Radiation Protection in Radiotherapy

Part 7

Design of Facilities and Shielding

Lecture 2: Shielding

บรรยายโดย นายณรงค์เวทย์ บุญเต็ม

Radiation safety

- Time
  - ...a working day
- Distance
  - to the control area...
- Shielding

Not much control over time and distance for staff

Therefore, adequate shielding design is essential during planning and building a radiotherapy facility

Objectives

- To understand the principles of shielding and other radiation safety measures
- To be able to perform simple shielding calculations
- To be able to judge the appropriateness of shielding using realistic assumptions and surveys

Contents of lecture 2

1. Fundamentals
2. Assumptions for shielding calculations
3. Basic shielding calculations
4. Shielding verification and surveys

1. Shielding fundamentals

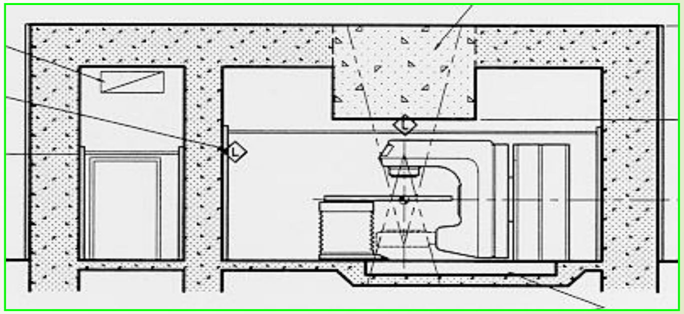
- Aim 1: to limit radiation exposure of staff, patients, visitors and the public to acceptable levels
- Aim 2: to optimize protection of patients, staff and the public
- Different considerations are required for:
  - superficial/orthovoltage X Ray units
  - Simulators, CT (dealt with in diagnostics course)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

Shielding

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

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 - in doubt measure
  - what critical areas close
    - radiology
    - nuclear medicine
- Consider future developments



Equipment placement

- Minimize shielding requirements by placing it
  - near low occupancy walls
  - using distance to best advantage (inverse square law)
- But check if there is enough space around the equipment for
  - safe operation
  - servicing

Shielding considerations

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

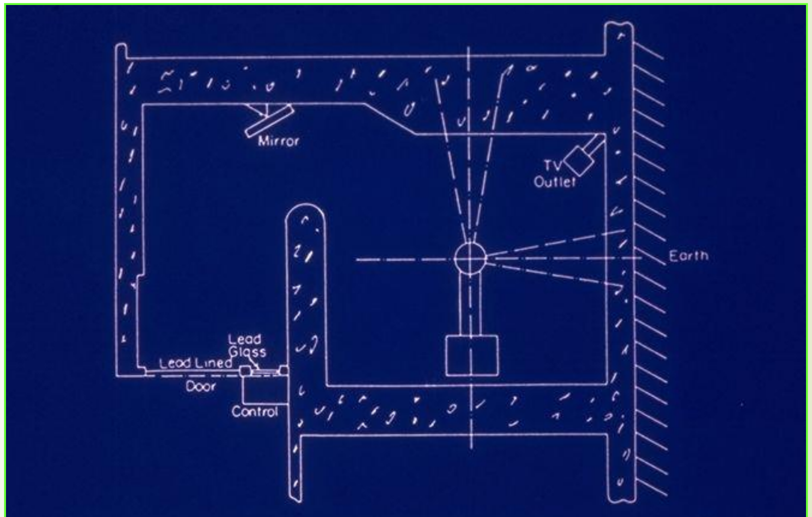


Fig. 4-9. Typical maze design for megavoltage therapy installation. The door and window are exposed only to radiation which has been scattered at least twice.

Shielding design uses assumptions about the future use of the equipment

- Assumptions must be based on justifiable estimates
- Conservative assumptions should be used as under-shielding is significantly worse (and more costly) than over-shielding

Information required

- Equipment type
- Workload
- Target dose
- Use factor and direction of primary bear
- Distance to the area of interest
- Occupancy of area to be shielded
- Limit value in area to be shielded

Equipment type

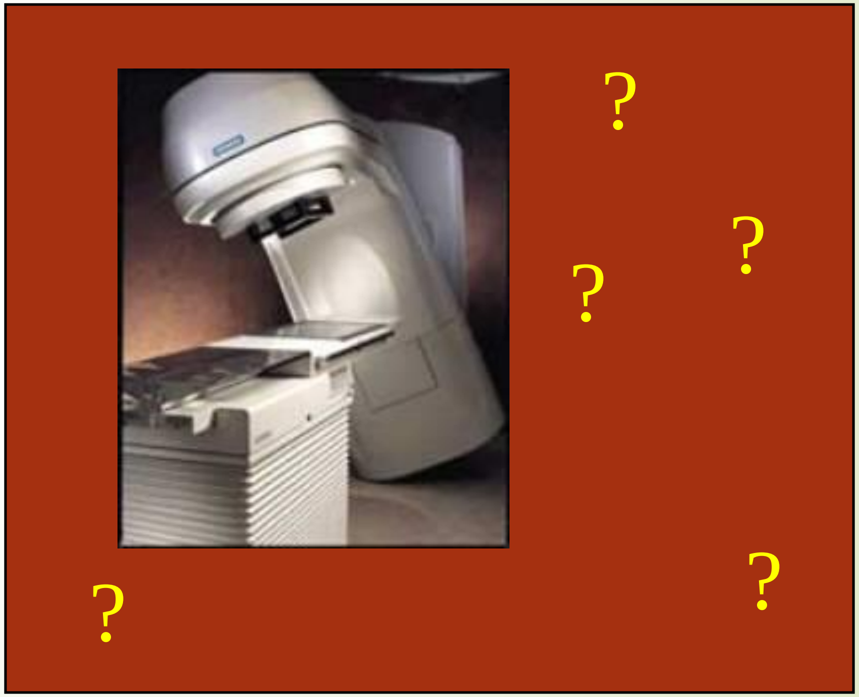
- Type, manufacturer, serial number,…
- Source isotope, activity (date of calibration!), air KERMA, ...
- Radiation quality
- Dose rate
- Field size
- Extras: *e.g.* MLC, IMRT, EPID, ...

