Radiation Vault Design and Shielding

Rajat Kudchadker, PhD

Associate Professor

Department of Radiation Physics

THE UNIVERSITY OF TEXAS

MD Anderson Cancer Center

NCRP Report No. 151

This report addresses the structural shielding design and evaluation for medical use of megavoltage x- and gamma-rays for radiotherapy and supersedes related material in NCRP Report No. 49, *Structural Shielding Design and Evaluation for Medical Use of X Rays and Gamma Rays of Energies Up to 10 MeV*, which was issued in September 1976.

The descriptive information in NCRP Report No. 49 unique to **x-ray therapy installations of less than 500 kV** and brachytherapy is not included in this Report and that information in NCRP Report No. 49 for those categories is still applicable.

Similarly **therapy simulators are not covered** in this report and the user is referred to the recent Report 147 for shielding of imaging facilities.

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New Issues since NCRP # 49

- New types of equipment with energies above 10 MV
- Many new uses for radiotherapy equipment
- Dual energy machines and new treatment techniques
- Room designs without mazes
- Varied shielding materials including composites
- More published data on empirical methods

New Modalities

<u>New modalities include:</u>

- Cyberknife Robotic arm linacs
    - No fixed isocenter
    - All barriers except ceiling are primary
    - Uses only 6 MV

- Helical Tomotherapy
    - Radiotherapy CT
    - Uses only 6 MV
    - Uses a beam stopper

- Serial Tomotherapy
    - MIMIC device attached to conventional linac
    - Uses table indexer to simulate helical treatment
    - Outdated

Special Procedures

<u>New modalities include:</u>

- Intensity Modulated Radiation Therapy (IMRT)
  - Usually at 6 MV
  - Leakage workload >>primary, scatter workload
  - Could be >50% of the workload on a linac
- Stereotactic radiosurgery
  - Use factors are different from 3D CRT
  - High dose, however long setup times
- Total Body Irradiation (TBI)
  - Source of scatter is not at the isocenter
  - Primary, leakage workload is greater than prescribed dose

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Increased data for:

- neutron production
- capture gamma rays
- scatter fractions
- scatter albedo
- activation
- laminated barrier
- IMRT 'efficiency' factors

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1) Introduction (purposes, units, basic principles)
2) Calculation Methods
3) Workload, Use Factor and Absorbed-Dose Rate Considerations
4) Structural Details
5) Special Considerations (skyshine, side-scatter, groundshine, activation, ozone, tomotherapy, robotic arms, IORT, Co-60
6) Shielding Evaluations (Surveys)
7) Examples (calculations)

Appendix A. Figures

Appendix B. Tables

Appendix C. Neutron Monitoring

NCRP 151 - Terminology

- 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 target to measurement point
- F: Area of the beam in the plane of scatterer (cm^2)
- B: Barrier transmission factor

Shielding Goals

- Aim 1: to limit radiation exposure of staff, patients, visitors and the public to acceptable levels
- Aim 2: to optimize protection of patients, staff and the public
- Different considerations are required for:
    - superficial/orthovoltage X Ray units
    - simulators, CT
    - cobalt 60 units
    - linear accelerators
    - brachytherapy

Design Process

- Designate architect, planner, coordinator
- Define design team – Participants (“Owners”… there are different levels of ownership)
- Planning questionnaire – Program objectives
- Functional space program
- Spatial relationships of functions (review space function, block diagram, floor plan, etc.)
- Specifications (Systems, equipment, shielding, vendors)
- Plan review and acceptance

Physicists are important members of the design team

Shielding - Planning and Layout

- When planning a new facility assumptions must be clearly stated, verified and documented
- Conservative assumptions should be used as under-shielding is significantly worse (and more costly) than over-shielding
- Plan for the future - consider expansions and increase in workload - The design should be adequate for the next 20 years including room for expansion
- Megavoltage treatment rooms are typically in the basement
- It is best to place bunkers together to use common walls
- Size matters - bunkers should be generous

Planning and Layout

Planning Activities

- Site visit to other facilities
- Design Team: technologists, therapists, physics, physicians, administrators
- Facility design aspects – with architects
- Equipment decision and specifications with vendors
- Equipment routes to rooms for installation - riggers
- Specific room layouts, shielding consultant/specification
- Planning for the future: potential and unknowns
- Clustering/segregation of areas
- Communication and review of all plans
- Requirements: State, local building codes, Rad Prot regs
- Timeline for planning and construction

Equipment Selection

- Actively participate in recommending beam energies
- Most patients treated with IMRT/VMAT these days
- Do we really need beam energies >10 MV?
  - 18 MV: D=10 cm %DD(10x10 cm^2) = 80%
  - 15 MV: D=10 cm %DD(10x10 cm^2) = 77%
  - 10 MV: D=10 cm %DD(10x10 cm^2) = 75%
- Neutron production
  - 18 MV: 0.15% Sv/Gy at isocenter
  - 15 MV: 0.1% Sv/Gy at isocenter
  - 10 MV: 0.004% Sv/Gy at isocenter
- Almost 40 times neutron production at 18 MV vs. 10 MV
- 3”-4” greater polyethylene in doors (700 lbs = $$$)

Keys to Successful Planning

- Well written device specifications – radiological treatment and imaging devices, their receipt, installation and acceptance testing
- Well written shielding specifications – shielding materials, thicknesses, shielded door mechanical and radiological properties, materials and components to match specifications (eg. Concrete – density 147 lb/ft^3 or 2.35 gm/cm^3)
- Ask to be consulted on any potential changes on vendors for any radiological devices or components
- As physicists, be innovative to help solve problems
- Never revise anyone else's space without permission

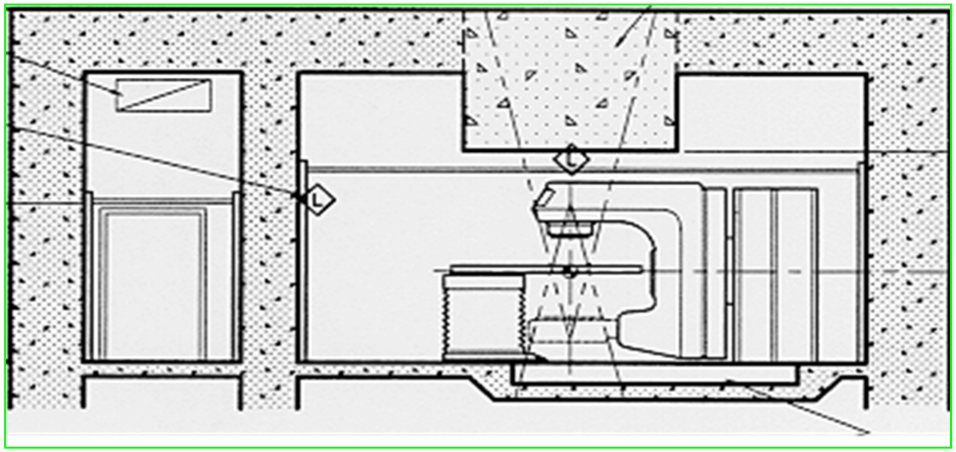
Possible Problem Areas

- Net versus Gross space – use templates
- Specification of shielded doors
  - mechanical and radiological parameters
- Wall penetrations:
  - signal cables, network, utilities,
- Design/layout of operator control areas
- Laser wall-mounting systems
- Signage, Interlocks, etc.
- Route for equipment entry (size and weight)
- Lead versus concrete shielding
- Room accommodations for the future
- Designation of utilities chases – always eat up space in the end

Shielding Design Approach

- Obtain a plan of the treatment room and surrounding areas (it is a 3D problem!!!)
  - how accurately are wall and ceiling materials and thicknesses known – when in doubt, measure
  - what critical areas close
    - imaging
    - patient waiting area

Cross sections are helpful to see adjacent areas/rooms



Information Required

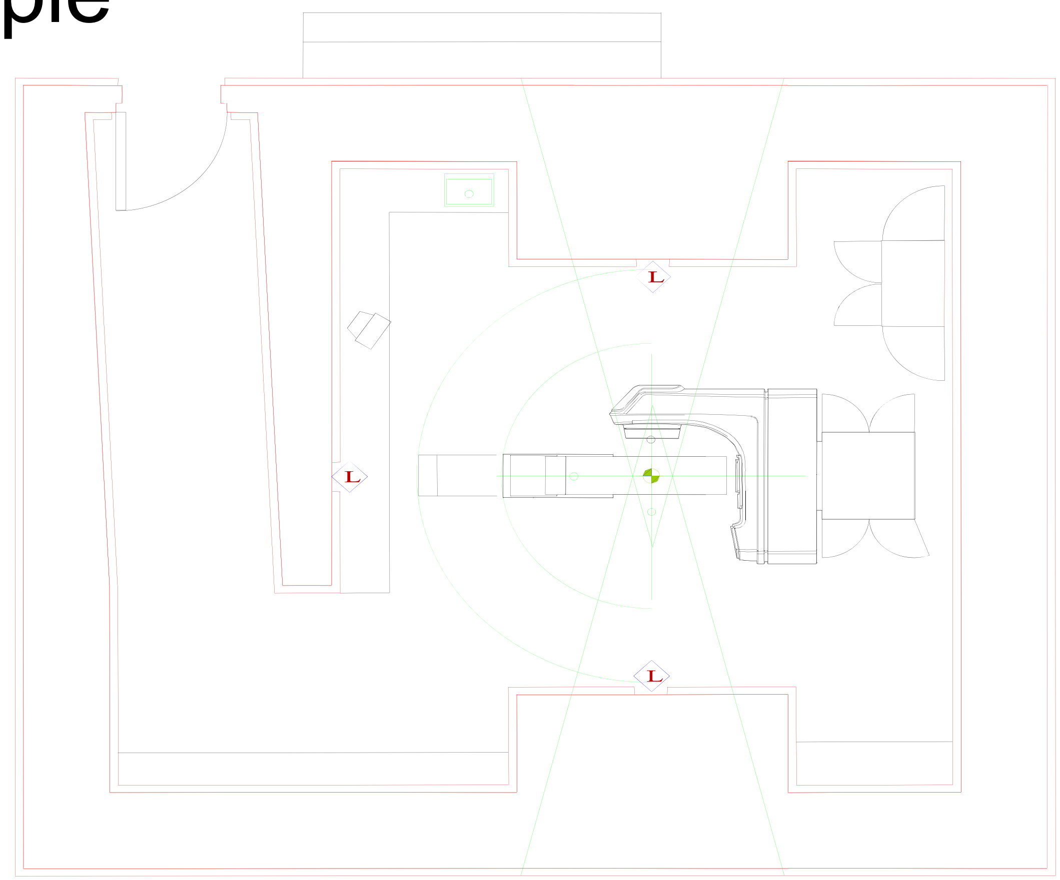
- Equipment type
- Treatment techniques
- Workload
- Target dose and dose rate
- Use factor and direction of primary beam
- Distance to the area of interest
- Occupancy of area to be shielded
- Dose limit value in area to be shielded

Linac: Facilities Considerations

- Power -high electrical power consumption, power quality critical.
- Cooling Water -specific requirements per manufacturer.
- Compressed Air -some systems require this as well.
- Air Conditioning
- Routing all of the above into the room is complicated by shielding needs
- Alignment lasers -rigid mounting critical
- Video monitoring
- Audio intercom
- Radiation monitor

Shielding Considerations

- Make sure that all room penetrations are correctly dimensioned and positioned on the plans, for example
  - doors
  - windows
  - utilities
    - electrical
    - plumbing
    - dosimetry



Room Location

- Is the room
  - controlled or uncontrolled area?
  - accessible to working staff only?
  - accessible to patients or general public?
  - adjacent to low occupancy areas (toilet, roof)?

Equipment Placement

- Minimize shielding requirements by placing it
  - near low occupancy walls
  - using distance to best advantage (inverse square law)
- Check if there is enough space around the equipment for
  - Safe operation
  - Servicing
  - Patient treatment aids
  - QA equipment
  - Imaging equipment
  - Stretcher/wheelchair

Shielding Design– Regulations

- Must be designed by a qualified radiation expert
- The role of the licensee and the regulator:
  - verify the assumptions and design criteria (*e.g.* dose limit values) are adequate
  - ensure the design has been checked by a certified expert
  - approve the design and receive notification of all modifications

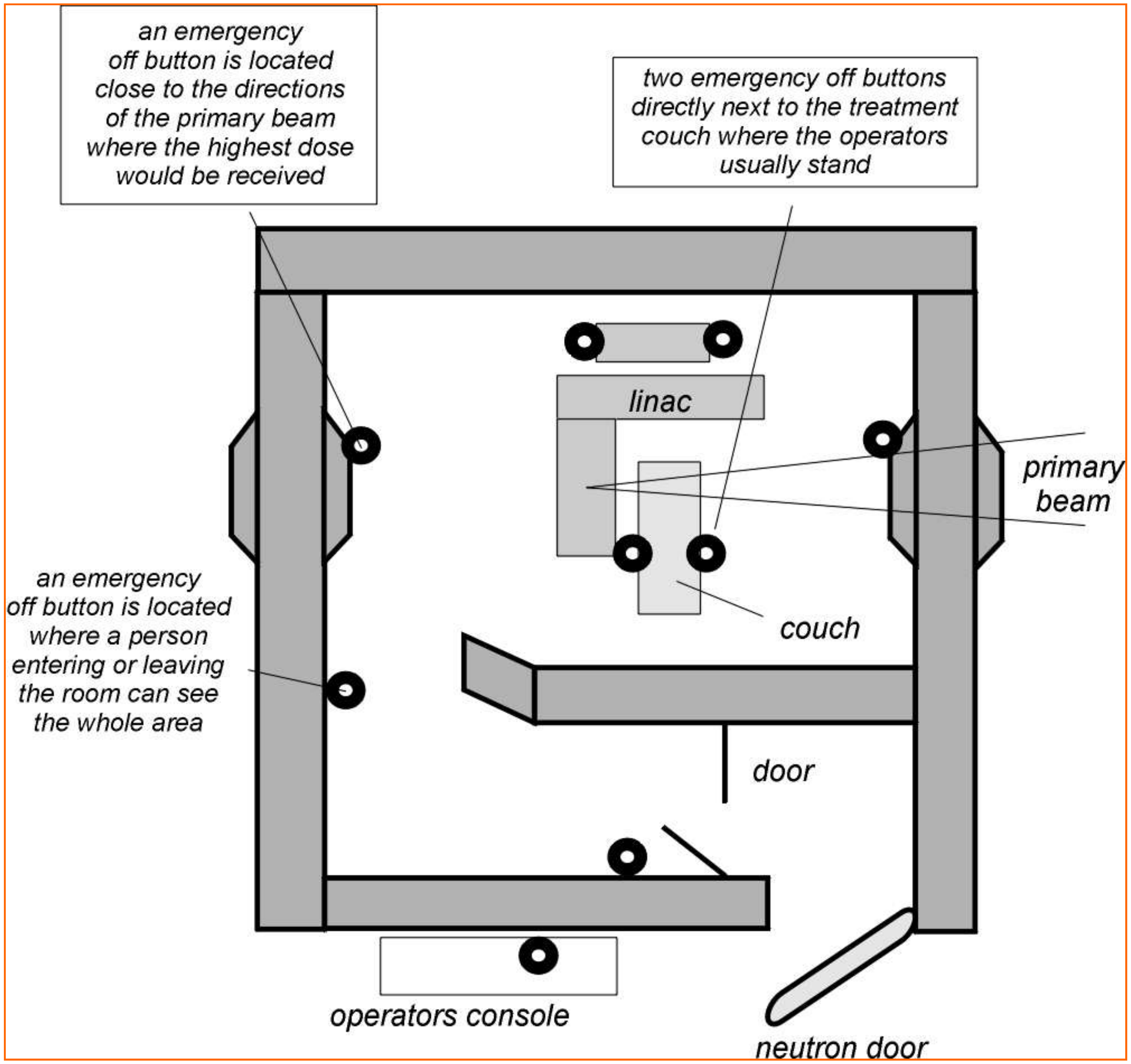
Design Criteria

- Clear signs are required in areas leading to treatment units
- Patient and visitor waiting areas and patient changing areas should be positioned so that patients are unlikely to enter treatment areas accidentally
- Positioning the control room and the equipment so that staff have a good view of
    - the treatment room
    - access corridors
    - entrance to the treatment room

Other Design Considerations

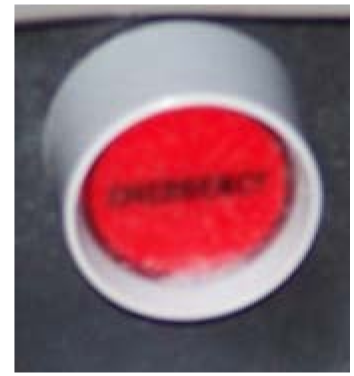
- Treatment rooms
  - Shielding/door/maze (Is a door or maze needed?)
  - Interlocks
  - Door interlock protocol
  - Emergency off buttons
  - Warning signs
  - Beam on/off indicator

Emergency off buttons: where should they go?



