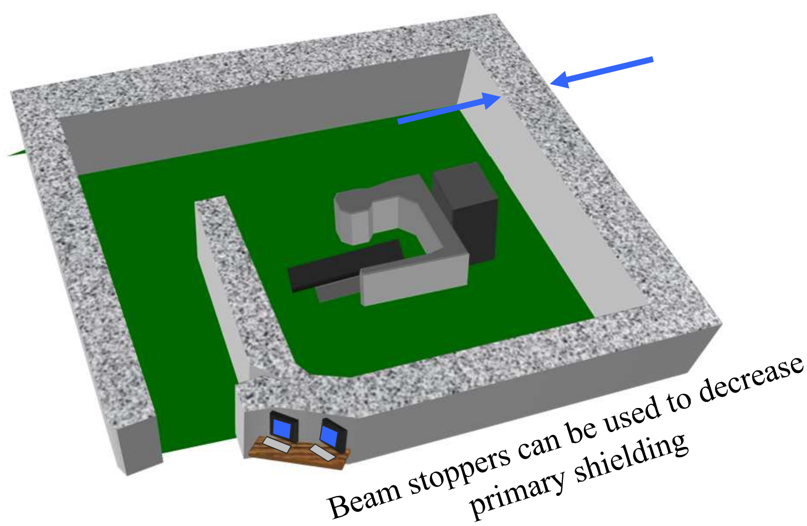
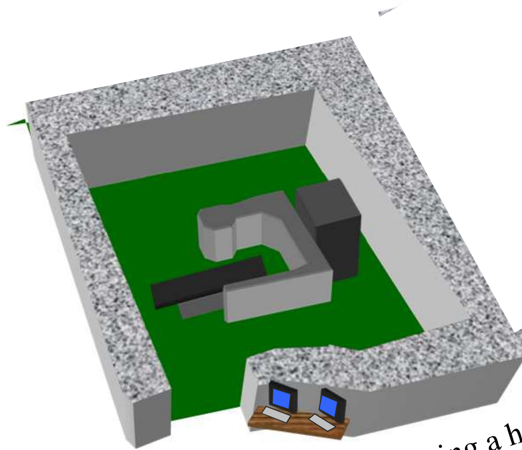
Treatment Vault Design



Treatment Vault Design



Treatment Vault Design

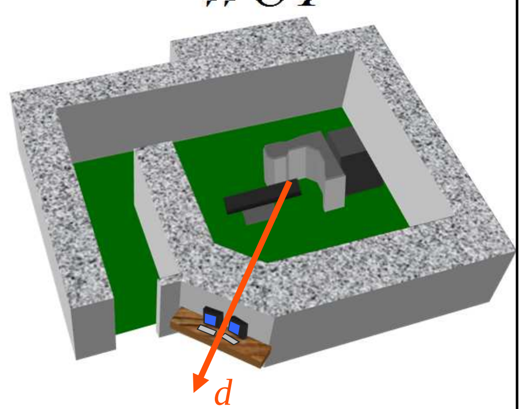


Eliminating the maze and using a heaver door will also decease the footprint

Distance from Isocenter

- The distance is measured from isocenter to the calculation point
- The units in the calculation must be defined in meters
- The dose is assumed to decrease as a function of $1/r^2$
- The dose actually falls of faster, so this is a conservative calculation

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



Radiation Workload

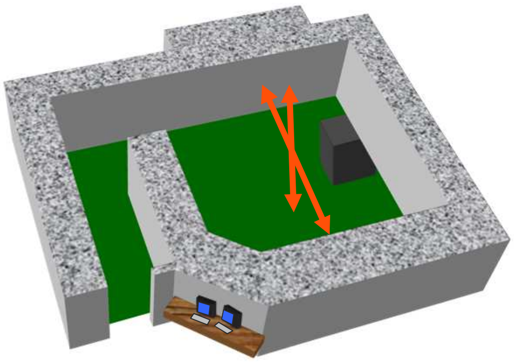
- The radiation workload is determined from the average amount of time (*or monitor units*) that the treatment machine is operated
- The workload is typically defined in Gy/week at the machine isocenter
- Example: *50 Patients/Day, 250 MU/Patient, 0.01 cGy/MU, 5 Days/Week = 625 Gy/week*