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

2. Assumptions for shielding calculations

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



Workload

- A measure of the radiation output
- Measured in
  - mA-minutes for X Ray units
  - Gy for cobalt 60 units, linear accelerators and brachytherapy
- Should consider ALL uses (*e.g.* include QA measurements)

Target dose

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

Example for workload on linac

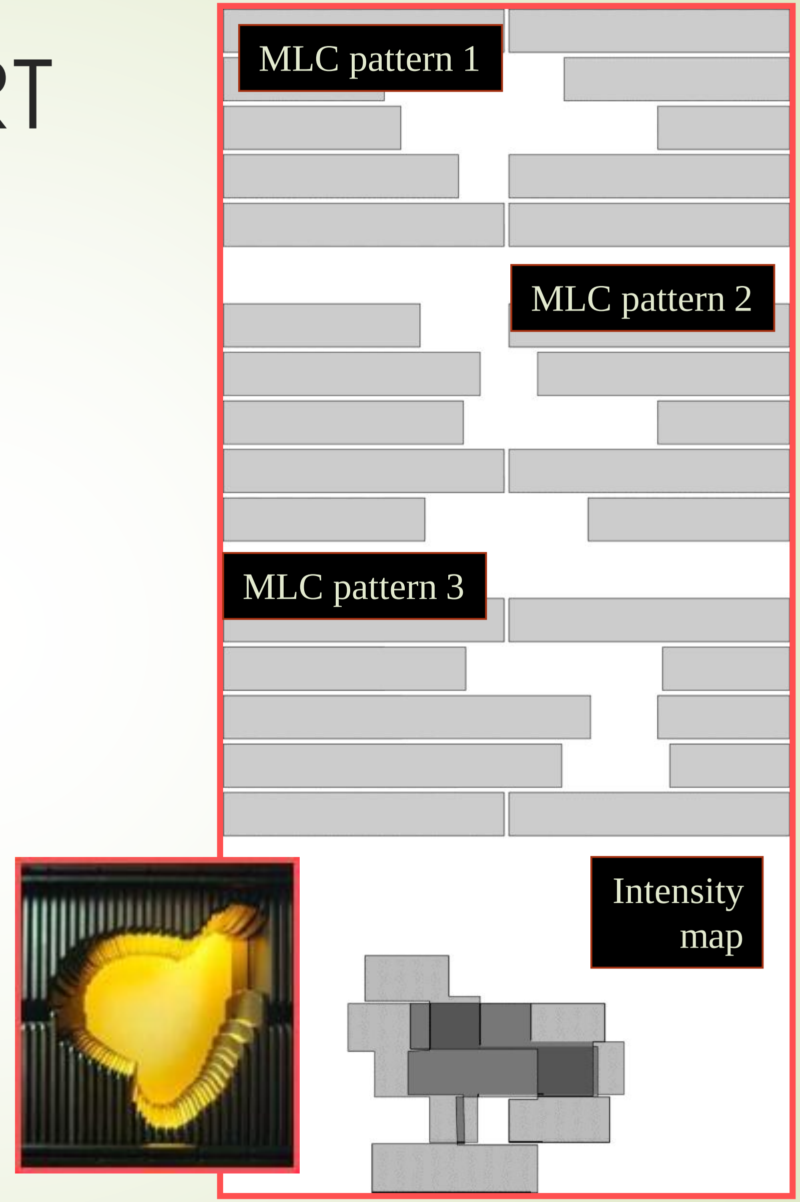
- Assume T = 2.5Gy at isocentre
- 50 patients treated per day on 250 working days per year

W = 50 x 250 x 2.5 = 31250 Gy per year

- allow for other uses such as physics, blood irradiation, ...
- Total : 40000Gy per year at isocentre

Workload and IMRT

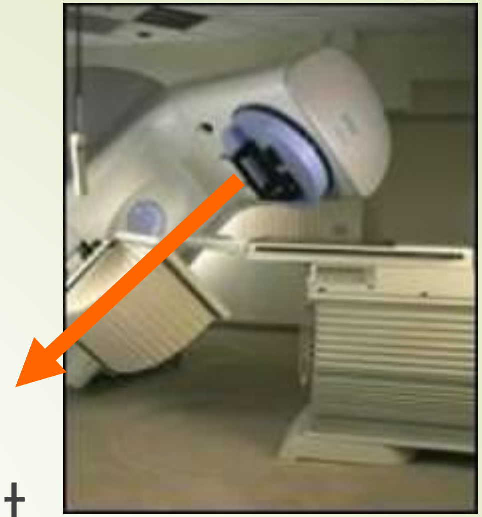
- Most types of Intensity Modulated Radiation Therapy (IMRT) deliver a radiation field in many field segments
- Therefore, many more monitor units are delivered per field than in conventional radiotherapy



IMRT and shielding

- In IMRT many more monitor units are delivered per field than in conventional radiotherapy.
  - The total target dose will still be the same - primary beam shielding will not be affected
  - However, the leakage radiation can be significantly increased (a factor of 10 is often assumed)