Linac Emergency Stop

HARD STOP



GENTLE STOP

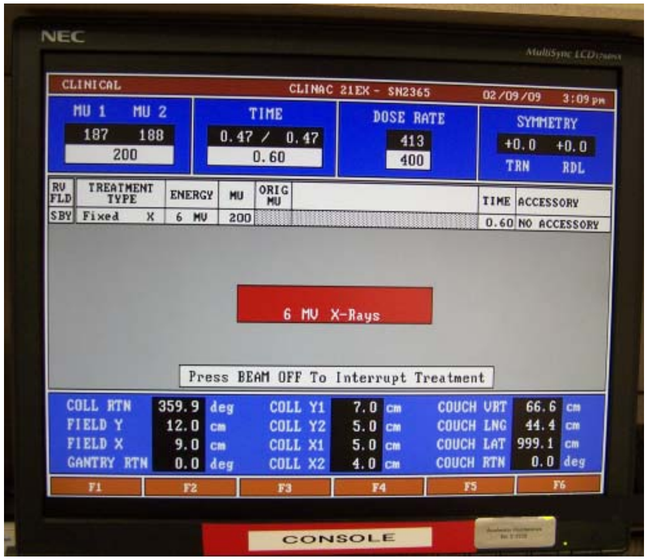
Keyboard control key

"Beam off" button

Door open

Warning Signals

- There should be a visible sign when radiation is being produced at the entrance of the maze, control area and in the treatment room
- There should be an audible sound when radiation is being produced



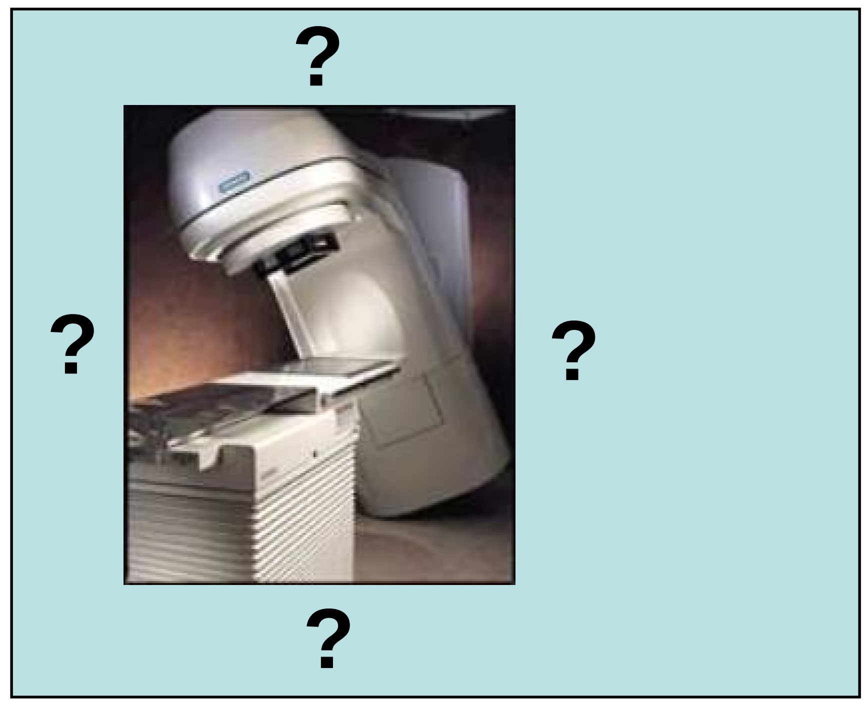
Rad Sign Posting Requirements

- Unrestricted Area
  - Less than **2 mrem in 1 hr or 100 mrem in 1 yr**
  - Typical shielding design criteria for X-ray suites, accelerator vaults, etc.
- Radioactive Materials Use or Storage Area
- Radiation Area
  - **5 mrem in 1 hr at 30 cm** from source or surface
- High Radiation Area
  - **100 mrem in 1 hr at 30 cm** from source or surface
- Very High Radiation Area
  - **500 rads in 1 hr at 1 m** from source or surface

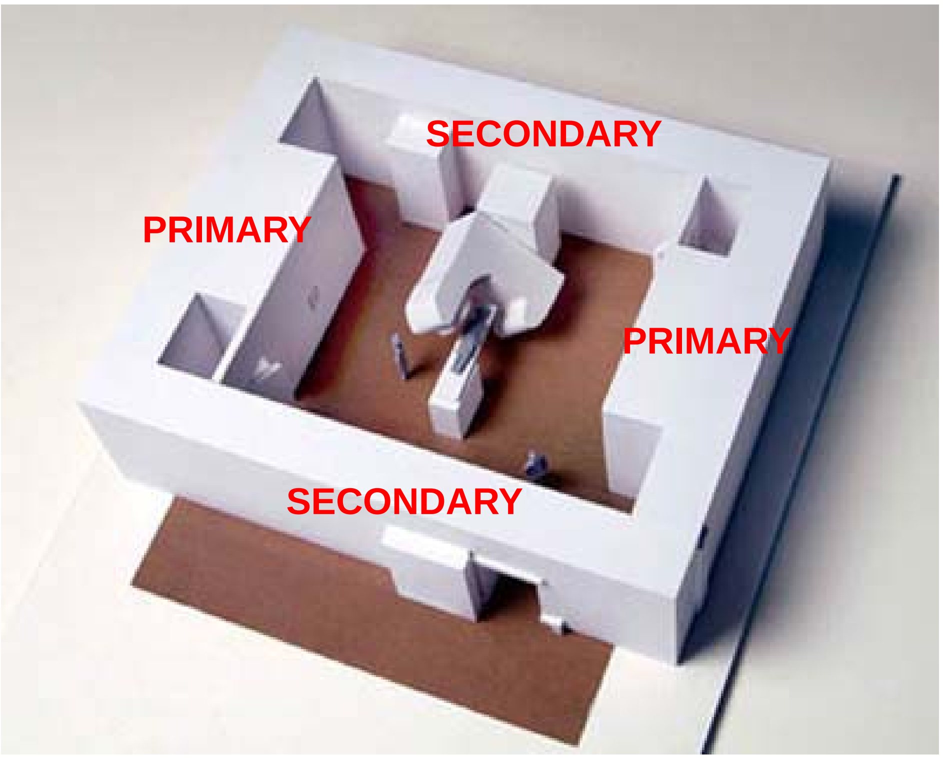
Basic Shielding Calculations

We calculate the dose rate at a certain distance from the source due to primary, scattered, and leakage radiation and from it derive how many TVL's we need to bring the radiation levels to the dose constraints (occupational or public)

- Radiation limits
- Workload
- Use factor
- Occupancy
- Distance
- Materials



Primary & Secondary Barriers



Shielding materials

The most appropriate shielding material depends on the radiation type

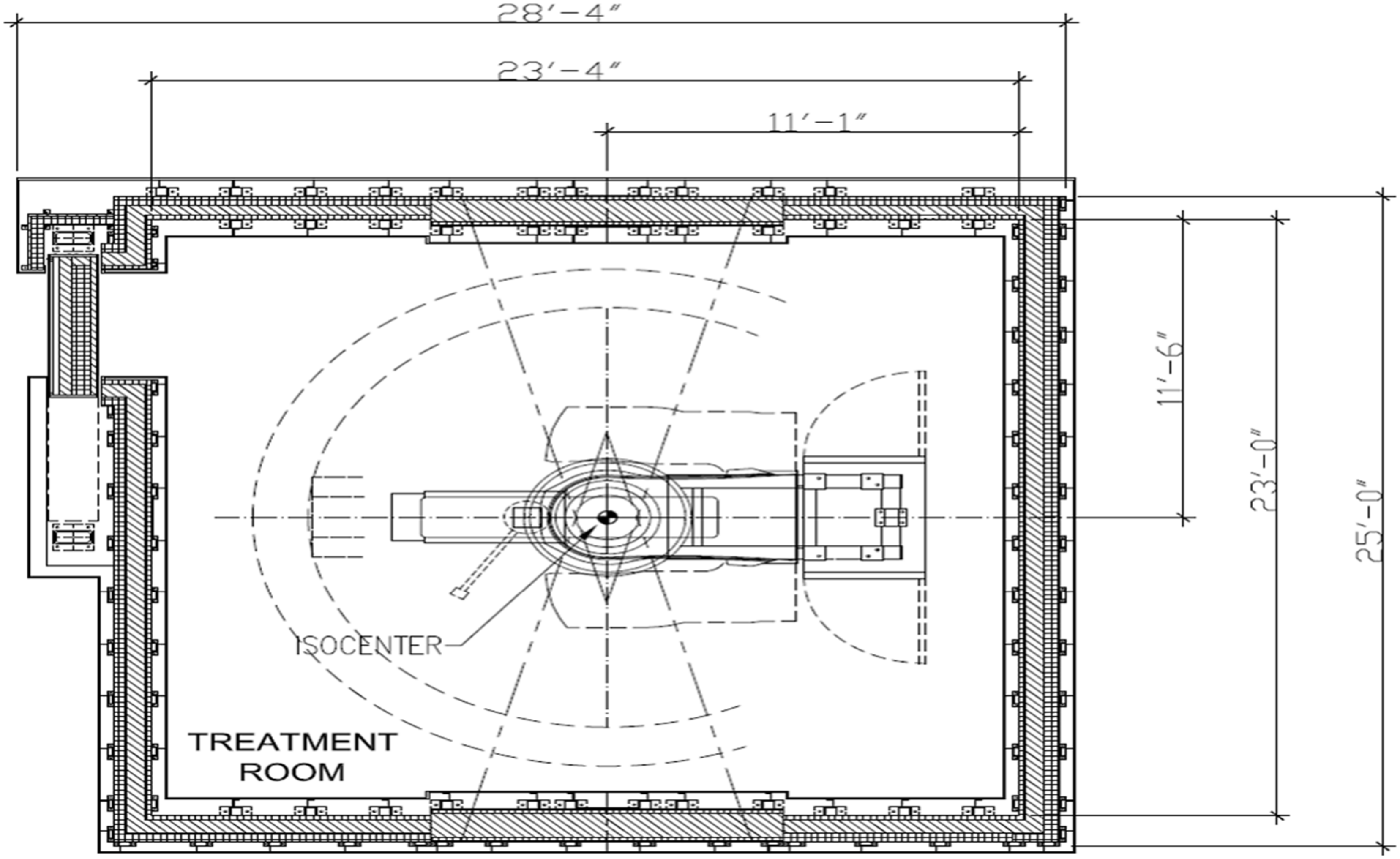
- Low energy Gamma and X Rays: lead, compare also diagnostic applications
- High energy (>500keV) Gamma and X Rays: concrete (cheaper and self supporting), high density concrete
- Electrons: Usually shielded appropriately if photons are accounted for
- Neutrons: Low Z materials

Shielding materials

Lead

- High physical density - small space requirements
- High atomic number - good shielding for low energy X Rays
- Relatively expensive
- Difficult to work with
- Needs structural support particularly in the ceiling
- Good when upgrading facilities due to space limitation

Lead



Shielding materials

Iron/Steel

- Relatively high physical density - space requirements acceptable
- Self supporting structure - easy to mount
- Relatively expensive
- More rigid than lead, but needs to be anchored to concrete
- Produces fewer photoneutrons than lead

Shielding materials

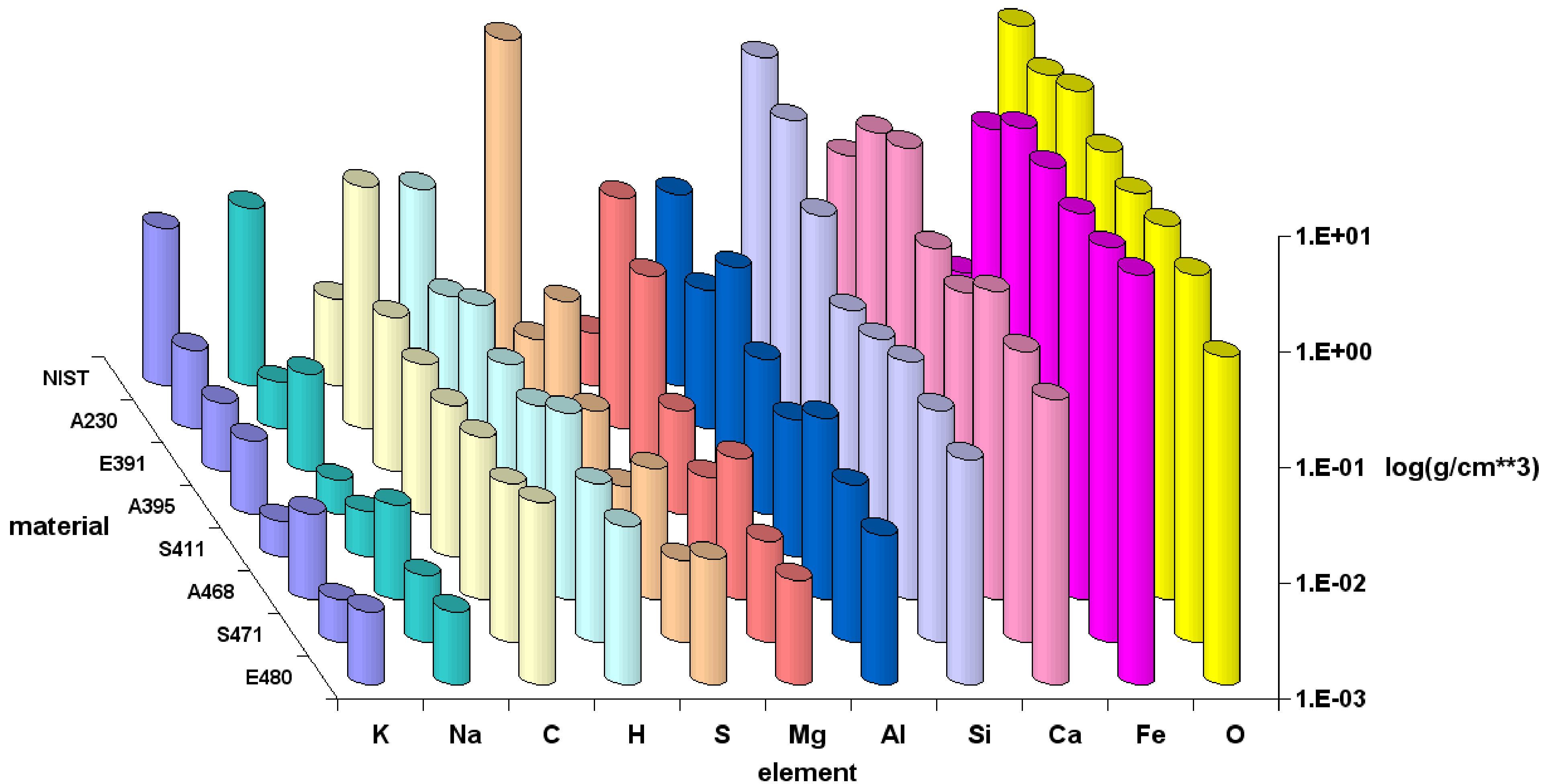
Concrete

- Concrete is made by mixing Portland Cement with small pieces of material called aggregate
- The standard aggregate is stone or gravel which creates concrete with a density of around 145-147 lb/ft^3
- High density concrete is created by simply changing the aggregate
- Generally, high-density concrete are available in prefabricated blocks. Original supplier called the material “Ledilite” but there is no lead used.
- High density aggregates are usually iron ores which create concrete with densities between 240 – 288 lb/ft^3

Shielding materials

Concrete

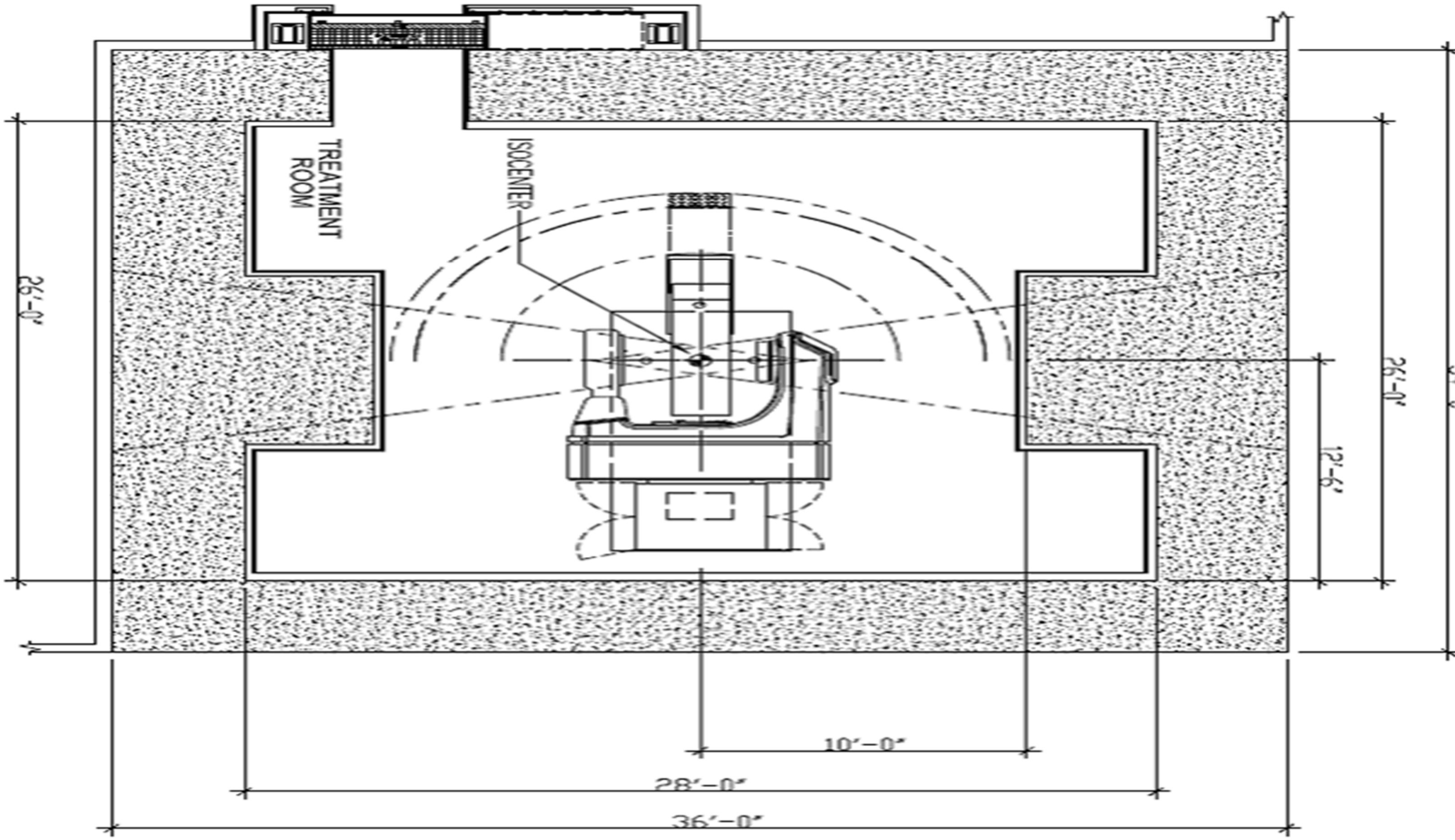
- Inexpensive (when poured at the time of construction)
- Self supporting - easy to use
- Relatively thick barriers required for megavoltage radiation
- Variations in density may occur - needs checking
- Regular density of 2.35 g/cm^3, high density up to 3.85 g/cm^3 (addition of iron barytes, ilmenite, etc.)
- High density concrete is harder to obtain and much costlier than regular density concrete
- Concrete blocks lack structural integrity



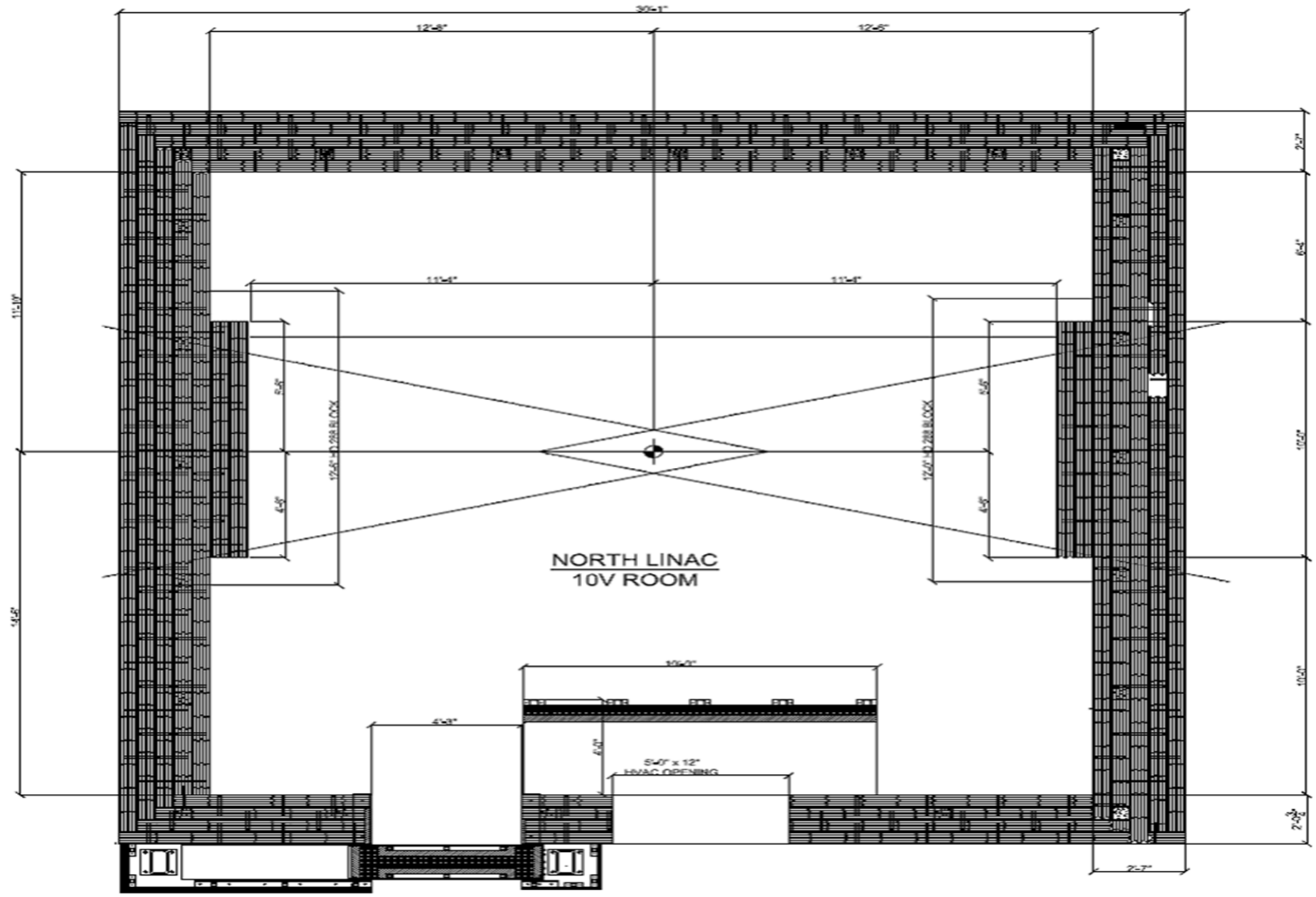
Elemental composition of 7 concrete samples ted from compared to that of NIST evaluation. Each sample is identified by a letter denoting the manufacturer, followed by its density (x 100 g/cm^3). Three manufacturers have been included: '**A**' for **Atomic International**, '**E**' for **New England Lead Burning**, '**S**' for **Nuclear Shielding Supplies and Services**.