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

Use Factor

- The Use Factor (U) is the amount of time that the beam is pointing at a barrier
- Relevant only to primary dose
  - Floor: 1
  - Walls: 0.25
  - Ceiling: 0.25 to 0.50
- The Use Factor is always 1 for scatter and leakage

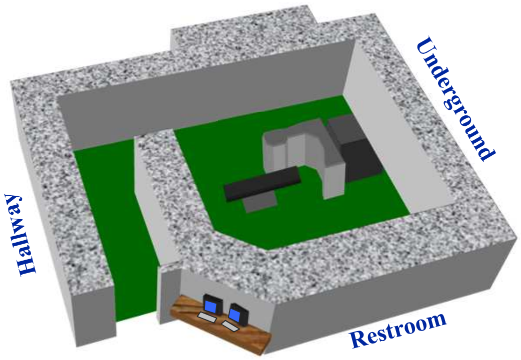
$$B = \frac{Pd^2}{WUT} \cdot M$$



Occupancy Factor

- The Occupancy Factor (T) is the fraction of time a location is occupied by a human
  - **Full occupancy (*1*):** Offices, laboratories, shops, wards, nurses stations, living quarters, children's play areas, and occupied space in nearby buildings
  - **Partial occupancy (*1/4*):** Corridors, rest rooms, elevators with operators, unattended parking lots
  - **Occasional occupancy (*1/16*):** Waiting rooms, toilets, stairways, unattended elevators, janitor's closets, outside areas used only for pedestrian or vehicular traffic

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



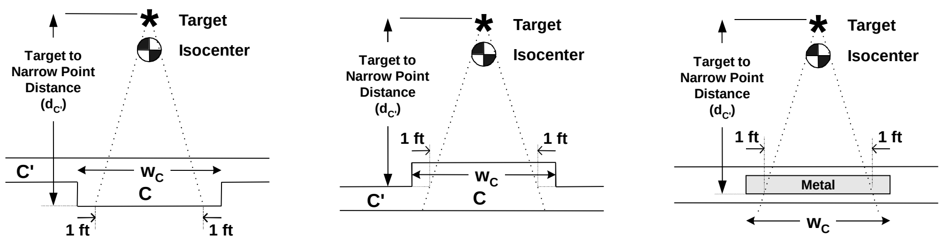
Primary Barrier TVL's

	Lead		Concrete		Steel		Earth		Borated Poly	
MV	**TVL1**	**TVLe**	**TVL1**	**TVLe**	**TVL1**	**TVLe**	**TVL1**	**TVLe**	**TVL1**	**TVLe**
0.2	1.7	1.7	84	84	15	15	135	135	84	84
0.25	2.9	2.9	94	94	19	19	151	151	94	94
0.3	4.8	4.8	104	104	22	22	167	167	104	104
0.4	8.3	8.3	109	109	29	29	175	175	109	109
0.5	11.9	11.9	117	117	33	33	188	188	117	117
1	26	26	147	147	54	51	236	236	147	147
2	42	42	210	210	76	69	336	336	210	210
4	53	53	292	292	91	91	468	468	292	292
6	56	56	367	323	100	100	572	572	343	343
10	56	56	410	377	104	104	648	648	379	379
15	56	56	445	416	108	108	720	720	379	379
18	56	56	462	432	109	109	740	740	379	379
20	56	56	470	442	110	110	752	752	390	390
24	56	56	483	457	110	110	773	773	401	401

NCRP 49 **NCRP 51** **Nelson & LaRiviere** **McGinley** **Estimated from Concrete**

Primary Barrier Width

- The is typically a 0.3 meter (*1 foot*) margin on each side of primary beam shield for a 40 x 40 field size
- The Barrier is typically thicker for the primary beam barrier (*although metal can be used to decrease the thickness*)
- The Primary Shield can be placed on the inside or outside of the bunker depending on the desired room layout



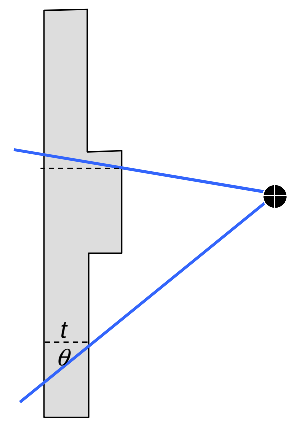
Barrier Thickness

The number of TVL's can be calculated from

$$n = \log_{10}\left(\frac{1}{B}\right)$$

Obliquity Correction

- The Slant Factor is the path from isocenter to the protected location diagonally through barrier
  - — *Incident angle (θ) is defined as the angle between the incident beam and the calculation point*
  - — *The required barrier thickness is reduced by the cos(θ)*
- In room scatter causes the slant factor to underestimate the shielding requirements
  - — *Multiplying the corrected thickness by an obliquity factor compensates for this effect*