Use factor

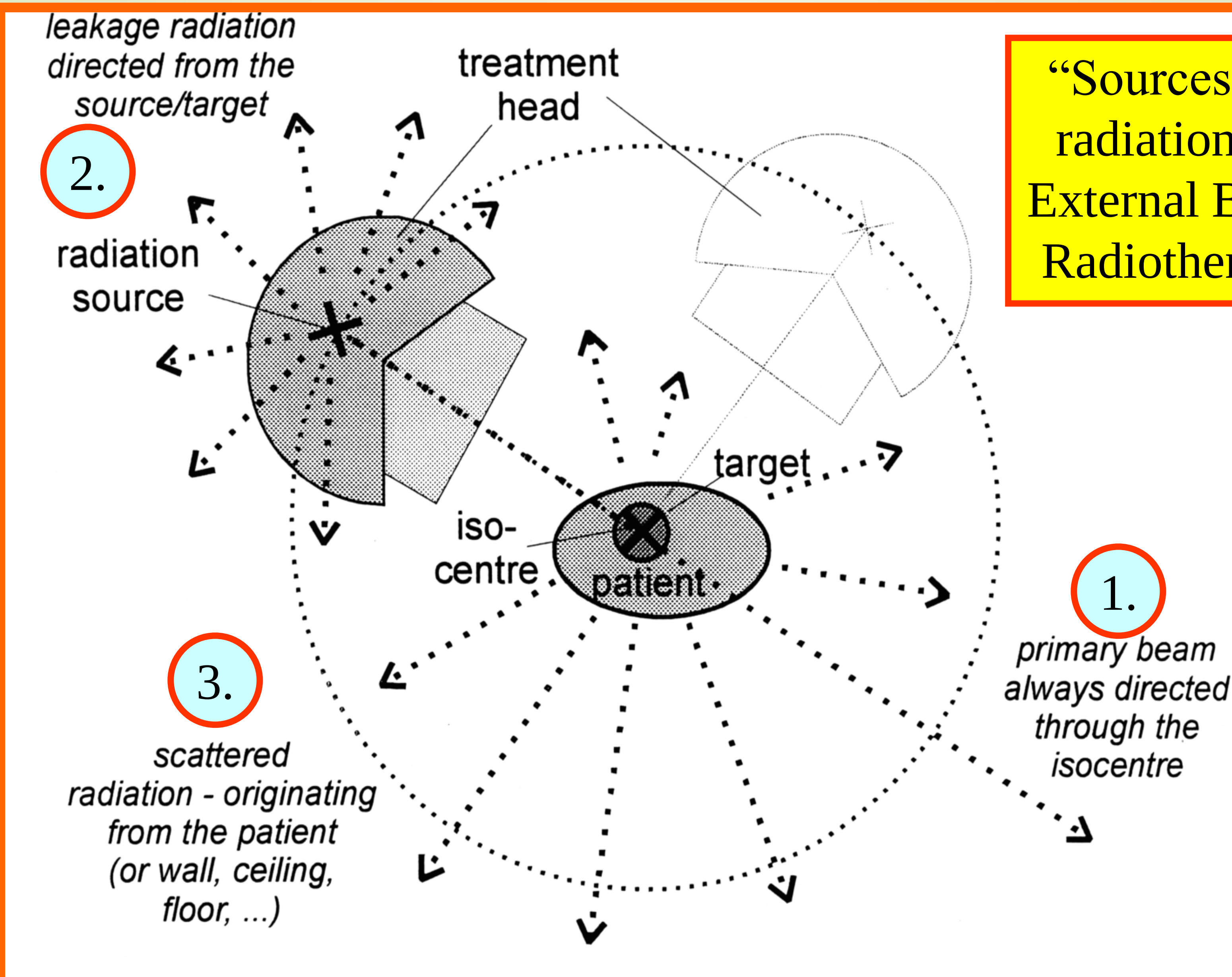


- Fraction of time the ***primary*** beam is in a particular direction *i.e.* the chosen calculation point
- Must allow for realistic use
- For accelerators and cobalt 60 units usually the following is used:
  - 1 for gantry pointing down
  - 0.5 for gantry pointing up
  - 0.25 for lateral directions

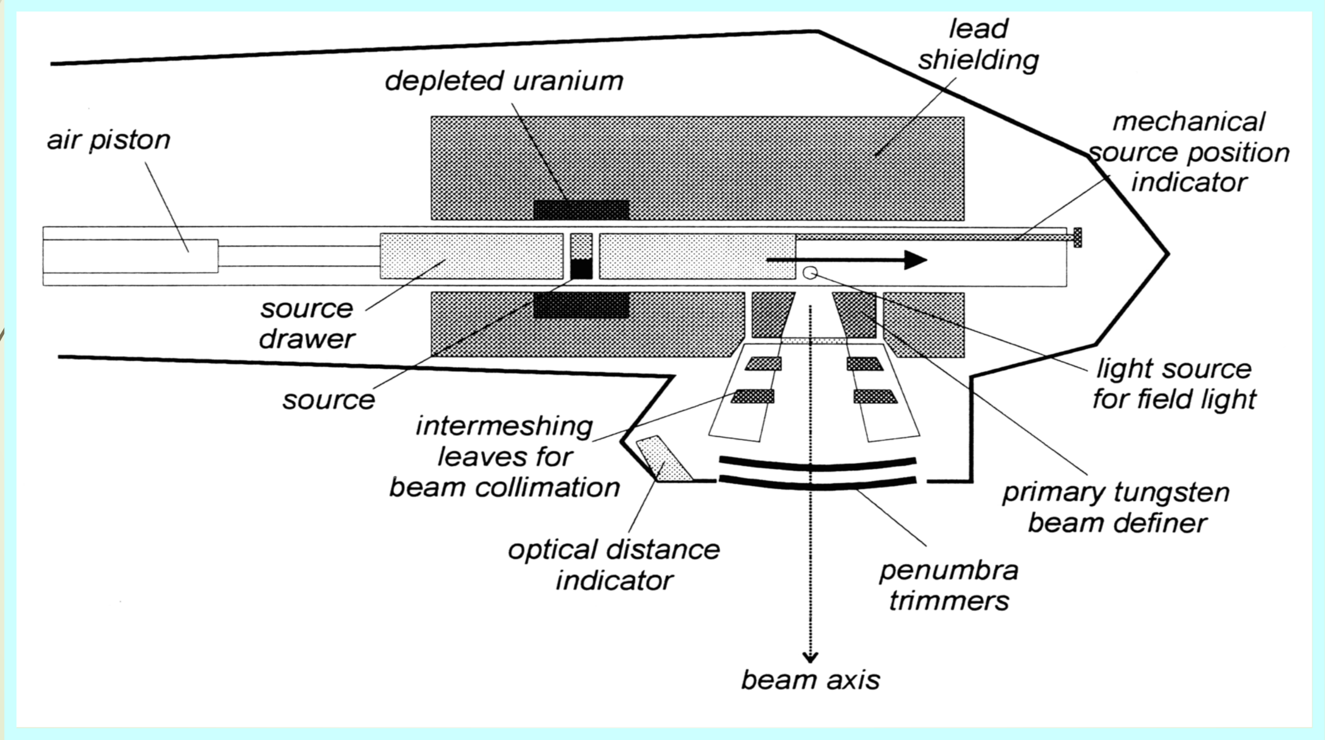
Primary and secondary shielding

- Shielding must consider three source types of radiation:
  - primary (apply use factor)
  - scatter (no use factor - U = 1)
  - leakage (no use factor - U = 1)
- Brachytherapy does not apply a use factor (U = 1)

“Sources” of radiation in External Beam Radiotherapy



Please discuss briefly the location of the origin of the three types of radiation in the context of a Cobalt unit treatment head - this may be of importance when calculating distances...