Kase 2002

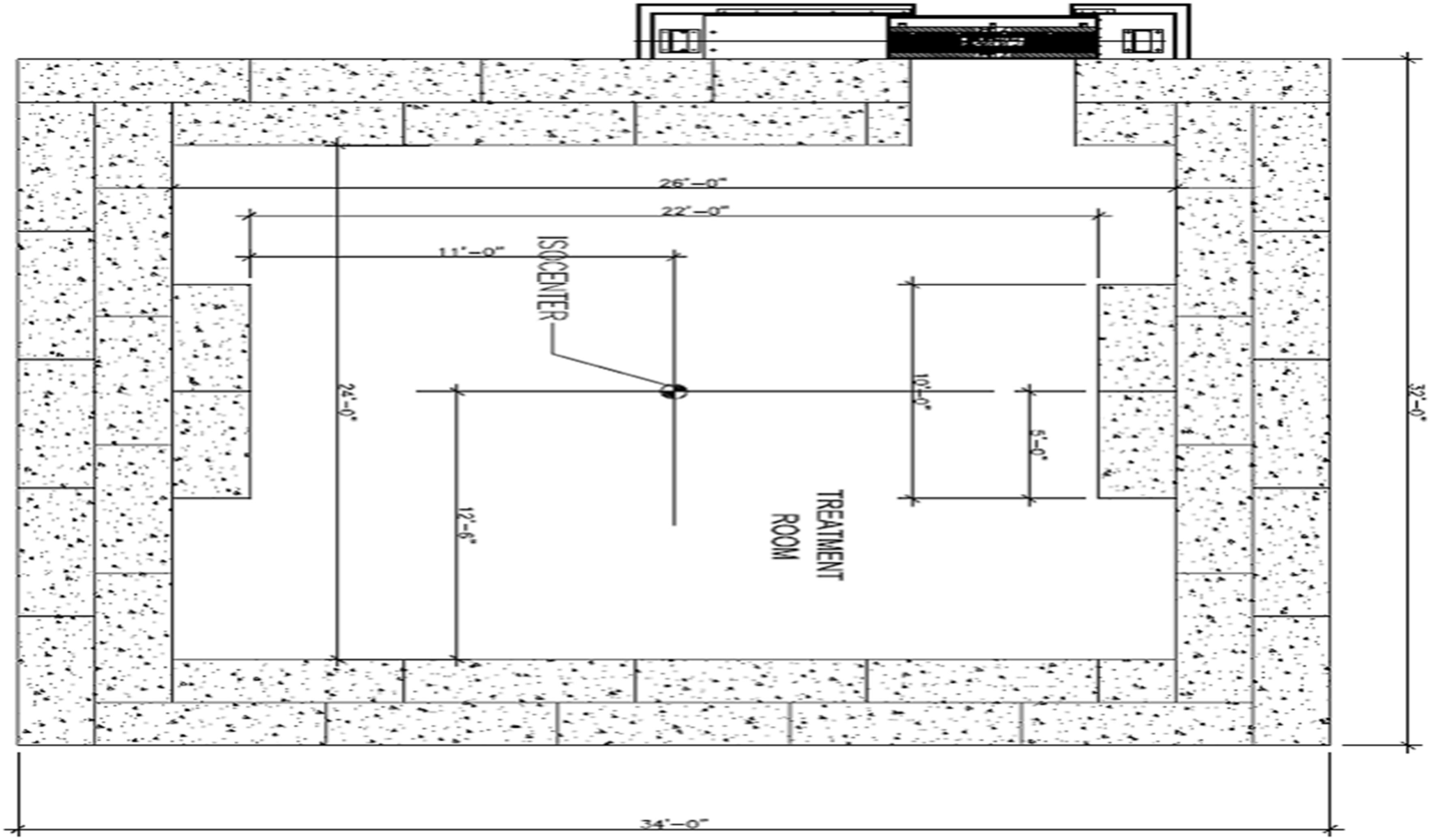
Standard Weight Concrete



High Density Concrete Block



Modular Concrete Block

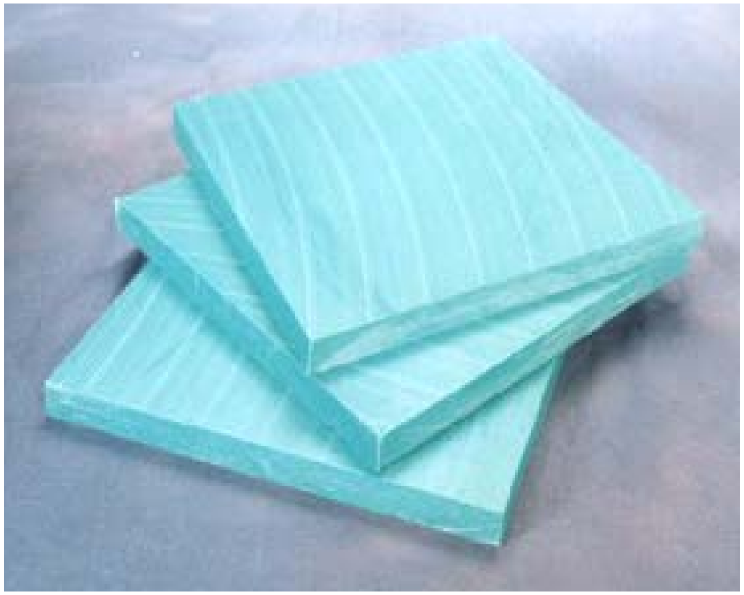


Other shielding materials

- Earth – Density of 1.5 g/cm^3, but this could be variable
- Bricks – Average density of 1.65 to 2.05 g/cm^3
- Borated (5%) polyethylene (BPE) – Shielding material used for neutrons in doors, on walls or around ducts. Used with lead or steel in high energy rooms. For doors, polyethylene can be substituted for some of the BPE to save on costs
- Composite materials, *e.g.*, metal bits embedded in concrete (*e.g.* Ledite)

Borated Polyethylene

- 5% Boric oxide and Polyethylene
- Used to shield neutrons
- Used when shielding linear accelerators in excess of 10 MV



Physical properties of shielding materials (adapted from McGinley 1998)

Material	Density (g/cm^3)	Atomic number	Relative costs
Concrete	2.3	11	1
Heavy concrete	~4	26	5.8
Steel	7.9	26	2.2
Lead	11.34	82	22
Earth, packed	1.5	variable	low

Shielding Materials Summary

- Concrete: High density concrete is expensive
- Concrete blocks: Lacks structural integrity of concrete; mortar of equivalent density should be used
- Lead: Great for photons; bad for neutrons; needs structural support; expensive
- Steel: Not as efficient as lead for photons
- Earth: Inexpensive; build vaults underground
- Polyethylene: Used to shield against neutrons in doors, ducts, etc.

Shielding Calculation Methods

Barrier calculations

Primary barriers

Secondary barriers

Maze design

Neutron shielding

Door design

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The quantity recommended in this Report **for shielding design calculations** when neutrons, as well as photons, are present is **dose equivalent (H)**. Dose equivalent is defined as the product of the quality factor for a particular type of ionizing radiation and the absorbed dose (D) [in gray (Gy)] from that type of radiation at a point in tissue (ICRU, 1993). The units of dose equivalent are J/Kg with the special name Sievert (Sv).

The recommended radiation protection quantity **for the limitation of exposure** to people from sources of radiation is **effective dose (E)**,defined as the sum of the weighted equivalent doses to specific organs or tissues (*i.e.*, each equivalent dose is weighted by the corresponding tissue weighting factor for the organ or tissue) (NCRP, 1993).

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In NCRP 151, **<u>shielding design goals (P)</u>** are levels of dose equivalent (H) used in the design calculations and evaluation of barriers constructed for the protection of workers or member of the public.

Shielding design goals (*P*) are practical values, for a single radiotherapy source or set of sources, that are evaluated at a reference point beyond a protective barrier. The shielding design goals will ensure that the respective annual values for E for controlled and uncontrolled areas are not exceeded.

The shielding design goals (*P* values) in NCRP 151 apply only to new facilities and new construction and will not require retrofitting of existing facilities.

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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.

NCRP recommendation for **<u>Controlled</u>** Areas:
Shielding design goal (*P*) (in dose equivalent):
<u>0.1 mSv/week (5 mSv/y)</u>

NCRP recommendations for **<u>Uncontrolled</u>** Areas:
Shielding design goal (*P*) (in dose equivalent):
<u>0.02 mSv/week (1 mSv/y)</u>

Shielding design goals are expressed most often as weekly values since the workload for a radiotherapy source has traditionally utilized a weekly format.

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CONSERVATIVE ASSUMPTIONS

- Attenuation of primary beam by the patient is neglected. The patient typically attenuates the primary beam by 30 % or more.
- The calculations of recommended barrier thickness often assume perpendicular incidence of the radiation.
- Leakage radiation from radiotherapy equipment is assumed to be at the maximum value recommended.
- The recommended occupancy factors for uncontrolled areas are conservatively high.
- The minimum distance to the occupied area from a shielded wall is assumed to be 0.3 m.

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CONSERVATIVE ASSUMPTIONS

- When data are hard to estimate, such as in the design of accelerator facilities that will employ special procedures, safety factors are recommended
- The "two-source rule" (i.e., the procedure when more than one source is involved) is applied whenever separate radiation components are combined to arrive at a barrier thickness. This has been shown to be a conservatively safe assumption since the tenth-value layer (*TVL*) and half-value layer (*HVL*) of the more penetrating radiation is always used (simultaneously cannot be used)

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DOCUMENTATION REQUIREMENTS

- Shielding design report including assumptions and specifications
- Construction documents showing location and amounts of shielding materials installed
- Post-construction survey reports
- Information regarding remedies if any required
- Any other re-evaluations if any required

Workload

- A measure of the radiation output
- It is specified as the projected absorbed dose delivered to the isocenter in a specified time (most often one week)
- Measured in
  - mA-minutes for X Ray units
  - Gy/week for cobalt 60 units, linear accelerators and brachytherapy
- Should consider ALL uses (*eg.* include QA measurements,etc.)
- For a busy linac this is about 100,000 cGy/week (NCRP 49) but is higher if used for IMRT
- If TBI patients are treated, this raises the workload, since each patient requires about 16x the number of MU's for the same treatment dose (patient located 4 m from isocenter)

Target dose

- The dose which is typically applied to the target in the treatment
- In external beam radiotherapy typically assumed to be around 2.5 Gy (to account for larger dose per fraction in some palliative treatments)
- Target dose may or may not allow for attenuation in the patient

Workload Linac

- Assume D = 2.5 Gy at isocenter
- 40 patients treated per day on 250 working days per year

W = 40 x 250 days/yr x 2.5 Gy/day = 25000 Gy/year

OR

W=40 x 5 days/week x 2.5 Gy/day = 500 Gy/week

- allow for other uses such as physics, IMRT QA, blood irradiation, …

Workload TBI

- Workload for TBI >> workload for conventional therapy due to 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
- Treatment time is much longer than conventional treatments

Workload TBI

Total Body Irradiation (TBI) Workload example

Number of patients: 1 per week; Dose: 12 Gy
Distance from x-ray target: 4 m

TBI workload: 1 pt/week x 12 Gy x $(4m)^2$ = 192 Gy/week

Consider, weekly conventional workload without TBI = 300 Gy/week

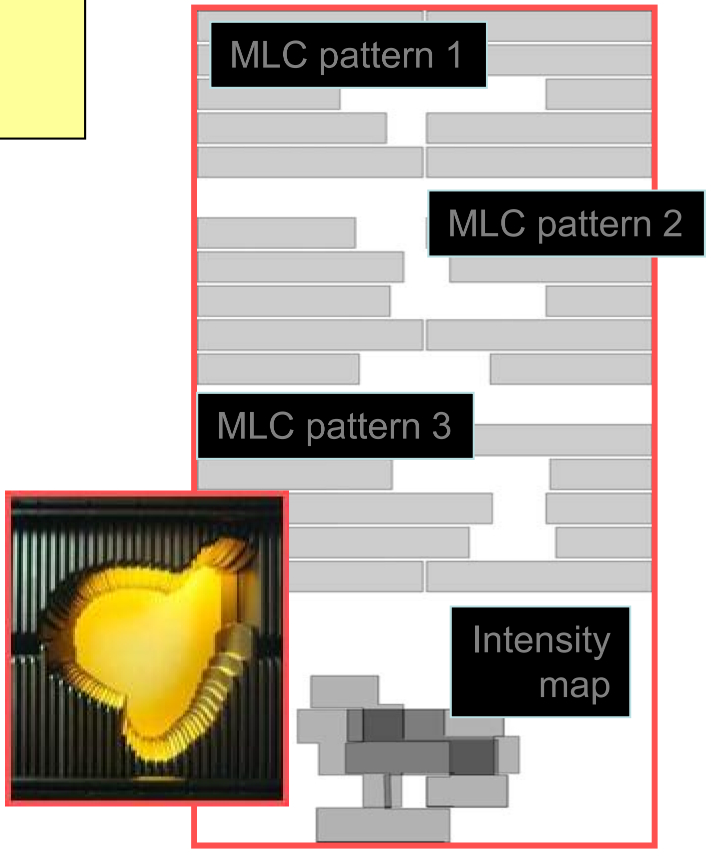
Thus the primary-radiation barrier workload at isocenter (1m) directed towards the TBI barrier is (Use Factor Table 3.1):

300 Gy/wk (0.21) + 192 Gy/wk (1.0) = 255 Gy/week

Thus dose equivalent to primary barrier behind patient increases.
Leakage radiation contribution (W_L) to all barriers also increases (Based on 192 Gy/wk + 300 Gy/wk = 492 Gy/wk).
Scatter radiation from isocenter to secondary barriers is not changed.