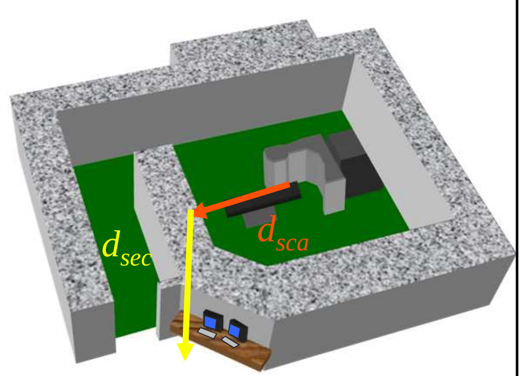


Angle	Lead			Concrete			Steel		
	4 MV	10 MV	18 MV	4 MV	10 MV	18 MV	4 MV	10 MV	18 MV
0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
30	1.03	1.02	1.03	1.02	1.00	1.00	1.02	1.02	1.04
45	1.07	1.07	1.10	1.07	1.04	1.04	1.07	1.07	1.08
60	1.21	1.21	1.22	1.20	1.14	1.08	1.20	1.17	1.20
70	1.44	1.47	1.52	1.47	1.28	1.22	1.48	1.42	1.45

Secondary Barrier (*Scatter*)

$$B = \frac{P}{\alpha WT} \cdot d_{\sec}^2 \cdot d_{sca}^2 \cdot \frac{400}{F}$$

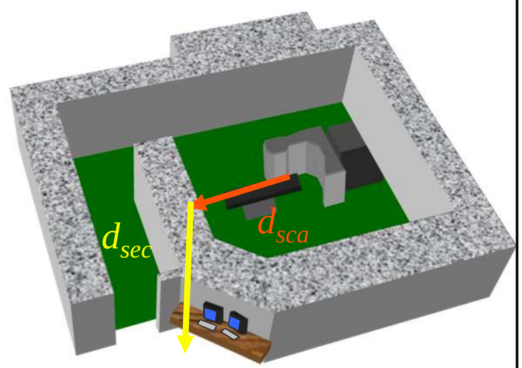
- Scatter inside and outside the treatment bunker must be calculated in order to determine the secondary shield thickness
  - — *d_{sca} is the distance from the source to the scatter*
  - — *d_{sec} is the distance from the scattering point to the calculation point*
  - — *F is field size in cm^2 at the scatter*
  - — *The use factor is always considered to by 1*
  - — *For patient scatter, d_{sca} is 1-m and F is typically 1600 cm2*



Secondary Barrier (*Scatter*)

- Scatter inside and outside the treatment bunker must be calculated in order to determine the secondary shield thickness
  - *The scatter beam is a lower energy than the primary beam (mostly Compton Scatter)*
  - *For MV beams, the maximum energy of a 90-degree Compton scatter is 500 keV*
  - *a is the ratio of the scattered dose to the incident dose*
  - *a is typically assumed to be 0.1% for 90-degree scatter*

$$B = \frac{P}{\alpha WT} \cdot d_{\sec}^{2} \cdot d_{sca}^{2} \cdot \frac{400}{F}$$



Secondary Barrier (*Scatter*)

- α vales (*shown below*) are based on simulation work by Taylor *et. al*.
- The scatter fraction increases as angle decreases
- Decreases with increasing MV at large scatter angles

Mean Scatter Energy

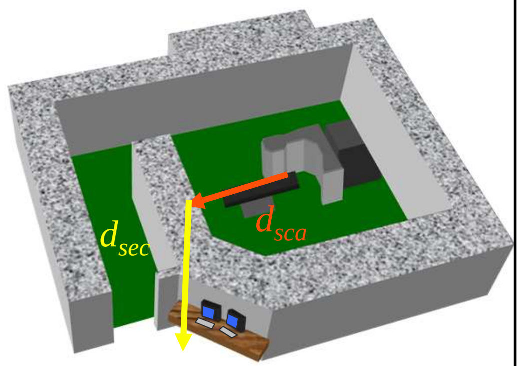
	Scatter Angle (degrees)			
MV	**0**	**20**	**45**	**90**
6	1.7	1.2	0.6	0.25
10	2.8	1.4	0.6	0.25
18	5.0	2.2	0.7	0.3
24	5.7	2.7	0.9	0.3