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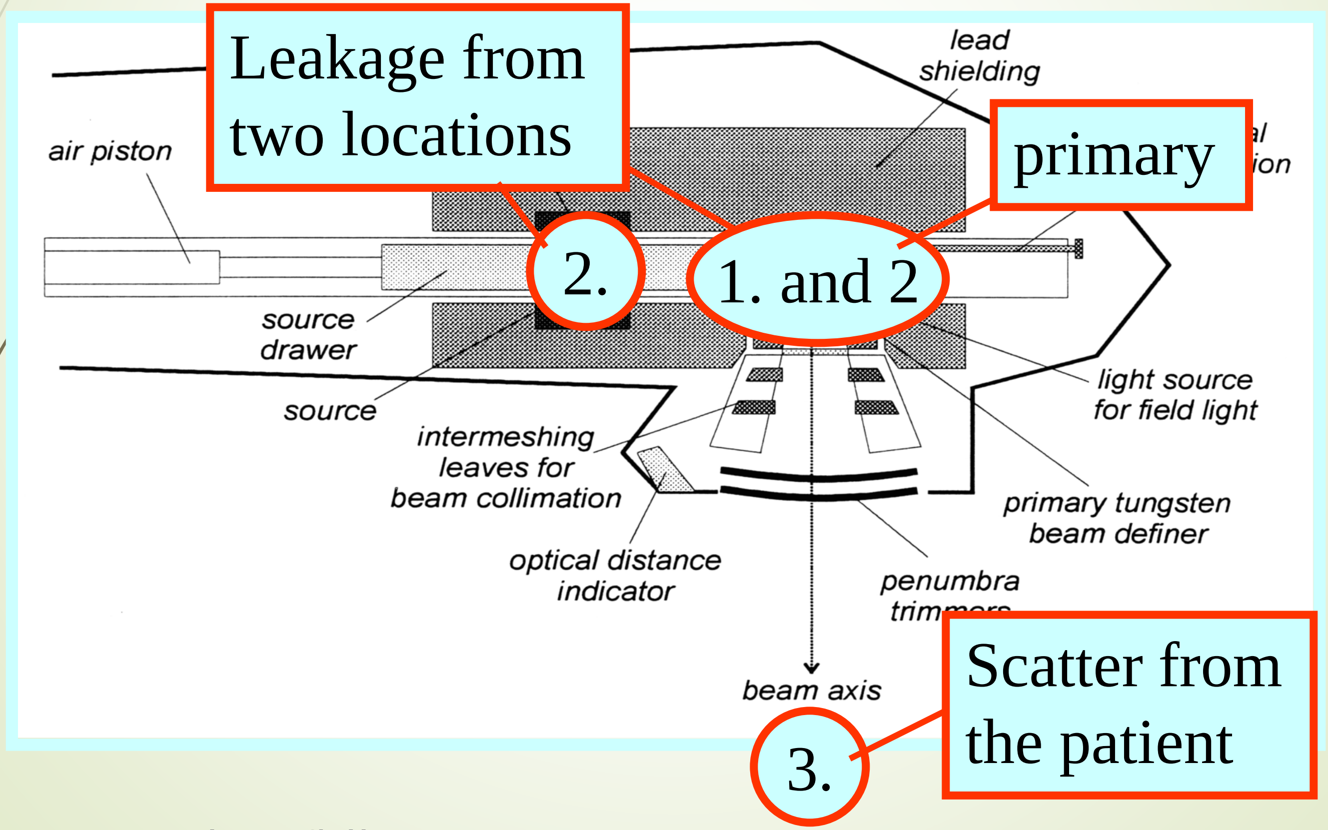
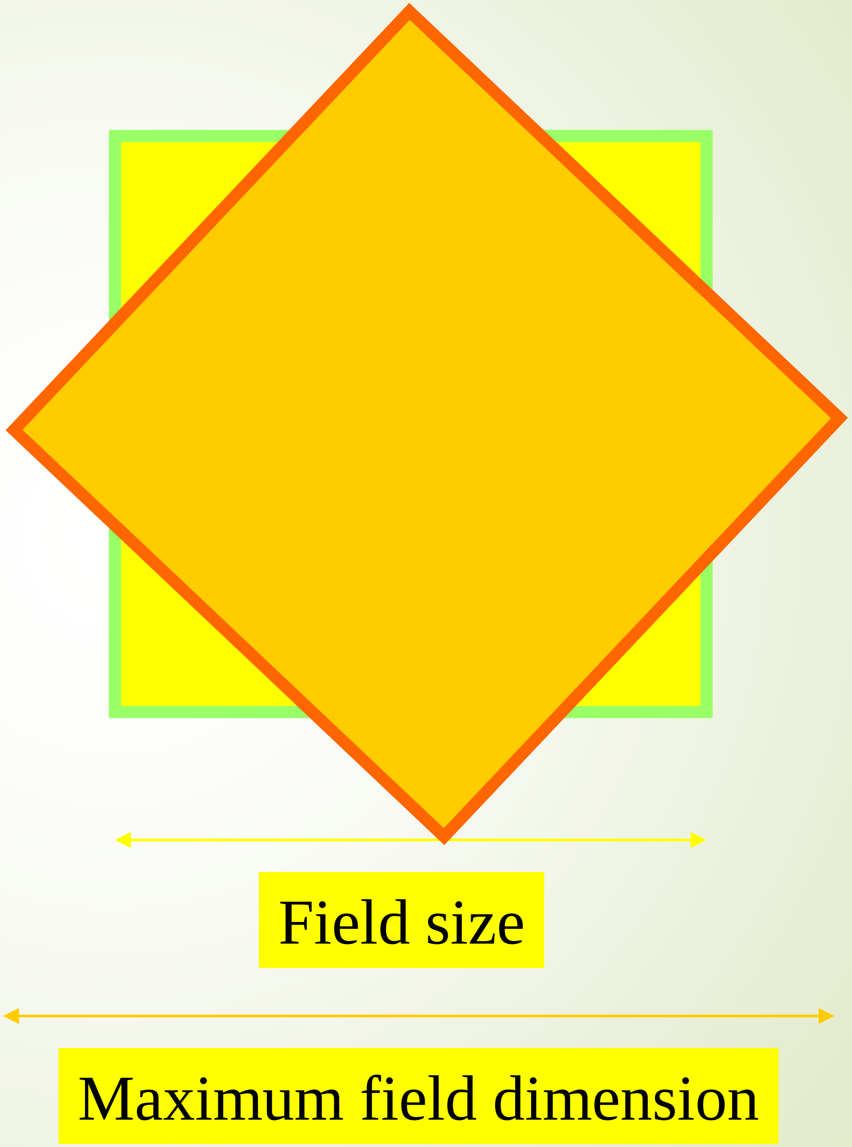