Workload IMRT

- In IMRT many more monitor units (2 to 10 times) are delivered per field than in conventional radiotherapy (depends on technology used).
    - ➢ The total target dose will still be the same - primary beam shielding will not be affected
    - ➢ However, the leakage radiation can be significantly increased



Example: For a 6/18 MV machine the energy use prior to IMRT was 20%/80% (MU). With 50% IMRT patient load, the use was 70%/30%

Workload and IMRT

The ratio of the average monitor unit per unit prescribed absorbed dose needed for IMRT (MU_{IMRT}) and the monitor unit per unit absorbed dose for conventional treatment (MU_{conv})

MU_{conv} can be measured at d=10 cm, FS10x10, SAD=100 cm

$$MU_{IMRT} = \Sigma_i \frac{MU_i}{(D_{pre})_i}$$

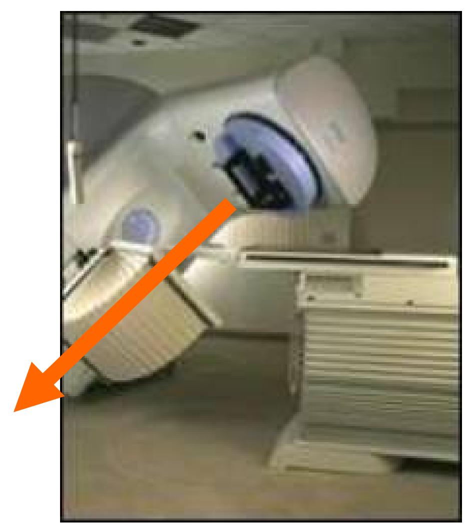
$$C_I = \frac{MU_{IMRT}}{MU_{CONV}}$$

IMRT - C_I range from 2 to 10 (Typically ~ 5); Cyberknife ~ 10

Note, $W_{IMRT} = W_{conv}$ for primary barrier and patient and wall scattered components of the secondary barrier, because same dose being delivered to patient. However, ***leakage W_L is significantly higher by the factor C_I*** *depending upon number of pts being treated with IMRT*

Use factor

- The use factor (U) is the fraction of a primary-beam workload that is directed towards a primary barrier
- Must allow for realistic use
- A significant TBI load will require one wall to have an increased use factor
- IMRT may also change values assigned to the use factor
- NCRP 49 recommends the following use factors:
  - 1 for gantry pointing down (floor)
  - 0.25 for gantry pointing up (ceiling)
  - 0.25 for lateral directions (walls)

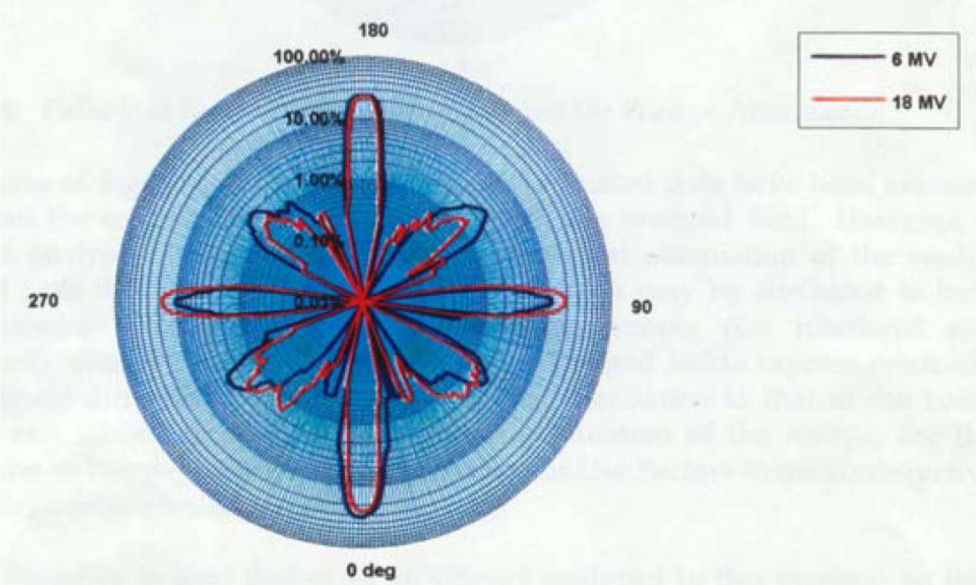


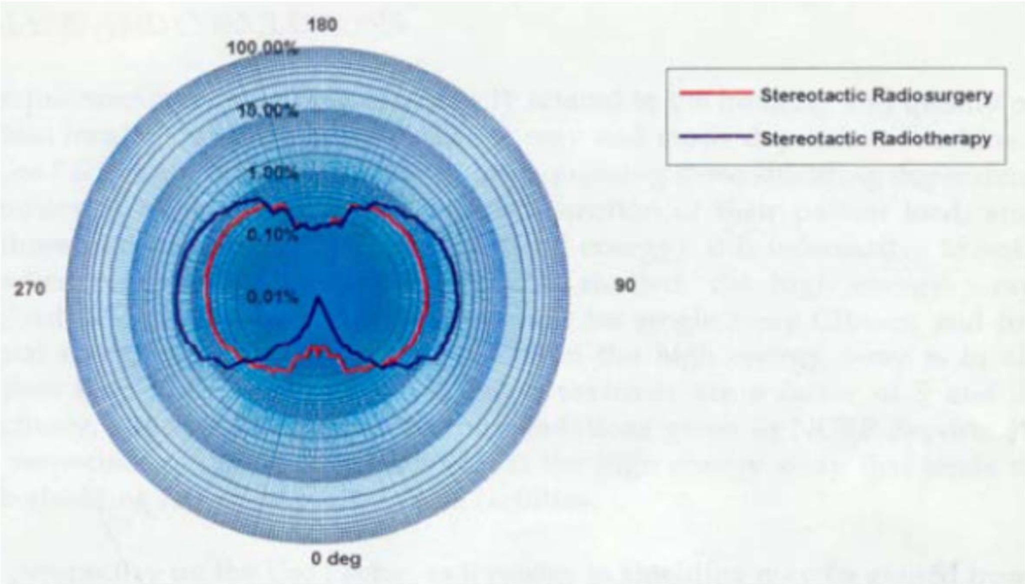
NCRP Report No. 151 – Use Factors (U)

Angle Interval Center	U(%)
90° interval	
0° (down)	31.0
90° and 270°	21.3 (each)
180° (up)	26.3
45° interval	
0° (down)	25.6
45° and 315°	5.8 (each)
90° and 270°	15.9 (each)
135° and 225°	4.0 (each)
180° (up)	23

NCRP 151 Table 3.1 - High energy (dual x-ray mode) use-factor distribution at 90 and 45 degree gantry angle intervals (omitting special procedures)

NCRP Report No. 151 – Use Factors (U)





Biggs 2009

Workload Summation

Low Energy (Gy/wk)	High Energy (Gy/wk)	Reference
1000		NCRP 49
	500	NCRP 51
< 350	< 250	Kleck & Elsalim (1994)
450	400 (dual energy machine)	Meckalakos (2004)

Due to sophistication of treatment techniques, it is often not possible to use single estimates for W and U in shielding design.

$$WU]_{pri} = WU]_{wall\ scat} = (W_{conv}\,U_{conv} + W_{TBI}\,U_{TBI} + W_{IMRT}\,U_{IMRT} + W_{QA}\,U_{QA} + \ldots)$$

$$W_L = W_{conv} + W_{TBI} + C_I\,W_{IMRT} + C_{QA}\,W_{QA} + \ldots$$

$$W_{patscat} = W_{conv} + W_{IMRT} + W_{QA} + \ldots$$

$WU]_{pri}$ & $WU]_{wall\ scat}$ = workload-use factor product for the primary and wall scattered radiation barrier

W_x = workload in gray/week at 1 m for procedure type “x”

U_x = use factor or fraction of time that the beam is likely to be incident on the barrier for procedure type “x”

Occupancy Factor, T

- The occupancy factor (T) for an area is the average fraction of time that the maximally exposed individual is present while the beam is on.
- Has to be conservative
- NCRP 49 lists the following values for T:
  - 1 for work areas, labs, shops, nurses' stations, living quarters, children's play areas
  - 1/4 for corridors, rest rooms, elevators using operators, unattended parking lots
  - 1/16 for waiting rooms, toilets, stairways, unattended elevators, outside pedestrian areas

NCRP Report No. 151 – Occupancy Factors (T)

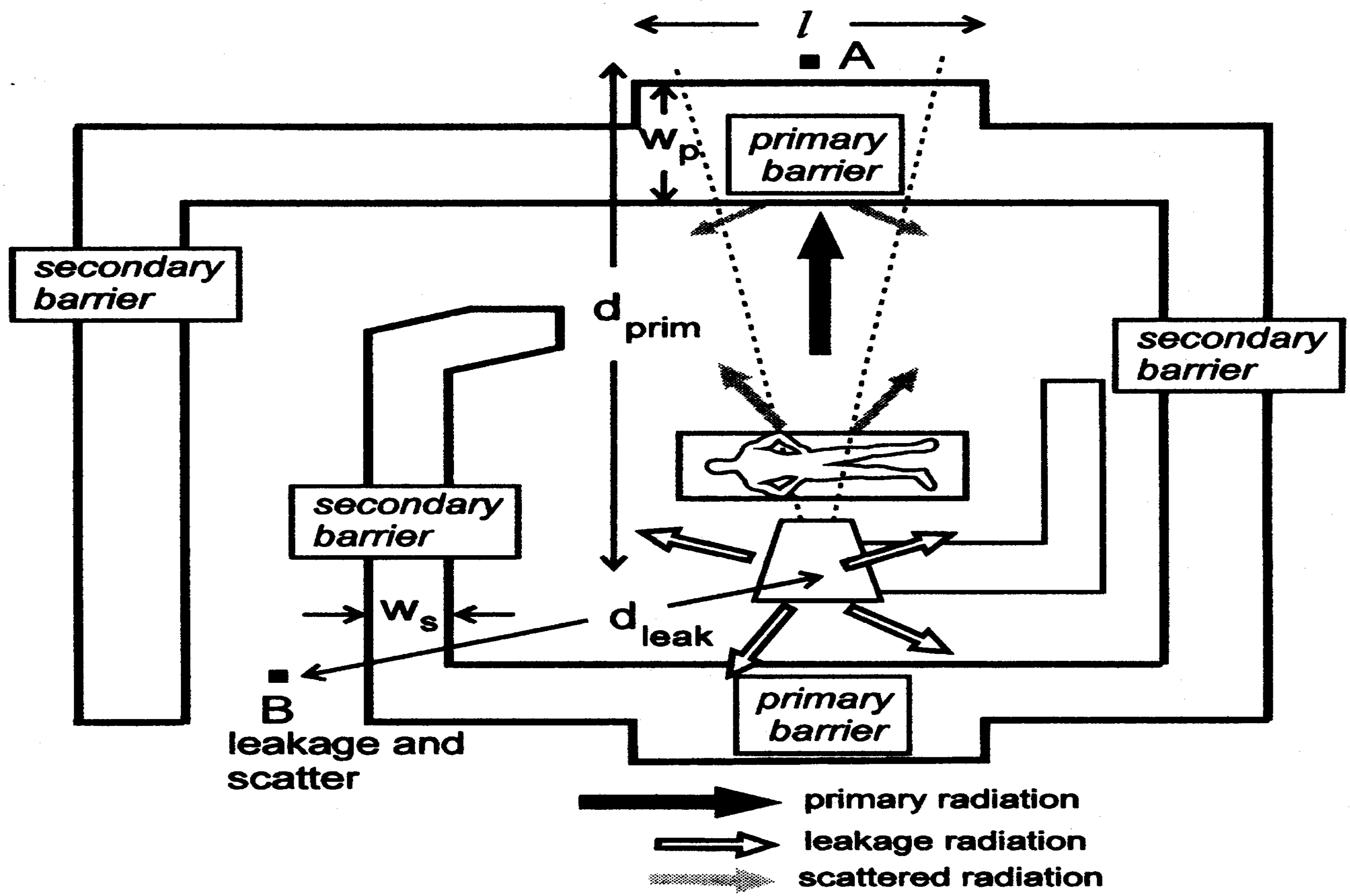
Location	Occupancy Factor (T)
Full occupancy areas (areas occupied full-time by an individual), e.g., administrative or clerical offices; treatment planning areas, treatment control rooms, nurse stations, receptionist areas, attended waiting rooms, occupied space in nearby buildings	1
Adjacent treatment room, patient examination room adjacent to shielded vault	1/2
Corridors, employee lounges, staff rest rooms	1/5
Treatment vault doors	1/8
Public toilets, unattended vending rooms, storage areas, outdoor areas with seating, unattended waiting rooms, patient holding areas, attics, janitor’s closets	1/20
Outdoor areas with only transient pedestrian or vehicular traffic, unattended parking lots, vehicular drop off areas (unattended), stairways, unattended elevators	1/40

Table B.1 – Suggested occupancy factors (for use as a guide in planning shielding when other sources of occupancy data are not available)

Sources in External Beam Radiotherapy

- Primary:
  - Primary beam
- Leakage:
  - dependent on design, typically limited to 0.1 to 0.2% of the primary beam
  - originates from target - not necessarily via the isocenter
- Scatter:
  - assumed to come from the patient
  - difficult to calculate - use largest field size for measurements
  - much different energies than leakage and hence need to compute separately

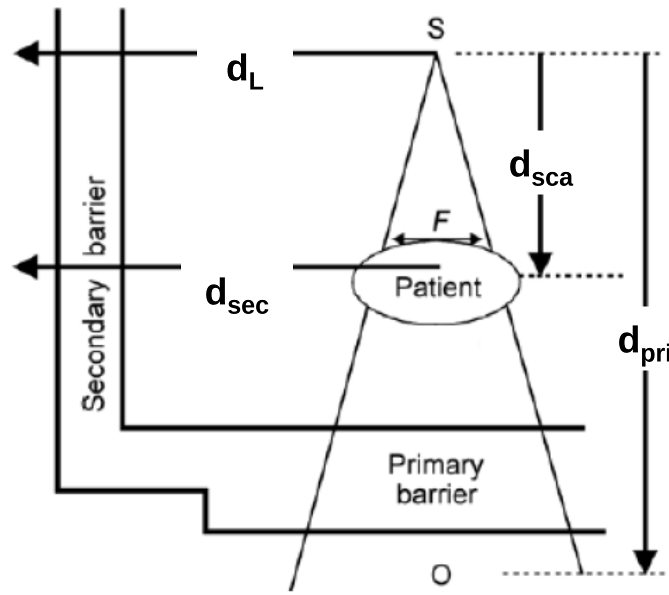
Linac Vault Design Considerations



NCRP Report No. 151 – Primary Barrier

The transmission factor of the primary barrier B_{pri} that will reduce the radiation field to an acceptable level is

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



P = shielding design goal (expressed as dose equivalent) beyond the barrier and is usually given for a weekly time frame (Sv/week)
W= workload or photon absorbed dose delivered at 1 m from the x-ray target per week (Gy/week)
U= use factor or fraction of the workload that the primary beam is directed at the barrier in question
T=occupancy factor for the protected location or fraction of the workweek that a person is present beyond the barrier
d_{pri} = distance from the x-ray target to the point protected (meters)

NCRP Report No. 151

The required number (n) of TVLs is given by:

$$n = -\log(B_{pri})$$

And the barrier thickness ($t_{barrier}$) is given by:

$$t_{barrier} = TVL_1 + (n-1)TVL_e$$

- As the radiation is attenuated the mean energy of the radiation is reduced and the second and subsequent TVL's (TVL_e) will be less than the first TVL. TVLe is the equilibrium TVL defined under broad beam conditions and is used to account for the spectral changes in the radiation as it passes through the barrier
- In NCRP 151, the TVL_e is used in an attempt to decrease the amount of concrete used.
- Hence instead of using the just the first TVL for the whole calculation, they introduce the TVL_e after the first TVL (could just use, ***n x TVL***).

NCRP Report No. 151

Endpoint Energy (MV)	Material	TVL1 (cm)	TVLe (cm)
Co-60	Concrete	21	21
	Steel	7.0	7.0
	Lead	4.0	4.0
6	Concrete	37	33
	Steel	10	10
	Lead	5.7	5.7
15	Concrete	44	41
	Steel	11	11
	Lead	5.7	5.7
18	Concrete	45	43
	Steel	11	11
	Lead	5.7	5.7

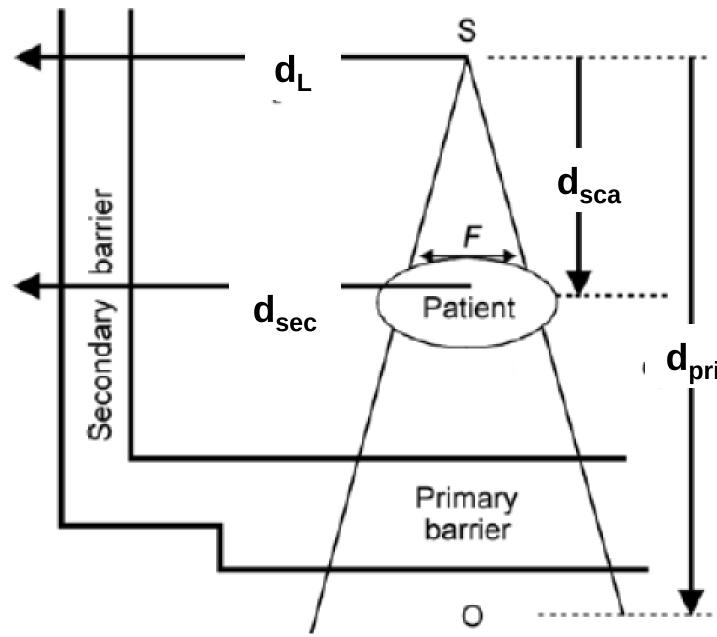
Table B.2 – Primary barrier TVLs for concrete, steel and lead

NCRP Report No. 151 – Primary Barrier

Rearranging any of the barrier transmission equations, one gets the dose equivalent beyond the barrier

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

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



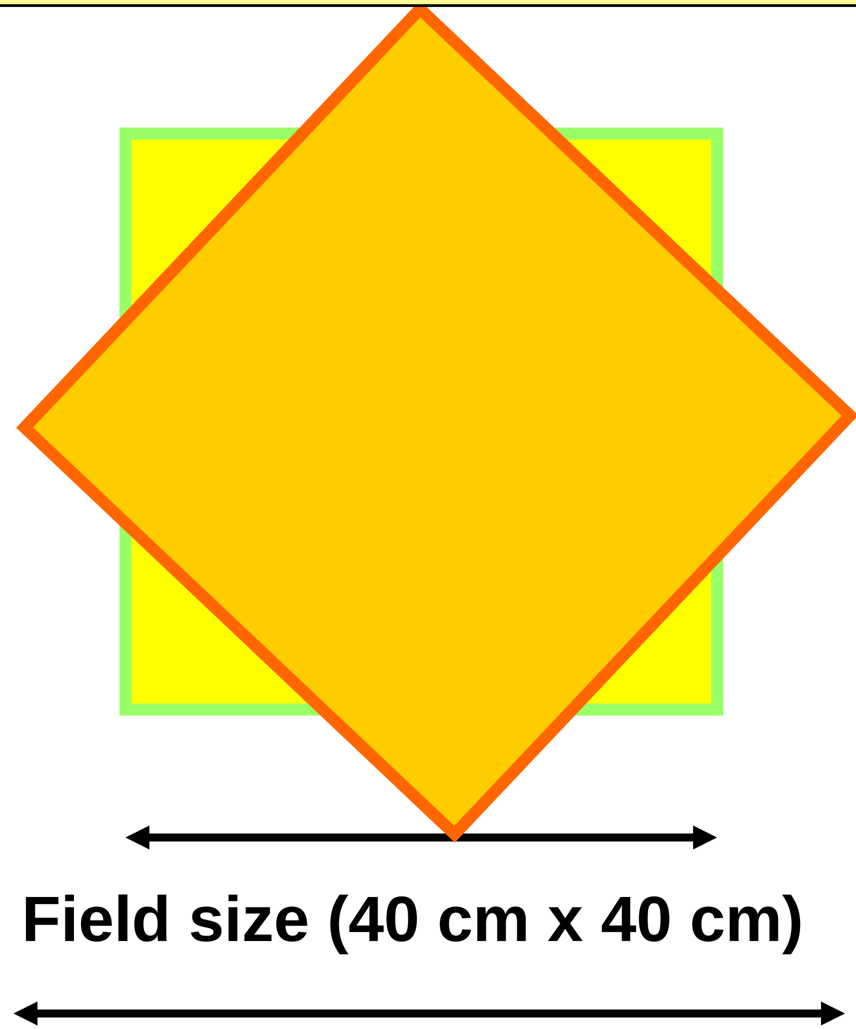
P = shielding design goal (Sv/week)
H_{pri} = Dose equivalent
W= workload (Gy/week)
U= use factor
T=occupancy factor
d_{pri} = distance from the x-ray target to the point protected (meters)

Absorbed dose $\rightarrow$ Dose equivalent (since Quality Factor = 1 for low LET radiation)

Primary Barrier Width and Length

Consideration of the maximum field size for primary beam shielding

Calculate the size of the diagonal of the largest beam and add at least 30 cm to each side



Field size (40 cm x 40 cm)