	Angle (degrees)							
MV	**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

Secondary Barrier (*Scatter*)

- Any given point is receiving scatter contribution from multiple directions, distances, and scatter angles
- There is no standardized scatter Tenth-Value Layer for shielding calculations
- The Tenth-Value Layer for 512 keV photons is often used for single bounce scattering
- 256 keV Tenth-Value Layers are often used for double bounce scattering interactions

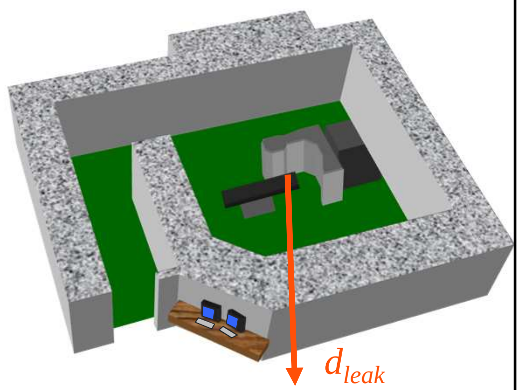
$$B = \frac{P}{\alpha WT} \cdot d_{\sec}^2 \cdot d_{sca}^2 \cdot \frac{400}{F}$$



Secondary Barrier (*Leakage*)

- Leakage dose is photons that originate in the gantry head that travel through the shielding to the calculation point without interaction
  - *The use factor is always considered to by 1*
  - *Typically assumes a 0.1% leakage fraction for the workload*
  - *Distances are measured from the linac head to the calculation point*
  - *The energy is about 2/3 of the primary, but conservatively assumed equal to the primary*

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



Secondary Barrier (*Leakage*)

Leakage Photon Tenth-Value Layers (mm)

MV	Lead TVL1	Lead TVLe	Concrete TVL1	Concrete TVLe	Steel TVL1	Steel TVLe	Earth TVL1	Earth TVLe	Borated Poly TVL1	Borated Poly TVLe
4	53	53	292	292	91	91	468	468	292	292
6	56	56	341	284	96	96	546	455	341	284
10	56	56	351	320	96	96	562	512	351	320
15	56	56	361	338	96	96	578	541	361	338
18	56	56	363	343	96	96	581	549	363	343
20	56	56	366	345	96	96	586	552	366	345
24	56	56	371	351	96	96	594	562	371	351

NCRP 49 — Nelson & LaRiviere — Kleck & Varian Average — Estimated from Concrete

Neutron Leakage

- Same form as photon leakage calculation
- Based on dose-equivalent neutron leakage fraction vs MV
  - 0.002%, 0.04%, 0.10%, 0.15% and 0.20% for 10, 15, 18, 20 and 24 MV
  - Based on Varian and Siemens neutron leakage data
    - Assumes quality factor of 10 for absorbed dose

$$S_N = \frac{W\,U\,N\,F}{\frac{t_2}{2} + t_3 + 0.305}\,10^{-t_1/TVL_P}\,10^{-t_3/TVL_N}$$

Neutron source strength for medical accelerators

Manufacturer	Model	Stated MV	Q neutrons/Gy
Siemens	KD	20	0.92×10^{12}
Varian	1800	18	1.22
Varian	1800	15	0.76
Varian	1800	10	0.06
Philips	SL-25	22	2.37
Philips	SL-20	17	0.69
GE	Saturne 43	25	2.40
GE	Saturne 43	18	1.50
GE	Saturne 41	15	0.47
GE	Saturne 41	12	0.24

Varian 2100C/D and 2300 C/D are similar to the 1800 series

Neutron Leakage

- **Photoneutrons are produced at x-ray energies above 10 MV**
- **0.002%, 0.04%, 0.10%, 0.15% and 0.20% for 10, 15, 18, 20 and 24 MV**
- **Shielded dose equivalent based on leakage neutron TVLs**
  - ***211 mm for concrete***
  - ***96 mm for borated polyethylene***

$$S_N = \frac{W\,U\,N\,F}{\frac{t_2}{2} + t_3 + 0.305}\,10^{-t_1/TVL_P}\,10^{-t_3/TVL_N}$$