Consideration of the maximum field size for primary beam shielding



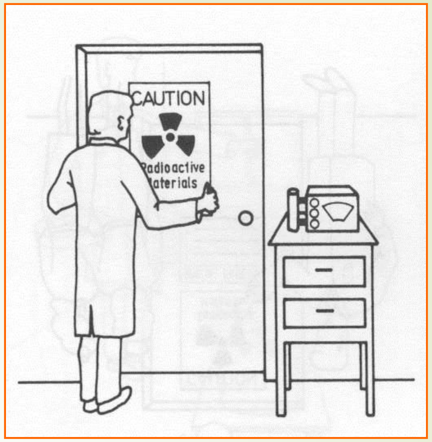
Secondary Sources in External Beam Radiotherapy

- Leakage:
  - dependent on design, typically limited to 0.1 to 0.2% of the primary beam
  - originates from target - not necessarily via the isocentre
- Scatter:
  - assumed to come from the patient
  - difficult to calculate - use largest field size for measurements
  - the lower the radiation energy, the more of a concern for photon beams

Distance to the point to be shielded

- Usually measured from the target or the source of radiation
- In linacs and isocentrically mounted Cobalt units measured ‘via’ the isocentre
- Very important for shielding as dose falls off with distance squared = Inverse Square Law (ISL)

Room location



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

Occupancy of the area to be shielded

- Fraction of time a particular place is occupied by staff, patients or public
- Has to be conservative
- Ranges from 1 for all offices and work areas to 0.05 for toilets or 0.025 for unattended car parks
- Based on NCRP report 151

Occupancy (NCRP 151)

Area	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

Occupancy (NCRP 151)

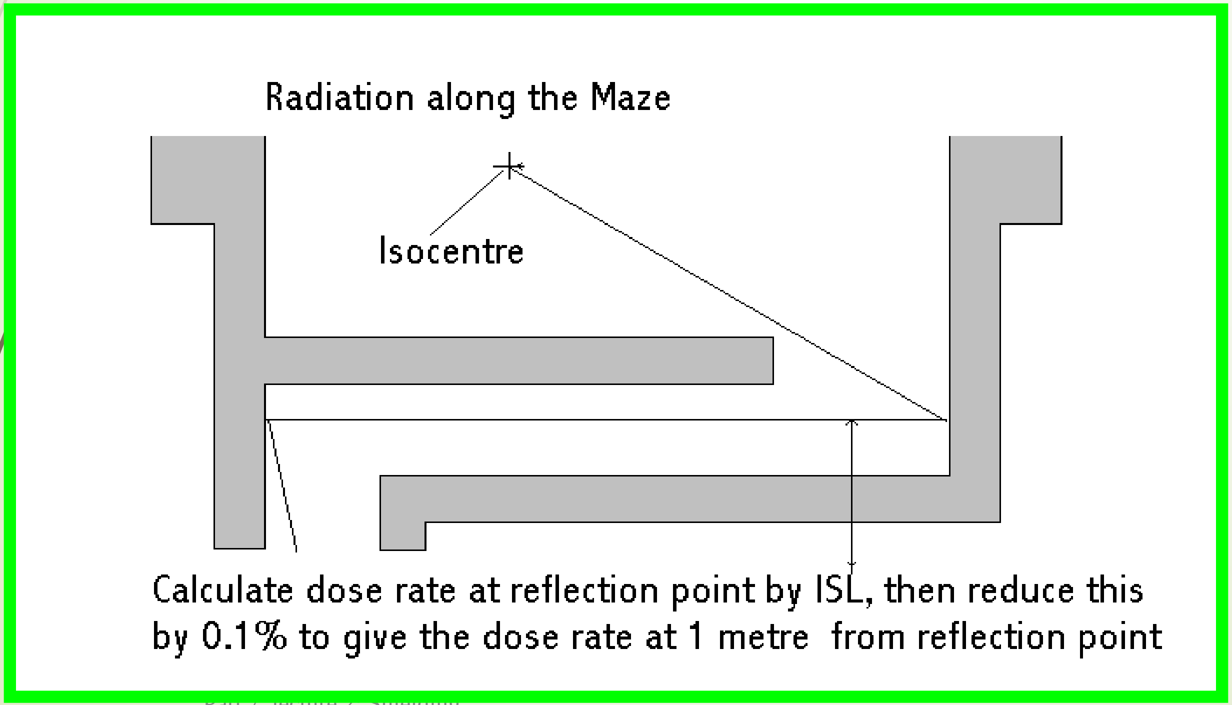
Area	Occupancy factor T
Treatment vault doors	1
Public toilets, unattended vending rooms, storage areas, outdoor areas with seating, unattended waiting rooms, patient holding areas, attics, janitors' closets	1/20
Outdoor areas with only transient pedestrian or vehicular traffic, unattended parking lots, vehicular drop off areas (unattended), stairways, unattended elevators	1/40

Limit value

- Also referred to as ‘design dose’ per specified time period
- Usually based on 5 mSv per year for occupationally exposed persons, and 1 mSv for public
- Can apply additional constraint *e.g.* 0.3 (to account for the fact that a person can be irradiated from multiple sources at the same time)
- Occupational dose only to be used in controlled areas *i.e.* only for radiographers, physicists and radiation oncologists

Considerations for the maze

- Calculations complicated as they depend on scatter from walls - in general try to maximize the number of scatter



Considerations for neutrons

- Complex issue - requires consideration by a qualified radiation expert.
- In brief:
  - Neutrons are produced by (gamma,n) production from high energy linacs (E > 10MV)
  - Issues are neutron shielding and activation of items in the beam

Neutron shielding

- Different concept from X Ray shielding
- Neutrons scatter more
- Attenuation (and scatter) depend VERY strongly on the neutron energy
- Best shielding materials contain hydrogen or boron (with high cross section for thermal neutrons)

Features of neutron shielding

- Long maze - many ‘bounces’
- Neutron door - typically filled with borated paraffin
- … however, care is required as neutrons generate gammas which may require other materials for shielding again...