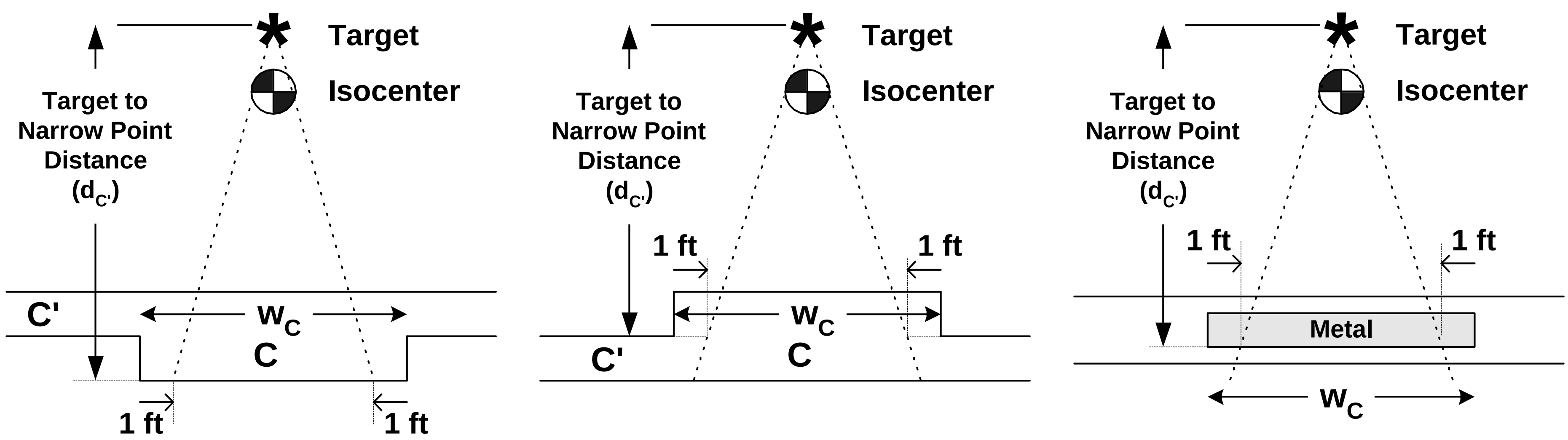
Maximum field dimension

Primary Barrier Width and Length

- 0.3 meter margin on each side of beam rotated 45 degrees
  - Barrier width required assuming 40 cm x 40 cm field size
- Field typically not perfectly square (corners are clipped)
  - 35 cm x 35 cm field size typically used to account for this

$$W_c = \left[\sqrt{(0.4)^2 + (0.4)^2}\, d_{c'}\right] meters + 0.305\, meters + 0.305\, meters$$

$$W_c = \left(0.566\, d_{c'} + 0.61\right) meters$$



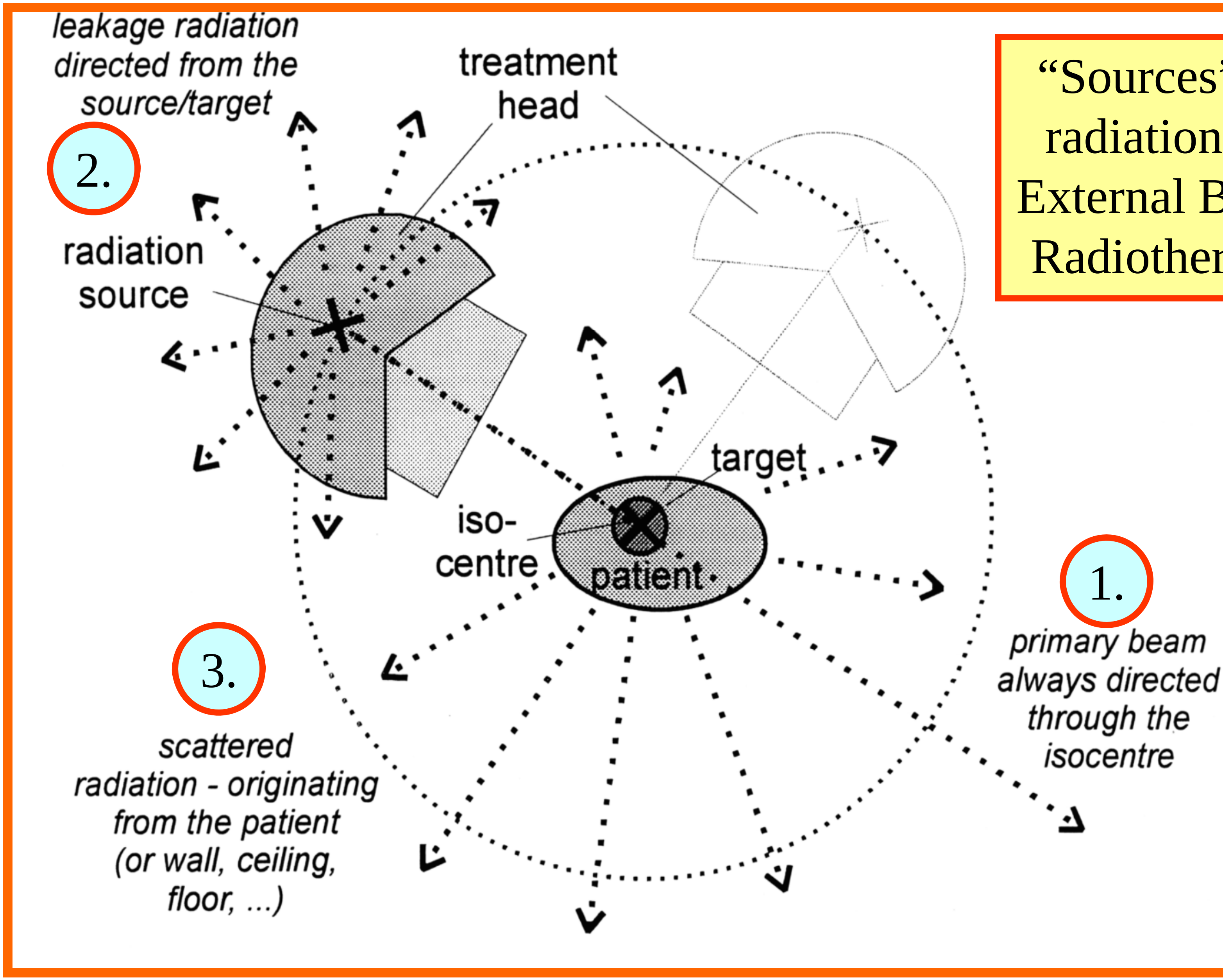
Secondary barriers

Secondary barriers need to be designed to adequately protect individuals beyond the accelerator room from:

- Leakage radiation
- Scattered radiation from the patient
- Scattered radiation from the walls
- Secondary radiation including photoneutrons and neutron capture gamma rays produced in the accelerator head or in scattering throughout the room

Since leakage and scattered radiation are of such different energies, the secondary-barrier requirements of each are typically computed separately and compared in order to arrive at the final recommended thickness

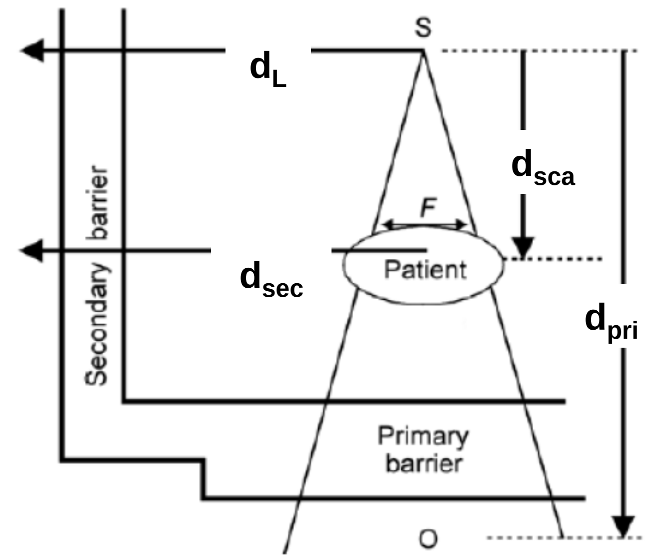
“Sources” of radiation in External Beam Radiotherapy



Patient scatter

The barrier transmission needed for radiation scattered by the patient B_{ps} is

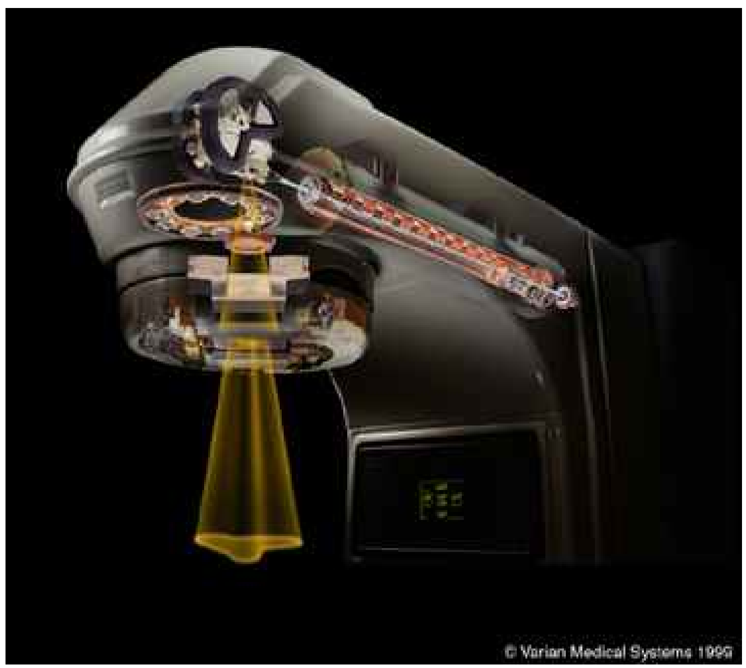
$$B_{ps} = \frac{P}{aWT} d_{sca}^2 \, d_{sec}^2 \, \frac{400}{F}$$



P = shielding design goal (expressed as dose equivalent) beyond the barrier and is usually given for a weekly time frame (Sv/week)
W = workload or photon absorbed dose delivered at 1 m from the x-ray target per week (Gy/week)
T = occupancy factor for the protected location or fraction of the workweek that a person is present beyond the barrier
F = field area at mid-depth of the patient at 1 m (cm^2)
d_{sca} = distance from the x-ray target to the patient or scattering surface (meters)
d_{sec} = distance from the scattering object to the point protected (meters)
a = scatter fraction or fraction of the primary-beam absorbed dose that scatters from the patient at a particular angle
Factor 400 assumes that the scatter fractions are normalized to those measured for a 20cm x 20cm field

Linac head leakage

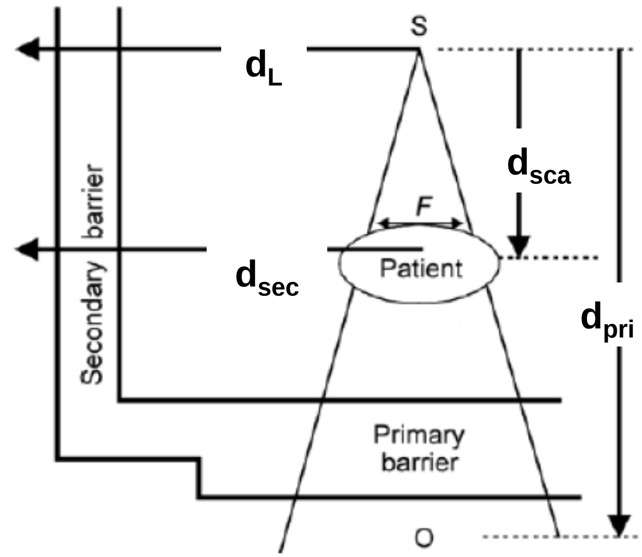
- At any point around the head 1 meter from the target the dose rate should not exceed 0.1% of the dose rate of the useful beam (at isocenter)
- This makes the heads of linacs very heavy due to the lead or depleted uranium shielding required



Leakage

The barrier transmission of leakage radiation alone B_L is

$$B_L = \frac{P\, d_L^2}{10^{-3}\, W\, T}$$



P = shielding design goal (expressed as dose equivalent) beyond the barrier and is usually given for a weekly time frame (Sv/week)

W= workload or photon absorbed dose delivered at 1 m from the x-ray target per week (Gy/week)

T=occupancy factor for the protected location or fraction of the workweek that a person is present beyond the barrier

d_L = distance from the x-ray target to the point protected (meters)

10^{-3} arises from the assumption that leakage radiation from the head is 0.1% of the useful beam

Two Source Rule

If the thickness of the required barrier is about the same for each secondary component, 1 HVL is added to the larger of the two barrier thickness. If the two thicknesses differ by a TVL or more, the larger barrier is used.

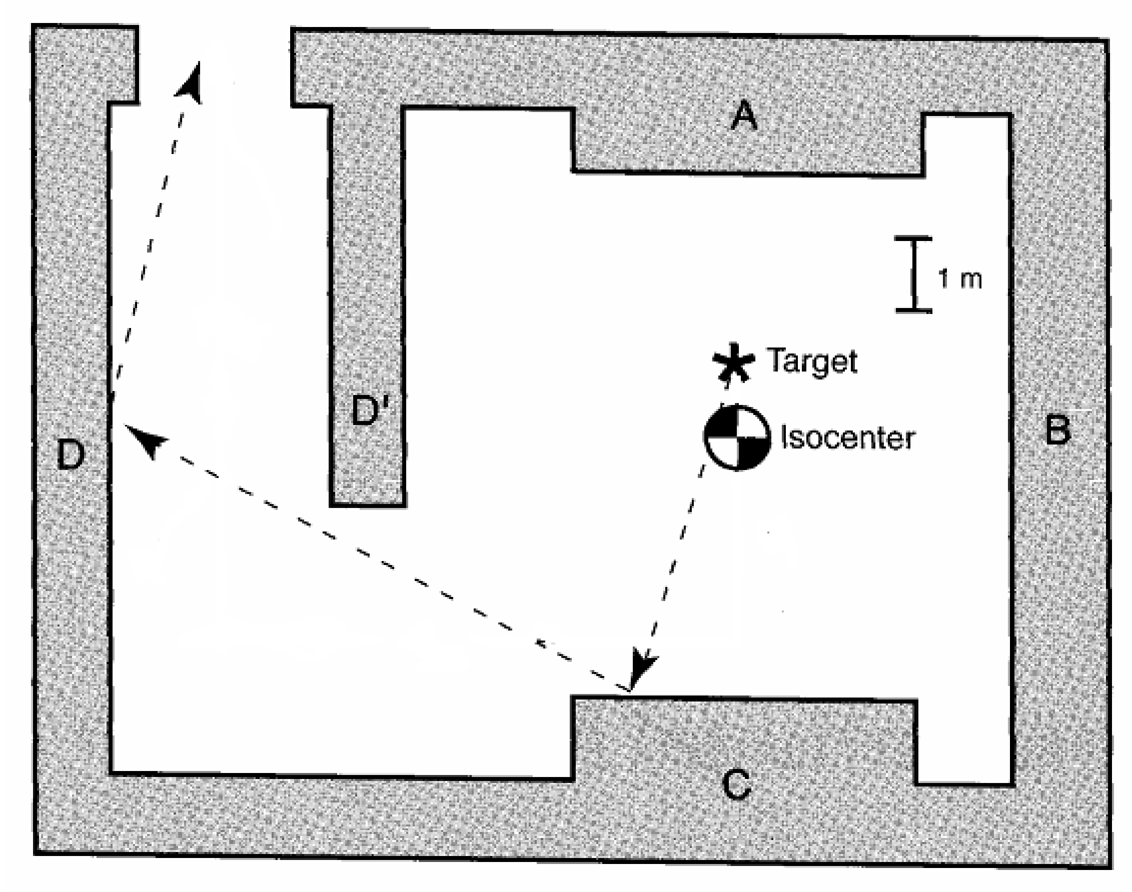
In most high-energy accelerator facilities, a secondary barrier that is adequately designed for the leakage radiation component will be more than adequate for the scattered radiation with the possible exception of zones adjacent to the primary barrier intercepted by small angle scatter.

X-Ray Shielding Calculations Secondary Barriers Review

- Similar calculations as for primary barrier
- U is always 1
- Energy of scattered radiation is much lower than for primary and leakage radiation (almost always < 0.5 MeV) which reduces the thickness of the barriers considerably

Mazes and Doors

The maze wall (usually made of concrete) prevents once-scattered and leakage radiation from reaching the door



Mazes and Doors

Factors of importance:

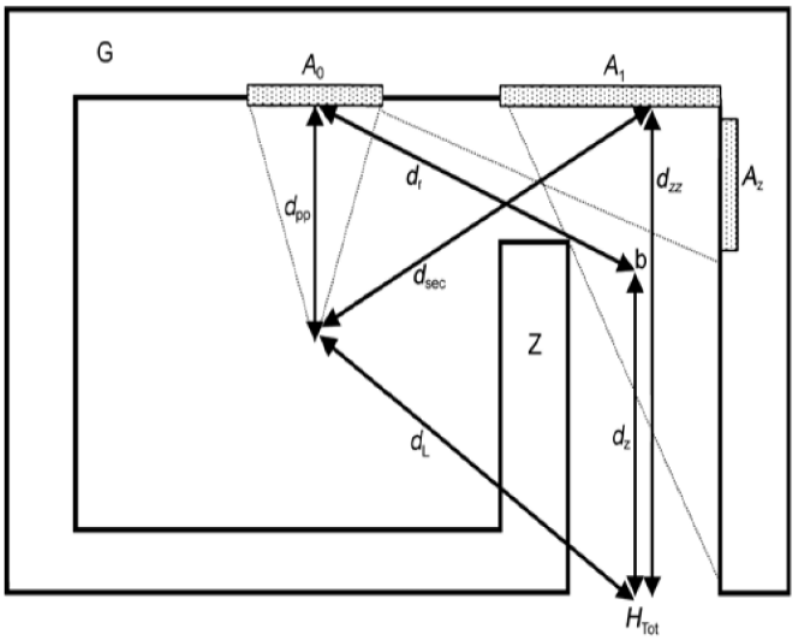
- thickness of the maze wall
- length of the maze
- width of the maze
- scatter distances
- beam energy
- maximum size and weight of the door

Main sources of radiation reaching maze door

- Scatter Mechanisms
  - Wall scatter (H_S)
  - Leakage scatter (H_{LS})
  - Patient scatter (H_{ps})
- Direct leakage
  - Conventional secondary barrier calculation (H_{LT})
- High energy accelerator mechanisms
  - Neutrons
  - Capture Gamma

Total Dose Equivalent at Maze Door

Total weekly dose equivalent at the maze door entrance (Eq. 2.22):