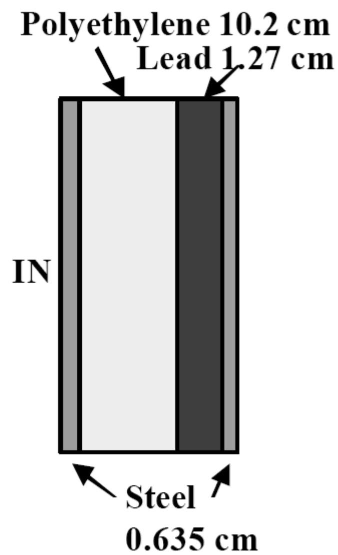
Neutron source strength for medical accelerators

Manufacturer	Model	Stated MV	Q neutrons/Gy
Siemens	KD	20	0.92×10^{12}
Varian	1800	18	1.22
Varian	1800	15	0.76
Varian	1800	10	0.06
Philips	SL-25	22	2.37
Philips	SL-20	17	0.69
GE	Saturne 43	25	2.40
GE	Saturne 43	18	1.50
GE	Saturne 41	15	0.47
GE	Saturne 41	12	0.24

Varian 2100C/D and 2300 C/D are similar to the 1800 series

Bunker Door

- **Most medical accelerators operating above 10 MV use a maze with a door shielded for neutrons and photons at the outer maze entrance.**
- **A typical door consists of a steel case 0.635 cm thick containing 10.2 cm of borated polyethylene (5% B by weight) and a 1.27 cm lead slab**
- **The polyethylene is used to moderate the fast and intermediate energy neutrons, which react with the boron ant produce a 0.473 MV photon**
- **The lead is placed after the polyethylene, where it will attenuate the photons produced in the boron and any capture gamma rays generated in the maze by neutron capture in the concrete walls, ceiling and floor**
- **Method was developed by Kersey (1979)**



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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 as far away from isocenter as possible***
- **Ducts shielded with material similar to the door at entrance**
- **Material thickness 1/2 to 1/3 that required 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***
- **NCRP 49 recommends that shielding extend at least a factor of three times the width of the HVAC penetration**

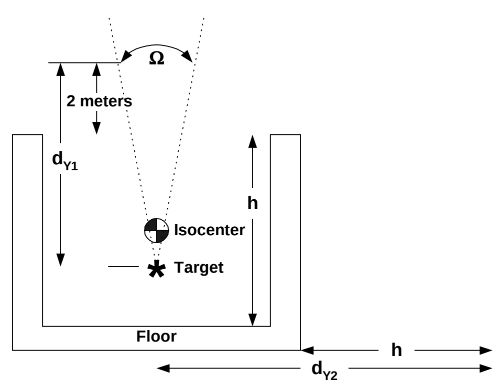
Photon Skyshine

- **Unshielded dose**

$$S_{sky} = \frac{0.0249\, W\, U\, W^{1.3}}{d_{Y1}^{2}\; d_{Y2}^{2}}$$

where

- **W (steradians) = 0.122**
  - **for 40 x 40 cm beam**
- **Multiplying by additional factor of two is recommended**
- **Primary TVLs used to calculate attenuation**



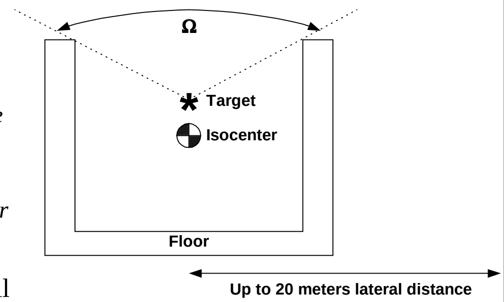
Neutron Skyshine

- Unshielded dose

$$H_{sky} = \frac{5.4 \cdot 10^{-4} H_{pri} W}{2p}$$

where

- *W = 2.71 (steradians) typical (target above isocenter)*
- *H_{pri} is neutron dose-eq in beam (0.00013, 0.002, 0.0039, 0.0043, and 0.014 times W for 10, 15, 18, 20, and 24 MV, respectively)*



- Use factor is not applied since neutrons in all orientations
- Multiplying by additional factor of two is recommended

Questions?