Activation

- Neutrons can activate materials in their beam
- High energy linacs are designed with materials with low activation cross section
- After high energy photon irradiation, beam modifiers such as wedges or compensators may become activated
- After prolonged use of high energy photons (e.*g*. for commissioning) it is advisable to let activation products decay prior to entering the room (>10min)

More information on neutrons

AAPM REPORT NO. 19

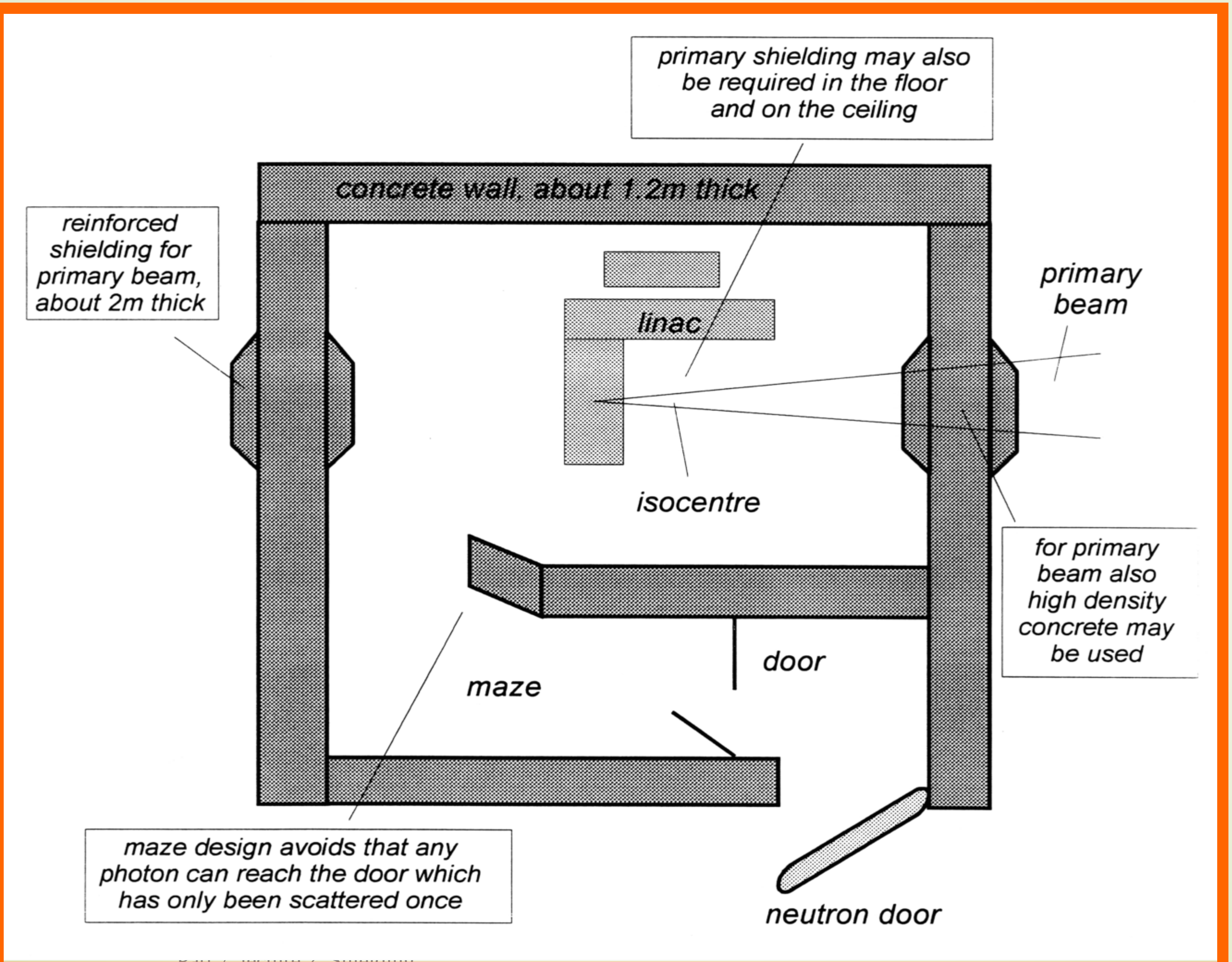
NEUTRON MEASUREMENTS AROUND HIGH ENERGY X-RAY RADIOTHERAPY MACHINES

A REPORT OF TASK GROUP 27
RADIATION THERAPY COMMITTEE
AMERICAN ASSOCIATION OF PHYSICISTS IN MEDICINE

Ravinder Nath, *Yale University*, Chairman
Arthur L. Boyer, *M.D. Anderson Hospital*
Philip D. La Riviere, *Varian Associates*
Richard C. McCall, *Stanford Linear Accelerator Center*
Kenneth W. Price, *Yale University*

July 1986

Schematic of a linac bunker



Other irradiation units: simulator and CT scanner

- Shielding-need and approaches for a simulator and CT scanner follow the same guidelines as the equipment in diagnostic radiology - this is discussed in the companion course of radiation protection in diagnostic radiology

Nucletron/Oldelft Simulix

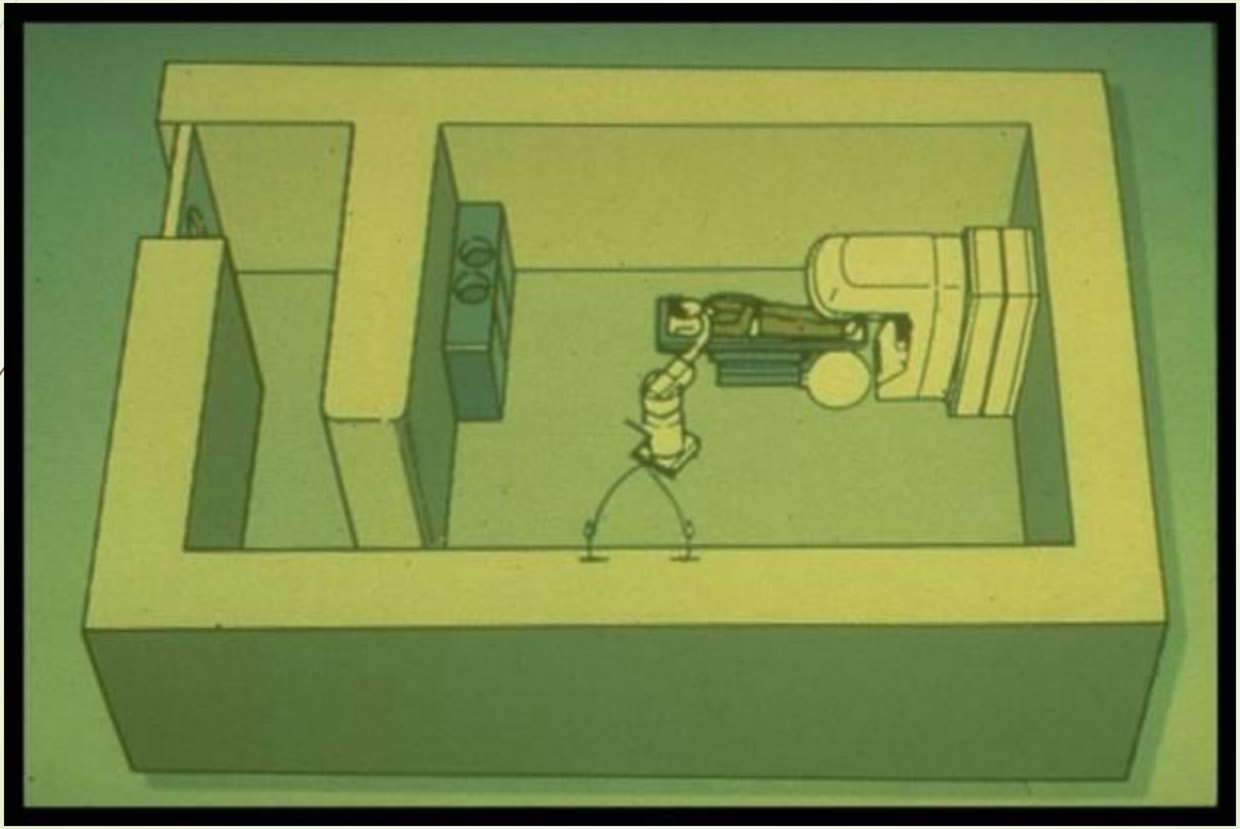
Other irradiation units: Kilovoltage treatment units