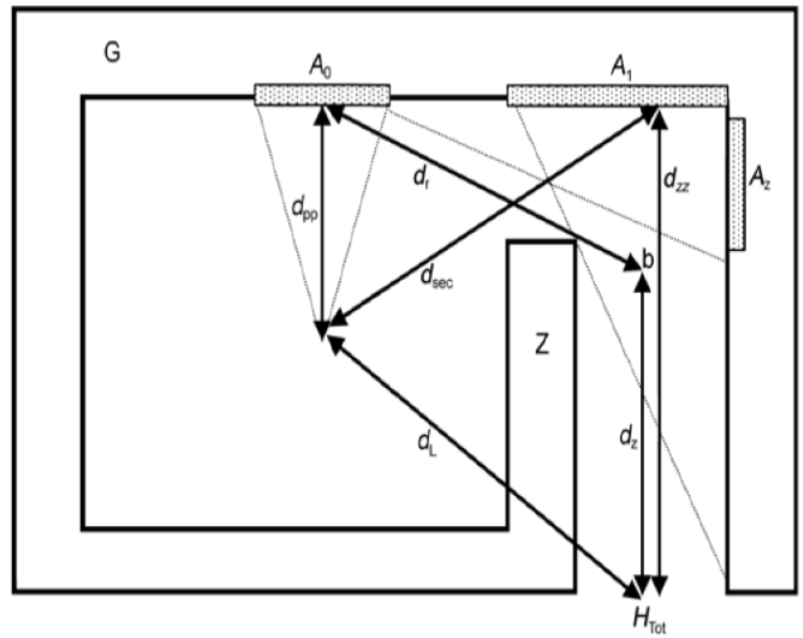
$$H_w = H_{Tot} + H_{cg} + H_n$$

$$H_{Tot} = 2.64\, H_G$$

$$H_G = f\, H_S + H_{LS} + H_{ps} + H_{LT}$$

Wall Scatter

$$H_S = \frac{W U_G \alpha_0 A_0 \alpha_z A_z}{(d_h d_r d_z)^2}$$



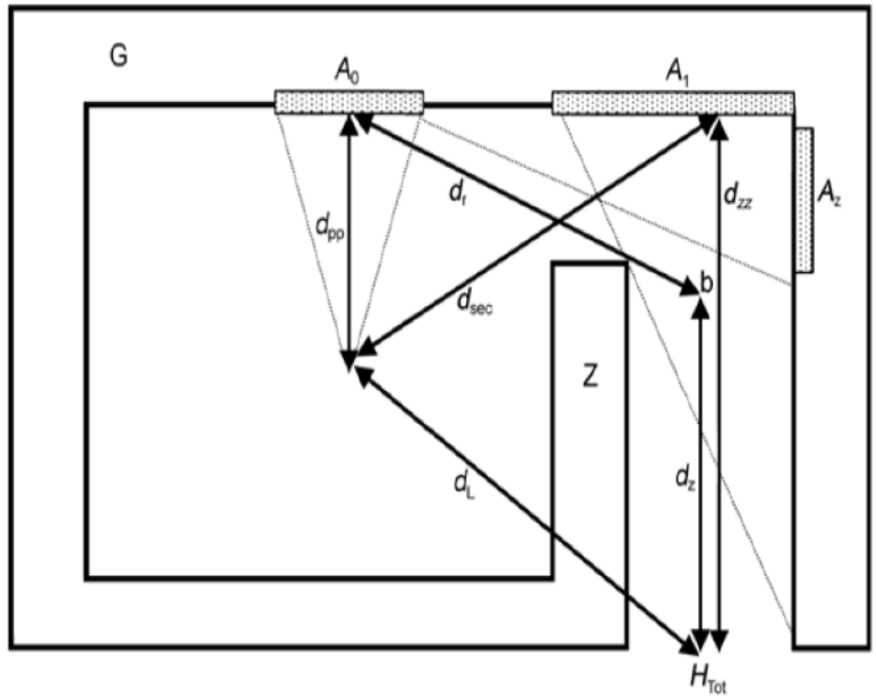
H_s = dose equivalent per week due to scatter of the primary beam from room surface ("G")
W = workload (Gy/week)
U_G = use factor for the wall G
α_0 = reflection coefficient at the first scattering surface A_0 (Tables B.8a – B.8f)
A_0 = beam area at the first scattering surface (m^2)
α_Z = reflection coefficient at the second reflection from the maze surface A_z (E ~ 0.5 MeV)
d_h = perpendicular distance from the target to the first reflection surface (equal to d_{pp} + 1 m)
d_r = distance from beam center at the first reflection to Point "b" on the midline of maze (meter)
d_z = centerline distance along maze from Point "b" to the maze door (meter)

Beam Area at Wall

- Beam area at wall (A_0) depends on distance from target
  - A_0=F $(d_H/1m)^2$ meters^2
  - F= Maximum field size at isocenter (1 m from target)
  - d_H = Distance from target to wall (meters)
- Traditional field size assumption
  - F = 0.40 m x 0.40 m = 0.16 m^2 (Conservative, worst case)
  - NCRP 151 recommends traditional field size
- Alternative field size assumption with IMRT
  - Maximum field size typically 0.15 m x 0.15 m = 0.0225 m^2
  - Maximum field size without IMRT = 0.16 m^2
  - F = (1 - %IMRT) X 0.16 + %IMRT x 0.0225

Leakage Scatter

$$H_{LS} = \frac{L_f\, W_L\, U_G\, \alpha_1\, A_1}{(d_{sec}\, d_{zz})^2}$$



H_{LS} = dose equivalent per week due to head leakage photons scattered by the room surfaces

L_f = head leakage radiation ratio at 1 m from the target (taken as 0.1%)

W_L = Workload for leakage radiation (Gy/wk)

α_1 = reflection coefficient for scatter of leakage radiation from Wall G (Table:B.8b)

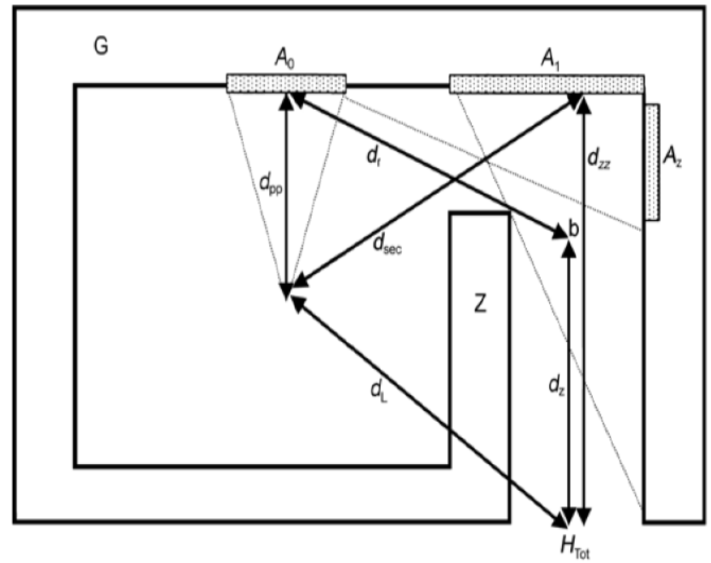
A_1 = area of wall G that can be seen from the door (m^2)

d_{sec} = distance from the target to the maze centerline at Wall G (meters)

d_{zz} = centerline distance along the maze (meters)

Patient Scatter

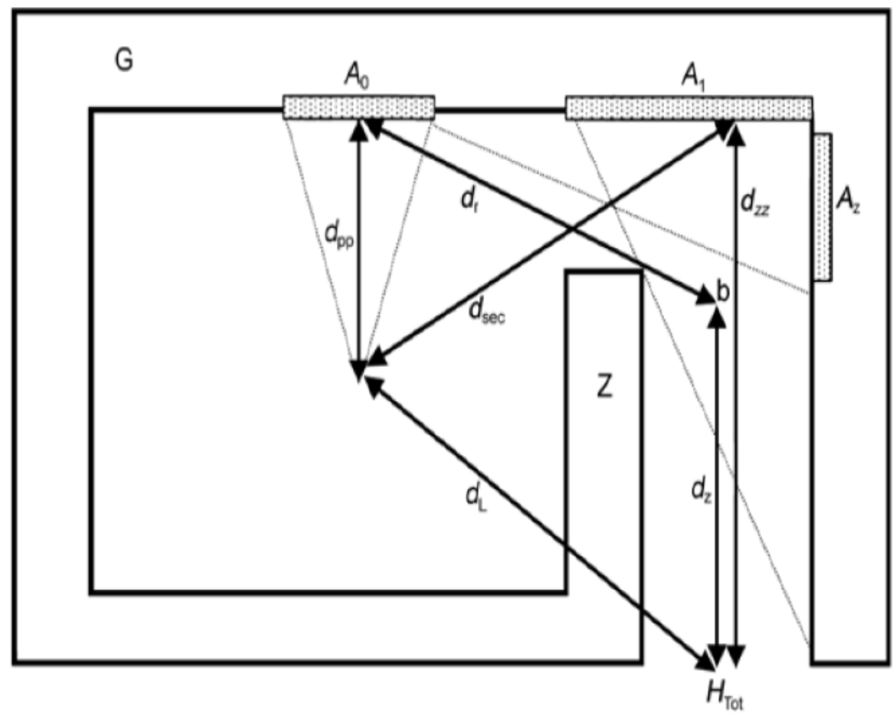
$$H_{ps} = \frac{a(\theta)\, W\, U_G\, (\frac{F}{400})\, \alpha_1\, A_1}{(d_{sca}\, d_{sec}\, d_{zz})^2}$$



H_{ps} = dose equivalent per week due to primary beam scattered from the patient
$a(\theta)$ = scatter fraction for patient scattered radiation at angle θ (Table B.4)
W = workload (Gy/week)
U_G = use factor for the wall G
F = field area at mid-depth of the patient at 1 m (cm^2)
d_{sca} = distance from the target to the patient (meters)
d_{sec} = distance from the target to the maze centerline at Wall G (meters)
d_{zz} = centerline distance along the maze (meters)
α_1 = reflection coefficient for scatter of leakage radiation from Wall G (E~0.5 MeV)
A_1 = area of wall G that can be seen from the door (m^2)

Direct Leakage

$$H_{LT} = \frac{L_f W_L U_G B}{d_L^{\,2}}$$



H_{LT} = dose equivalent per week due to leakage radiation which is transmitted through the inner maze wall

L_f = head leakage radiation ratio, which is taken conservatively as 10^{-3} of the useful beam

W_L = Workload for leakage radiation (Gy/wk)

U_G = use factor for the gantry orientation G

B = transmission factor for wall Z along the oblique path traced by d_L

d_L = distance from target to center of maze door through the inner maze wall (meters)

Maze Calculation

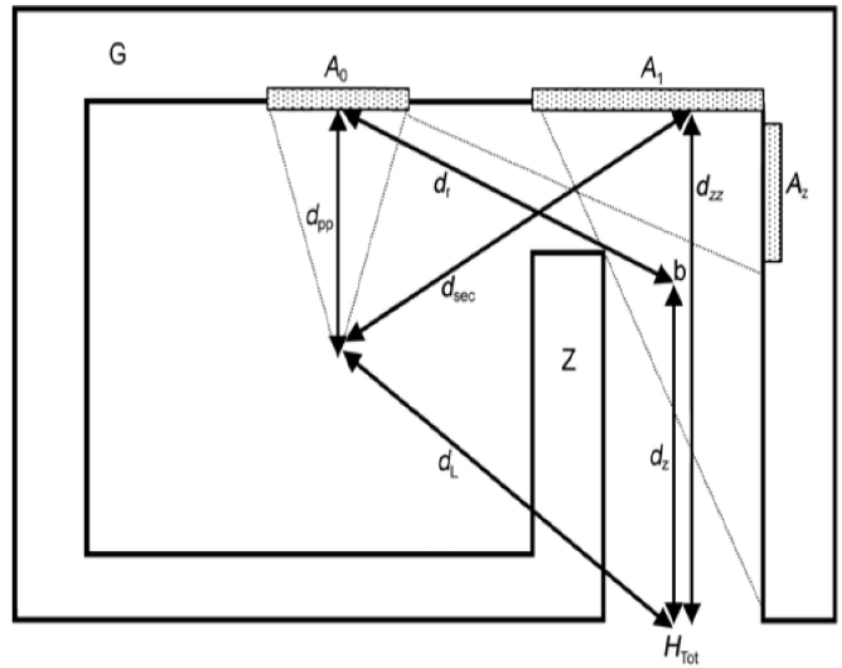
$$H_S = \frac{W\,U_G\,\alpha_0\,A_0\,\alpha_z\,A_z}{(d_h\,d_r\,d_z)^2}$$

$$H_{LS} = \frac{L_f\,W_L\,U_G\,\alpha_1\,A_1}{(d_{\sec}\,d_{zz})^2}$$

$$H_{ps} = \frac{a(\theta)\,W\,U_G\,(\frac{F}{400})\,\alpha_1\,A_1}{(d_{sca}\,d_{\sec}\,d_{zz})^2}$$

$$H_{LT} = \frac{L_f\,W_L\,U_G\,B}{d_L^{\,2}}$$

$$H_G = f\,H_S + H_{LS} + H_{ps} + H_{LT}$$



$$H_{Tot} = 2.64\,H_G$$

H_s = dose equivalent per week due to scatter of the primary beam from the room surfaces
H_{LS} = dose equivalent per week due to head leakage photons scattered by the room surfaces
H_{ps} = dose equivalent per week due to primary beam scattered from the patient
H_{LT} = dose equivalent per week due to leakage radiation which is transmitted through the inner maze wall
f = patient attenuation (~0.25 for 6 - 10 MV for 10x10 cm^2 phantom)

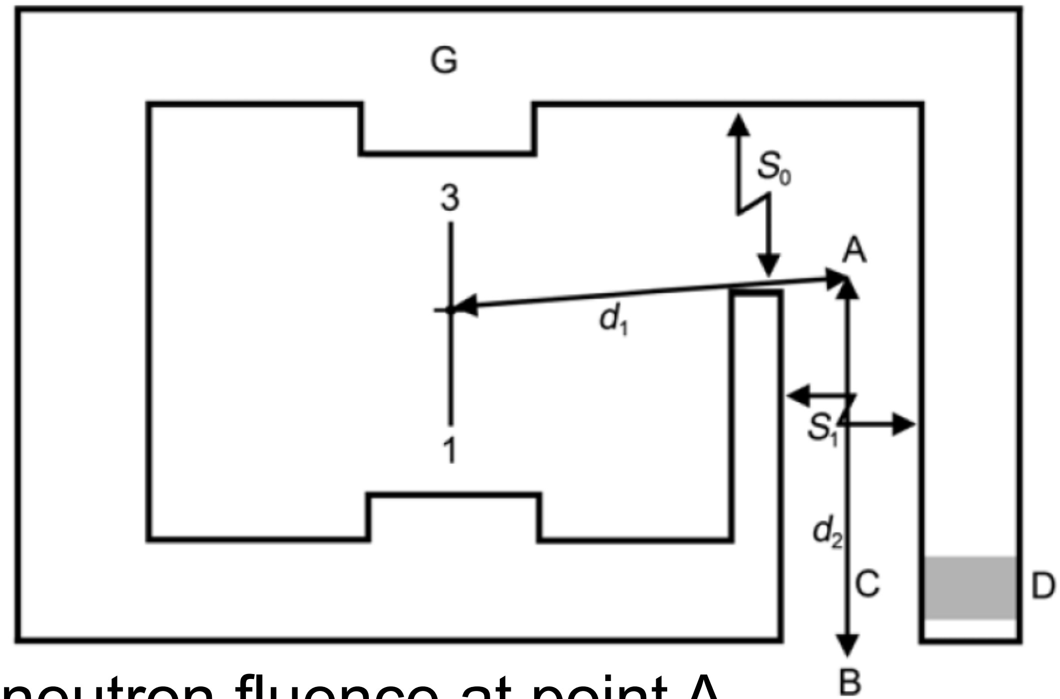
Maze Calculations

- For E > 10 MV, the described maze calculations are still valid, however, neutrons and capture gamma rays need to now be shielded
- Neutrons and capture gamma dominate the shielded dose
- If inner maze wall is very thin, then direct leakage H_{LT} will dominate H_G
- Scatter mechanisms continue to apply
  - But are invariably negligible for energies > 10MV
- If gantry angles are not uniformly distributed then factor 2.64 is invalid

Maze Calculations

- Transmission factor for door shielding is obtained by dividing P for area outside door by H_{Tot}
- Patient and wall scatter TVLs based on 0.2 MV broadbeam transmission (<10 MV)
  - TVL from NCRP 151 Fig A.1.
  - Low energy since two bounces
- Leakage scatter TVLs based on 0.3 MV broad beam transmission
  - 0.3 MV average energy for 6 MV linac (McGinley pg. 49)
    - Single bounce vs. two bounces for patient and wall scatter
  - TVL read from NCRP 151 Fig. A.1.
- Leakage TVL for direct leakage
  - Note that door may not shield direct leakage for short maze

Maze Neutrons and Capture Gammas



1. Calculate neutron fluence at point A
2. Calculate unshielded capture gamma dose rate at door
   - (Use neutron fluence at point A)
3. Calculate unshielded neutron dose equivalent rate at door
   - (Use neutron fluence at point A)
4. Calculate attenuation of maze neutrons and capture gammas by the door

NCRP151 Fig. 2.8

Neutron Fluence Calculation

The total neutron fluence at the inside maze entrance (location A) per unit absorbed dose from x-rays at the isocenter can be evaluated by use of the equation (2.16):

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

The three terms represent the direct, scattered and thermal neutron components, respectively

β = transmission factor for neutrons that penetrate the head shielding (1 for lead and 0.85 for tungsten head shielding)

d_1 = distance from the isocenter to location A (meters)

Q_n = neutron source strength in neutrons emitted from the accelerator head per gray of x-ray absorbed dose at the isocenter

S_r = total surface area of the treatment room (m^2)

$S_r = 2(d_L d_w + h d_L + h d_w)$ where h: vault height

Total Neutron Source Strength

Table B.9. – Neutron dose equivalent (H_0) at 1.41 m from the target per unit absorbed dose of x rays at the isocenter (mSv/Gy) and total neutron source strength (Q_n) emitted from accelerator head.