- Shielding need and approaches for kilovoltage treatment units are similar to diagnostic radiology principles
- However, high kVp and mAs means that more shielding is required.

Kilovoltage Units

- Need to estimate the shielding associated with the wall materials.
  - if concrete this is simple
  - if brick or concrete brick then they may have variable thickness and may be hollow
- Additional shielding is usually lead sheet or lead glued to plywood
- In a new building concrete may be cheaper

Brachytherapy shielding



Radiation Shielding Design - Brachytherapy

- The complexity of shielding for brachytherapy depends on the type of installation and source configuration
  - Automatic afterloading, single stepping source, for example HDR and PDR units
  - Automatic afterloading, pre-assembled source trains or pre-cut active wires
  - Manual afterloading

LDR treatment rooms

- Low Dose Rate (LDR) brachytherapy is usually performed in a ward occupied also by other patients
  - the preferable arrangement is to use a single bed room in order to minimize dose to all staff and other patients
  - Shielding is easiest and cheapest if the room is in a corner of the building and on the lowest or highest floor if it is a multi-storey building

Shielding of treatment room in the ward

- Can utilize existing walls which typically require increase in shielding
- Checks for hidden gaps, missing bricks or ducts which compromise shielding is necessary
- Shielding consideration must include rooms above and below the treatment room.

HDR treatment rooms

- The design of these rooms follow similar considerations to those of accelerator rooms
- Usually closed circuit TV and intercom is required for communication
- Similar interlocks to those used in accelerator rooms are required

PDR treatment rooms

- the instantaneous dose rate is approaching the level of an HDR unit (about a factor 10 lower)
- however, in practice, the treatment is similar to an LDR treatment and typically performed in a ward. Therefore stringent shielding requirements are applicable
- room design must take features from both HDR (shielding thickness, interlocks) and LDR room design (communication, location within the ward)

Instantaneous dose rate

- There is some debate as to what averaging period should be used for shielding calculations (not only for PDR):
  - Instantaneous dose rate?
  - Average over one treatment (*e.g.* a week)?
  - Average over a year?

Instantaneous dose rate

- In this case it must be considered what the potential exposure patterns are for someone at risk – *e.g.* a visitor may only be there for minutes, a patient in an adjacent room for days or weeks and nursing staff in the ward for the whole time.
- There may be legal requirements
- In doubt - use the most conservative approach (typically a small averaging period)

3. Basic shielding calculation

- Currently based on NCRP 57 and 151
- Assumptions used are conservative, so over-design is common
- Computer programs may be available, giving shielding in thickness of various materials

Shielding calculation

- Equipment type
- Workload W
- Target dose D
- Use factor U
- Distance d
- Occupancy of area to be shielded T
- Limit value in area to be shielded P

- *How can we calculate the required attenuation factor A (and therefore the barrier thickness B) by putting these parameters together?*

Shielding calculation

- (Equipment type)
- Workload W
- (D included in W)
- Use factor U
- Distance d
- Occupancy of area to be shielded T
- Limit value in area to be shielded P

- Need to achieve P

$P = WUT\ (d_{ref}/d)^2 \times A^{-1}$

- with d_{ref} as the distance from source to reference point (e.g. isocentre) and A as the minimum attenuation required for the barrier

Example

- Waiting room adjacent to a linac bunker, distance 6m
- The linac has a workload of 40000Gy at isocentre per year
- FAD = 1m

Example for primary beam

- Equipment type = linac, FAD = 1m, 6MV
- W = 40000Gy/year
- (D = 2.5Gy)
- U = 0.25 (lateral approach)
- d = 6m
- T = 0.25 (waiting room)
- P = 0.001Gy/year (no additional constraint)

$A = WUT\ (d_{ref}/d)^2 / P$

A = 69,444

Need nearly 5 orders of magnitude attenuation !

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

Shielding materials

- Iron/steel
  - Relatively high physical density - space requirements acceptable
  - Self supporting structure - easy to mount
  - Relatively expensive

Shielding materials

- Concrete
  - Cheap (when poured at the time of building construction)
  - Self supporting - easy to use
  - Relatively thick barriers required for megavoltage radiation
  - Variations in density may occur - needs checking

Other shielding materials

- Walls, bricks, wood, any structure used for building
- High density concrete (density up to 4g/cm^3 as compared with around 2.3 for normal concrete)
- Composite materials, *e.g.*, metal bits embedded in concrete (*e.g.* Ledite)

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	around 4	26	5.8
Steel	7.9	26	2.2
Lead	11.34	82	22
Earth, packed	1.5	variable	low

Tenth Value Layer Thicknesses (TVL) For Different Materials

	TVL (cm) for different photon qualities (endpoint energy)						
Shielding material (density g/cm^3)	**500 kVp spectrum**	**4 MVp spectrum**	**4 MV mono-energetic**	**6 MVp spectrum**	**10 MVp spectrum**	**20 MVp spectrum**	**References**
Lead (11.3)	1.19	5.3	3.7	5.7	5.5 - 5.8	5.7	NCRP 2005 Cember 1992 Siemens 1994
Steel/Iron (7.8)		9.1	9.9	10	9.7 - 11	11	Cember 1992 Siemens 1994
Concrete (1.8-2.4)	11.7	29.2	35	37	38 - 41	46	NCRP 2005 Cember 1992 Siemens 1994
Ledite (approx 4)		14					Manufacture specifications