Vendor	Model	Nominal Energy (MV)	H_0 mSv/Gy	(Q_n) Neutrons per gray ($\times 10^{12}$)	Reference
Varian	1800	18	1.02-1.6	1.22	McGinley (2002)
Varian	1800	15	0.79-1.3	0.76	McGinley (2002)
Varian	2100C	18		0.96	Followill (2003)
Varian	2300CD	18		0.95	Followill (2003)
Siemens	Primus	15		0.21	Followill (2003)
Siemens	MD	15		0.2	Followill (2003)
Philips	SL25	25	2.0	2.37	McGinley (2002)
Philips	SL20	18		0.46	Followill (2003)
GE	Saturn43	18	0.55	1.50	McGinley (2002)

Maze Capture Gamma Unshielded Dose Rate

Weekly dose equivalent at the door due to neutron capture gamma rays in Sv/week (Eq. 2.15 and 2.17):

$$H_{cg} = W_L h_\varphi$$

where, W_L is the workload for leakage radiation and

$$h_\varphi = K \varphi_A 10^{-\left(\frac{d_2}{TVD}\right)}$$

K = ratio of the neutron capture gamma-ray dose equivalent (sievert) to the total neutron fluence at Location A in Fig. 2.8 (an average of 6.9×10^{-16} Sv/m^2 per unit neutron fluence was found for K based on measurements carried out at 22 accelerator facilities)

φ_A = total neutron fluence (m^{-2}) at Location A per unit absorbed dose (gray) of x rays at the isocenter

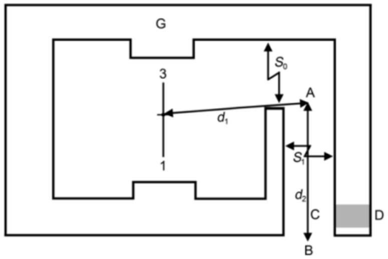
d_2 = distance from Location A to the door (meters)

TVD = tenth-value distance having a value of ~5.4 m for x-ray beams in the range of 18 to 25 MV, and a value of ~3.9 m for 15 MV x-ray beams

Maze Neutron Unshielded Dose Rate

Maze neutron dose-equivalent at door per neutron leakage workload at isocenter (Sv/Gy)- Eq. 2.19 (Mod Kersey's method):

$$H_{n,D} = 2.4\times10^{-15}\,\varphi_A \sqrt{\frac{S_0}{S_1}}\left[1.64\times10^{-\left(\frac{d_2}{1.9}\right)} + 10^{-\left(\frac{d_2}{TVD}\right)}\right]$$



$H_{n,D}$= neutron dose equivalent at the maze entrance in sievert per unit absorbed dose of x-rays (gray) at the isocenter and thus the constant has units of Sv m^2/n

S_0/S_1 = ratio of the inner maze entrance cross-sectional area to the cross-sectional area along the maze (Fig. 2.8)

TVD = tenth-value distance (meters) that varies as the square root of the cross-sectional area along the maze S_1 i.e. $TVD=2.06(S_1)^{1/2}$

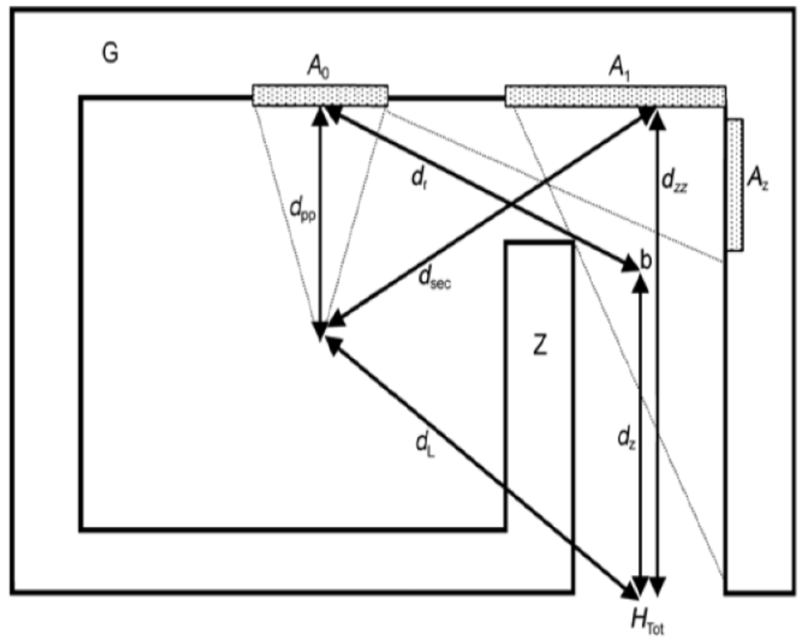
φ_A= neutron fluence per unit absorbed dose of photons ($m^{-2}Gy^{-1}$) at the isocenter as given by Eq. 2.16.

d_2 = distance from point A to door

Weekly neutron dose equivalent at door $H_n = W_L H_{n,D}$

Total Dose Equivalent at Maze Door

Total dose equivalent at the maze door entrance (Eq. 2.22):



$$H_G = f\,H_S + H_{LS} + H_{ps} + H_{LT}$$

$$H_{Tot} = 2.64\,H_G$$

$$H_w = H_{Tot} + H_{cg} + H_n$$

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, Pg 46)
- 161 mm TVL_n for concrete wall adjacent to the door
  - The average neutron energy at the maze entrance is reported to be ~**<u>100keV</u>** (NCRP 151, Pg 46)
  - NCRP 79 TVL_n for concrete with 0.1 MV neutron energy
    - TVL_n = 155 +56*0.1 = 161 mm

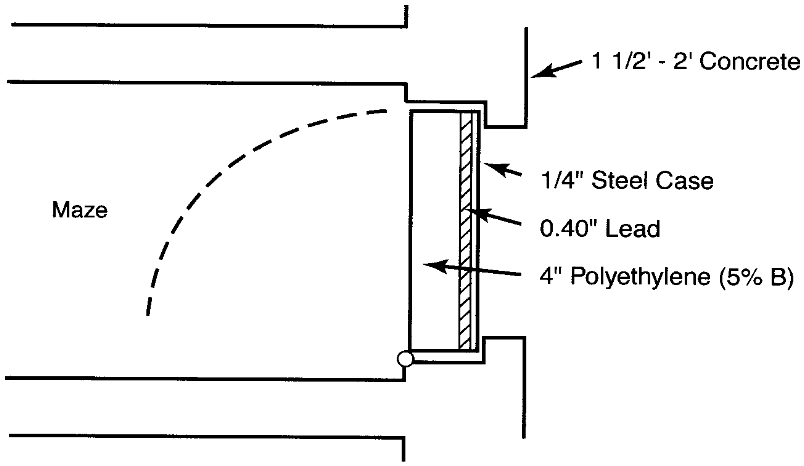
Maze Capture Gamma TVL

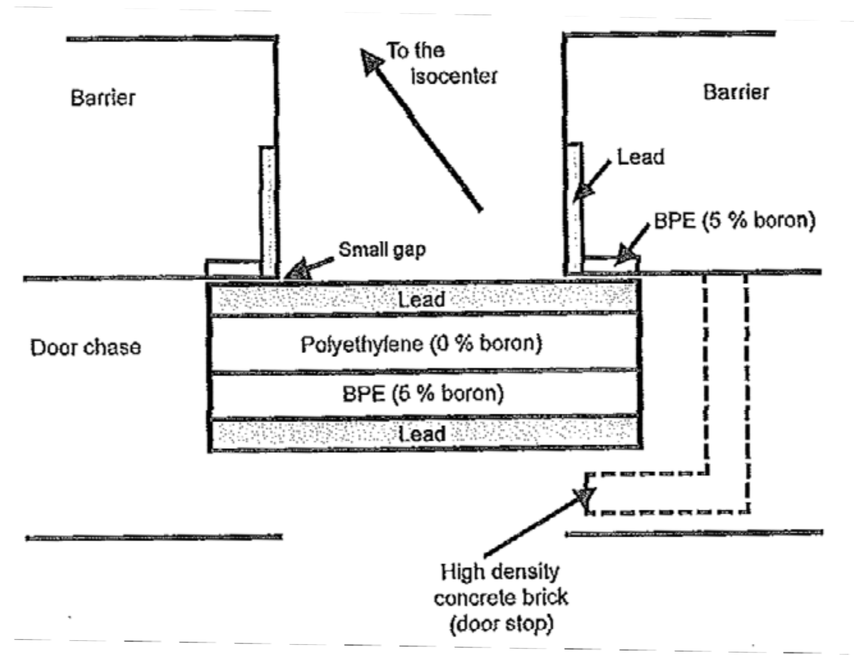
- From NCRP 151:
  - For very short mazes, a lead TVL of 6.1 cm may be required
  - Mazes longer than 5 m, a lead TVL of only about 0.6 cm may be required
- Reading between the lines:
  - Use 61 mm TVL for lead (NCRP 79) regardless of maze length
  - The average energy of neutron capture gamma rays is 3.6 MeV
    - Assumed to apply to long mazes ($d_2 > 5$ m)
    - Use NCRP 151, Fig A.1 TVLs at 3.6 MeV for concrete / steel
  - Can range as high as 10 MeV for very short mazes
    - Short maze assumed to be $d_2 < 2.5$ m
    - Use primary 10 MV TVLs (except 61 mm for lead vs. 57 mm 10 MV TLV)
  - 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 B2 TVLs at 7.2 MeV for concrete / steel

Neutron shielding for very high energy linac rooms

- Hydrogen-rich materials are good neutron attenuators
  - water, concrete, polyethylene
- In doors, polyethylene is usually borated
  - the polyethylene moderates (thermalizes) the neutrons and the boron captures the thermal neutrons
- Capture γ rays are released and these have high energies
  - follow by high-Z material such as Pb

Door construction

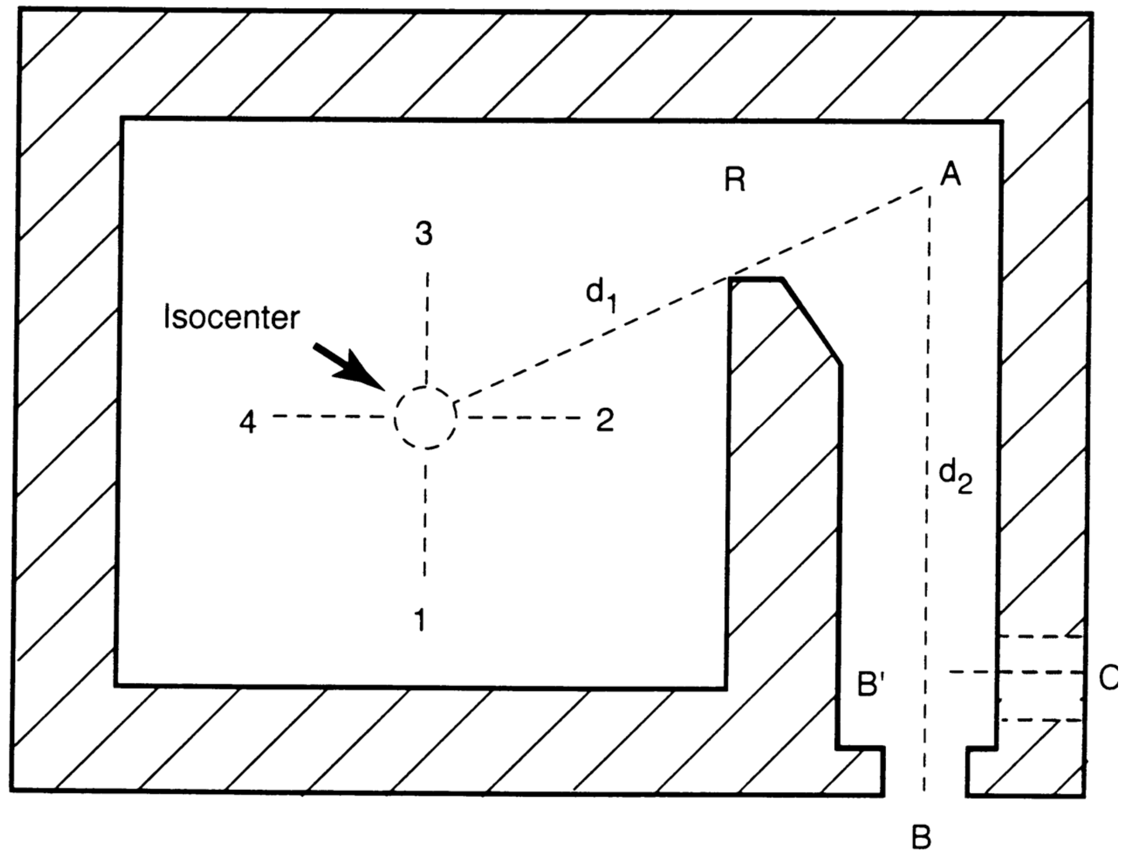




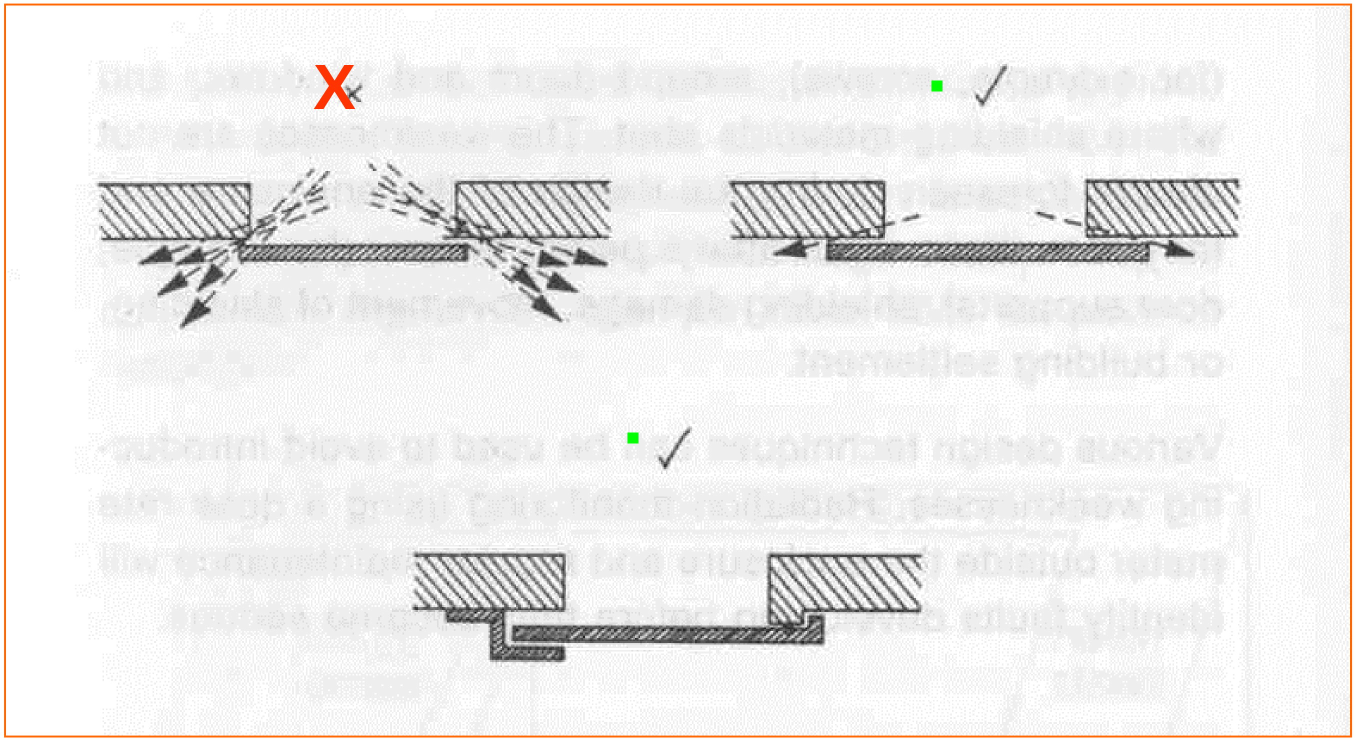
- For low energy linacs, maze doors are constructed solely of lead and steel/or wood
- For high energy linacs, in addition to lead, neutrons have to be considered and polyethylene/borated polyethylene is the material of choice

“Neutron” door calculations

The longer and narrower the maze the more the neutrons are scattered and hence fewer neutrons reach the door

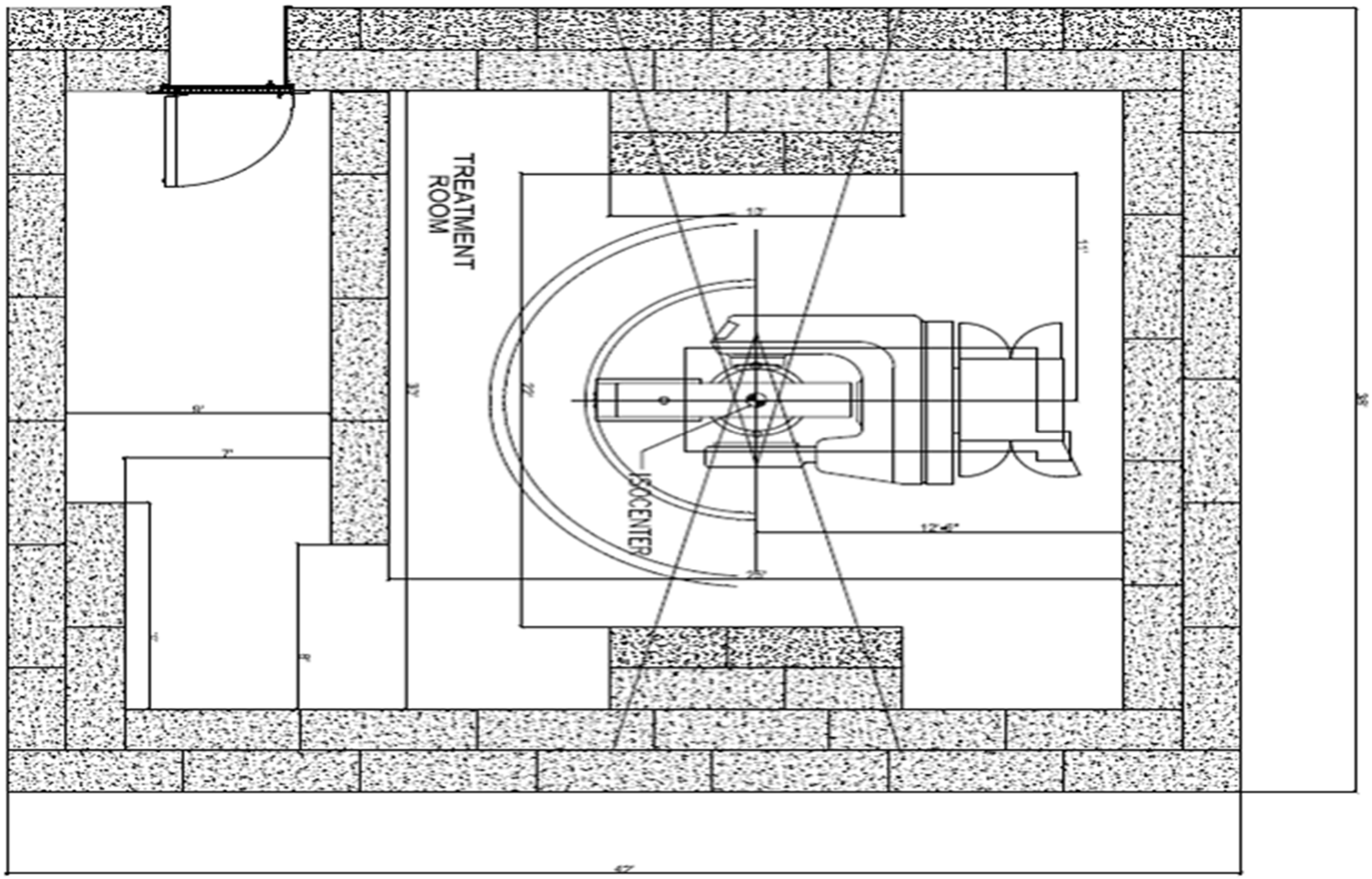


Doors leakage

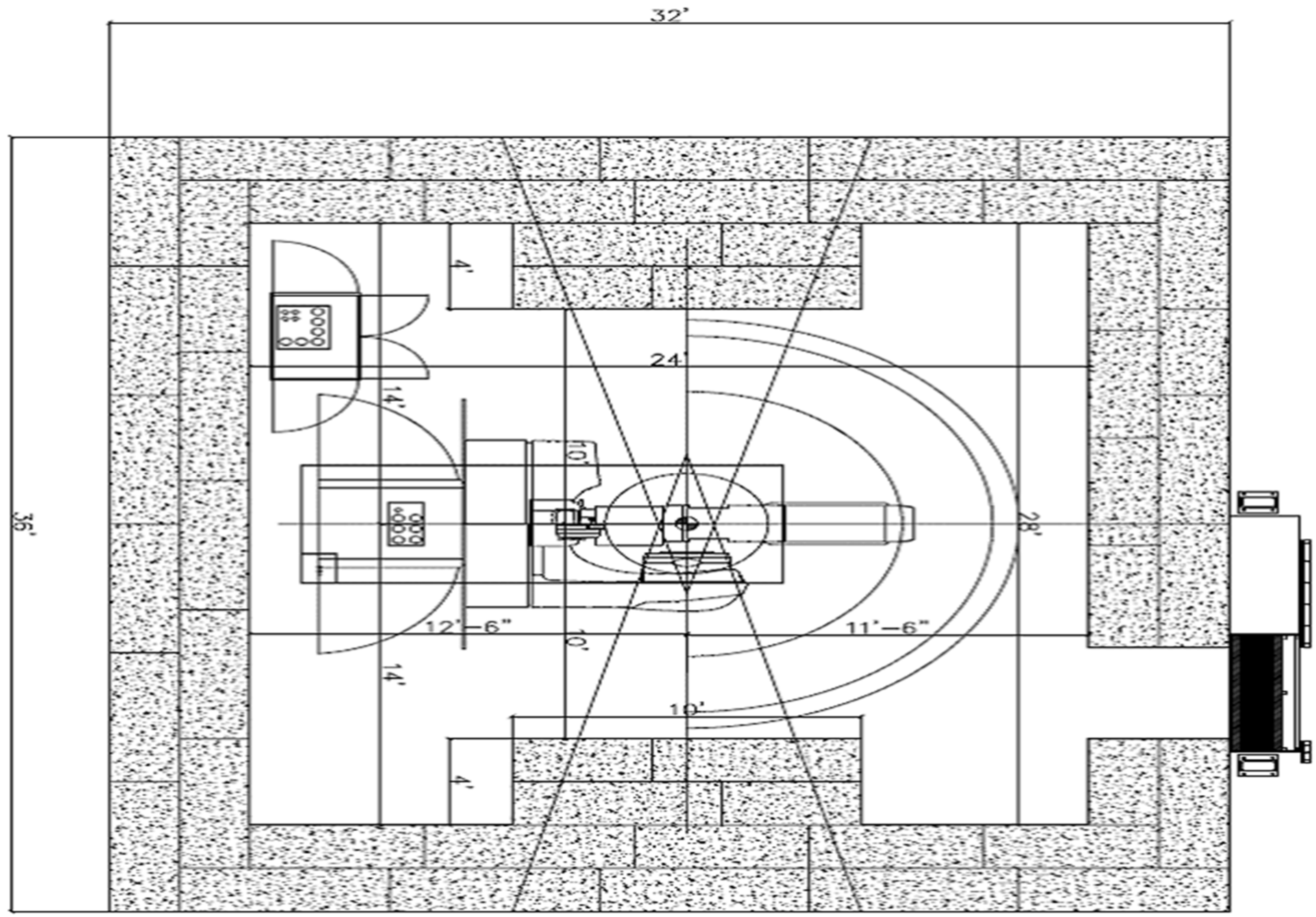


Be aware of leakage radiation

Maze v Mazeless



Maze v Mazeless



Direct Shielded Doors

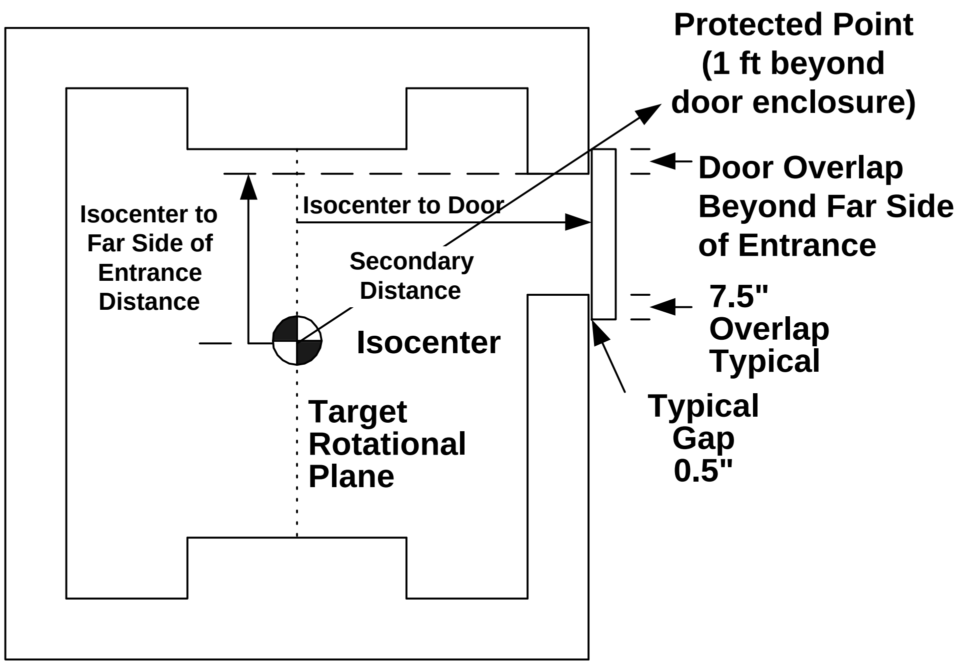
- Good option if space is minimal
- Amount of available room space is greater
- Easier access to room for therapists
- Shielding requirement same as adjacent secondary barrier
- Door is very heavy and thus expensive especially for energies >15 MV

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

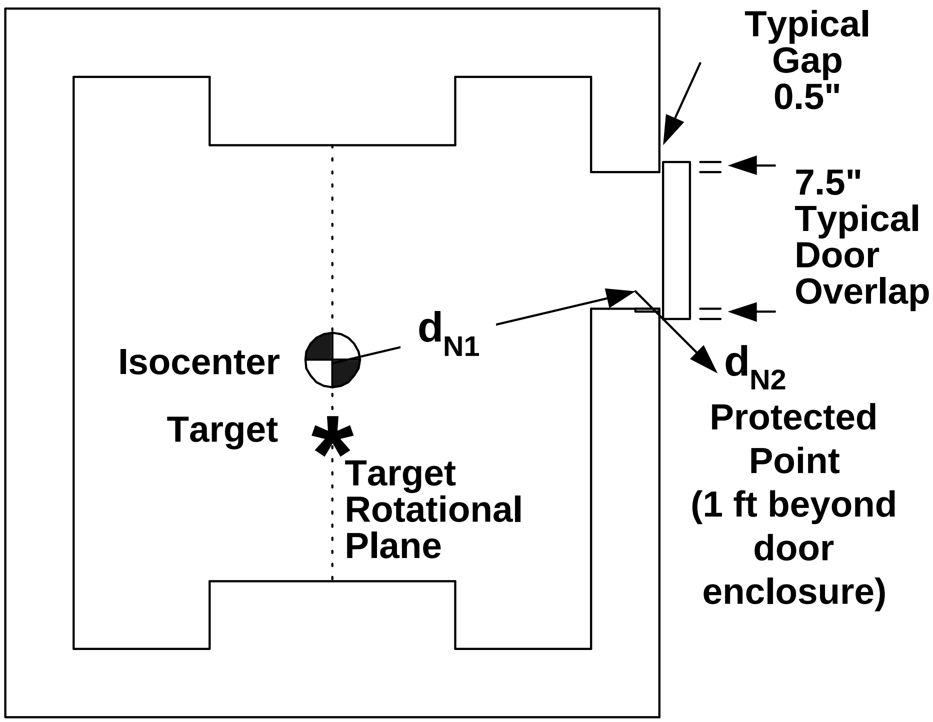
Direct-Shielded Door: Far Side of Entrance

- 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

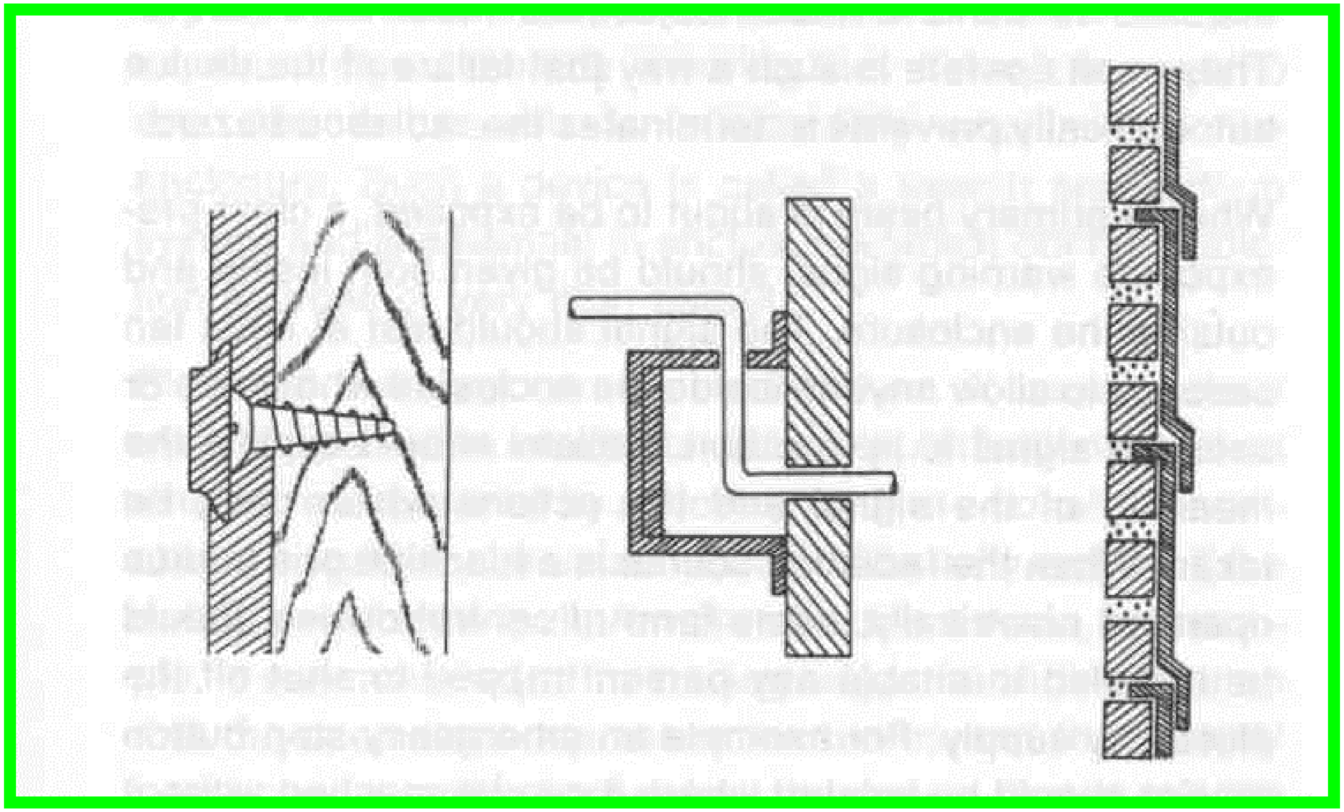


Direct-Shielded Door: Near Side of Entrance

- Geometry similar to short maze
  - Maze calculation can be used but is likely pessimistic
- Requires less material than far side of entrance
  - Lower unshielded dose
  - Lower energy

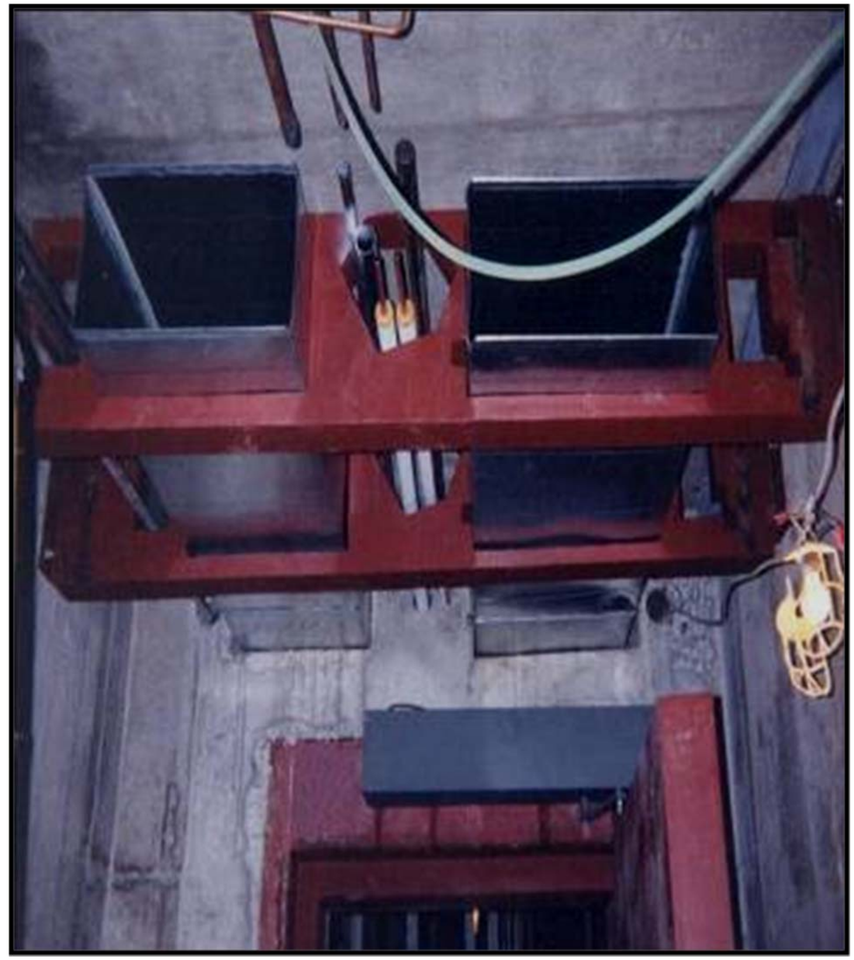


Cover potential holes



Penetrations

Penetrations



Time Average Dose Equivalent Rates

When designing radiation shielding barriers it is usual to assume that the workload will be evenly distributed throughout the year. Therefore, it is reasonable to design a barrier to meet a weekly value equal to one-fiftieth of annual shielding design goal (NCRP, 2004). However, further **scaling the shielding design goal to shorter intervals is not appropriate** and may be incompatible with the ALARA principle. Specifically, the **use of a measured instantaneous dose-equivalent rate (*IDR*), with the accelerator operation at maximum output, does not properly represent the true operating conditions and radiation environment** of the facility. It is more useful if the workload and use factor are considered together with the *IDR* when evaluating the adequacy of a barrier.

For this purpose, the concept of time averaged dose equivalent rate (TADR) is used in this report along with the measured or calculated *IDR*. The TADR is the barrier attenuated dose-equivalent rate averaged over a specified time or period of operation. TADR is proportional to IDR, and depends on values of *W* and *U*. There are two periods of operation of particular interest to radiation protection, the week and the hour.

Instantaneous Dose Rate (IDR)

- The measured IDR can be deceptive
- Was originally designed for Co-60 type sources which are continuous sources
- Linacs use pulsed beam
- IDR was introduced to assure adequate shielding if W used was exceedingly low
- Units in Sv/week
- Measured value depending on the absorbed dose output rate of machine
- Specified at 30 cm beyond barrier for U=1
- For accelerator measurements it is averaged over 20 to 60 seconds depending on the instrument activation response time and the pulse cycle of the accelerator

Weekly Time Averaged Dose Equivalent Rate

The weekly time averaged dose equivalent rate R_w is the TADR at the specified location averaged over a 40 h workweek. For primary barriers it is given by: (Eq 3.8)

$$R_W = \frac{IDR \; W_{pri} \; U_{pri}}{\dot{D}_o}$$

R_w = TADR averaged over one week (Sv/week)
IDR = instantaneous dose equivalent rate (Sv/h) measured with the machine operating at the absorbed dose output rate D_o. IDR is specified at 30 cm beyond the penetrated barrier, and for accelerator measurements it is averaged over 20 to 60 s depending on the instrument response time and the pulse cycle of the accelerator
D_o = absorbed-dose output rate at 1 m (Gy/h)
W_{pri} = primary-barrier weekly workload (Gy/week)
U_{pri} = use factor for the location

If R_w x T is less than P, the barrier is adequate

In-any-one-hour Time Averaged Dose Rate

The U.S. Nuclear Regulatory Commission (NRC) specifies that the dose equivalent in any unrestricted area from external sources not exceed 0.02 mSv **in-any-one-hour** (NRC, 10CFR20, 2005). $\boldsymbol{R}_{\mathrm{h}}$ derives from the maximum number of patient treatments that could possibly be performed in any one hour when the time for setup of the procedure is taken into account.

$$\boldsymbol{R_h = N_{\mathrm{max}}\, \bar{H}_{pt}}$$

N_{max} = maximum number of patient treatments in-any-one-hour with due consideration to procedure set-up time.

H_{pt} = average dose equivalent per patient treatment at 30 cm beyond the penetrated barrier.

In-any-one-hour Time Averaged Dose Rate

$$\bar{H}_{pt} = \frac{R_W}{\bar{N}_W}$$

H_{pt} is also equal to the time averaged dose equivalent per week (R_W) divided by the avg number of patient treatments per week (N_W)

$$\bar{N}_W = 40\,\bar{N}_h$$

N_h is the avg number of patient treatments per hour and 40 comes from 40 hours per week

$$R_h\ (\text{Sieverts}) = N_{\max}\,\bar{H}_{pt} = \frac{N_{\max}\,R_W}{\bar{N}_W} = \frac{N_{\max}}{\bar{N}_h}\,\frac{R_W}{40}$$

R_h not to exceed 0.02 mSv in-any-one-hour outside the barrier becomes the design goal if workload W is exceedingly low. R_h is not the shielding design goal P, but a separate requirement in some regulations, for the upper bound of the dose equivalent rate in-any-one-hour.

Construction Site

Construction Site

Construction Site

Shielding Summary

- Careful planning and shielding design helps to optimize protection and safe costs
- Shielding design and calculations are complex and must be performed by a qualified radiation expert based on sound assumptions
- All shielding must be checked by an independent expert and verified through monitoring on a long term basis