Note: Ledite is a mixture of lead shot in concrete available in bricks of various sizes. Ledite (and similar materials) are often used for shielding purposes as they combine a high physical density

Example for primary beam

- Equipment type = linac, FAD = 1m, 6MV
- W = 40000Gy/year
- D = 2.5Gy
- U = 0.25 (lateral approach)
- d = 6m
- T = 0.25 (waiting room)
- P = 0.001Gy/year (no additional constraint)

A = 69,444

Need to know the TVL (tenth value layer or thickness required to attenuate the beam by a factor of 10) of concrete in a 6MV beam

TVL = 30cm

Required barrier thickness:

B = 1.5m

Example for secondary barrier

- Equipment type = 60-Co, FAD = 80cm
- W = 40000Gy/year
- (D = 2.5Gy)
- (U = 1)
- $d_{to\ isocentre}$ = 5.2m
- T = 1 (office above)
- P = 0.001Gy/year
- Dose constraint factor 0.3 (Cobalt unit is only one potential source)

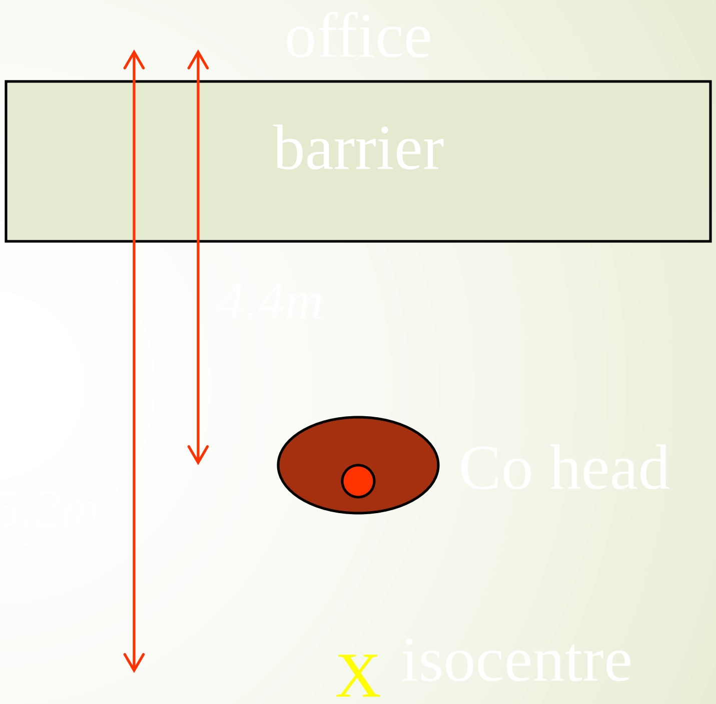
$A = L\ WT\ (d_{ref}/d)^2 / P$

L = "leakage and scatter factor" = 0.2%

A = ???

Secondary barrier example

- A = 8,815 (or approximately 4 orders of magnitude)
- TVL for 60-Co in concrete is 25cm
- Barrier thickness required 100cm !



Floor of bunker

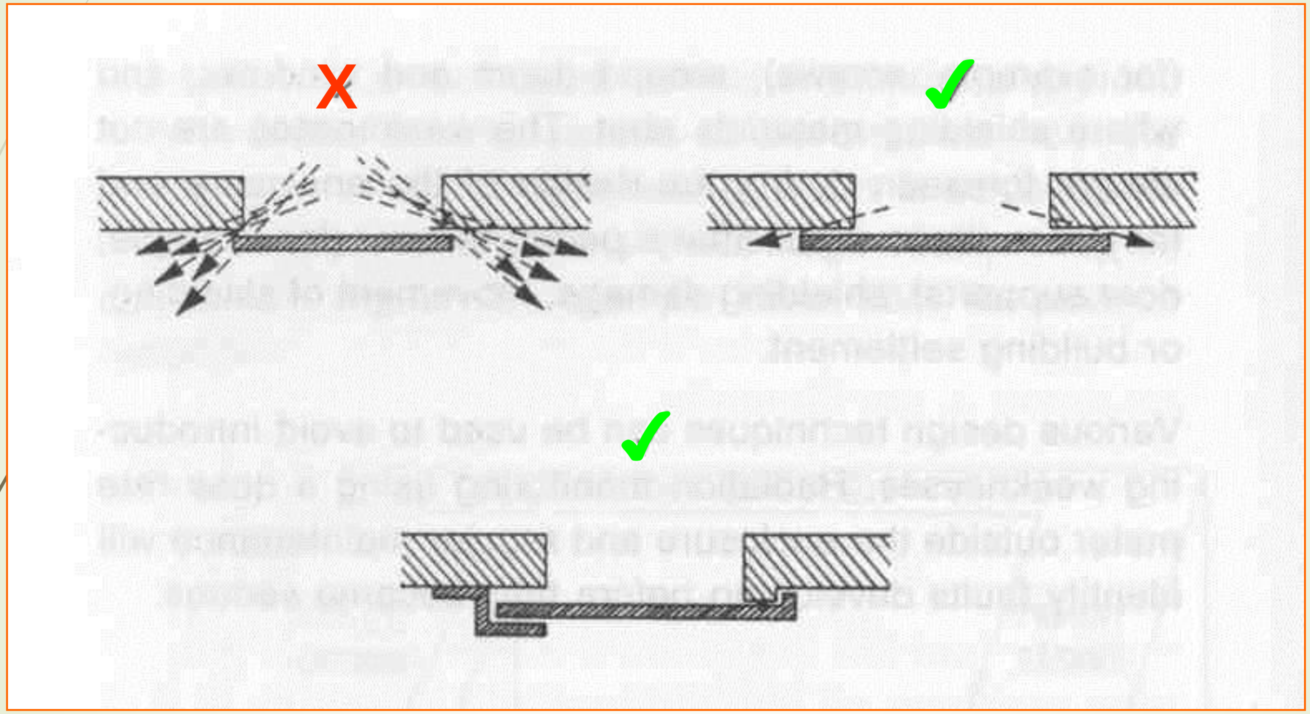
A note on doors

- Shielded doors are satisfactory for kilovoltage units although heavy duty hinges or door slides will be required
- Megavoltage units require a maze and may actually not require a door at all if the maze is long enough and well designed - in this case one must ensure no one enters the room during or before treatment
- A door-less maze requires warning signs and motion detectors which can determine if someone enters the room unauthorized and disable beam delivery

A note on doors

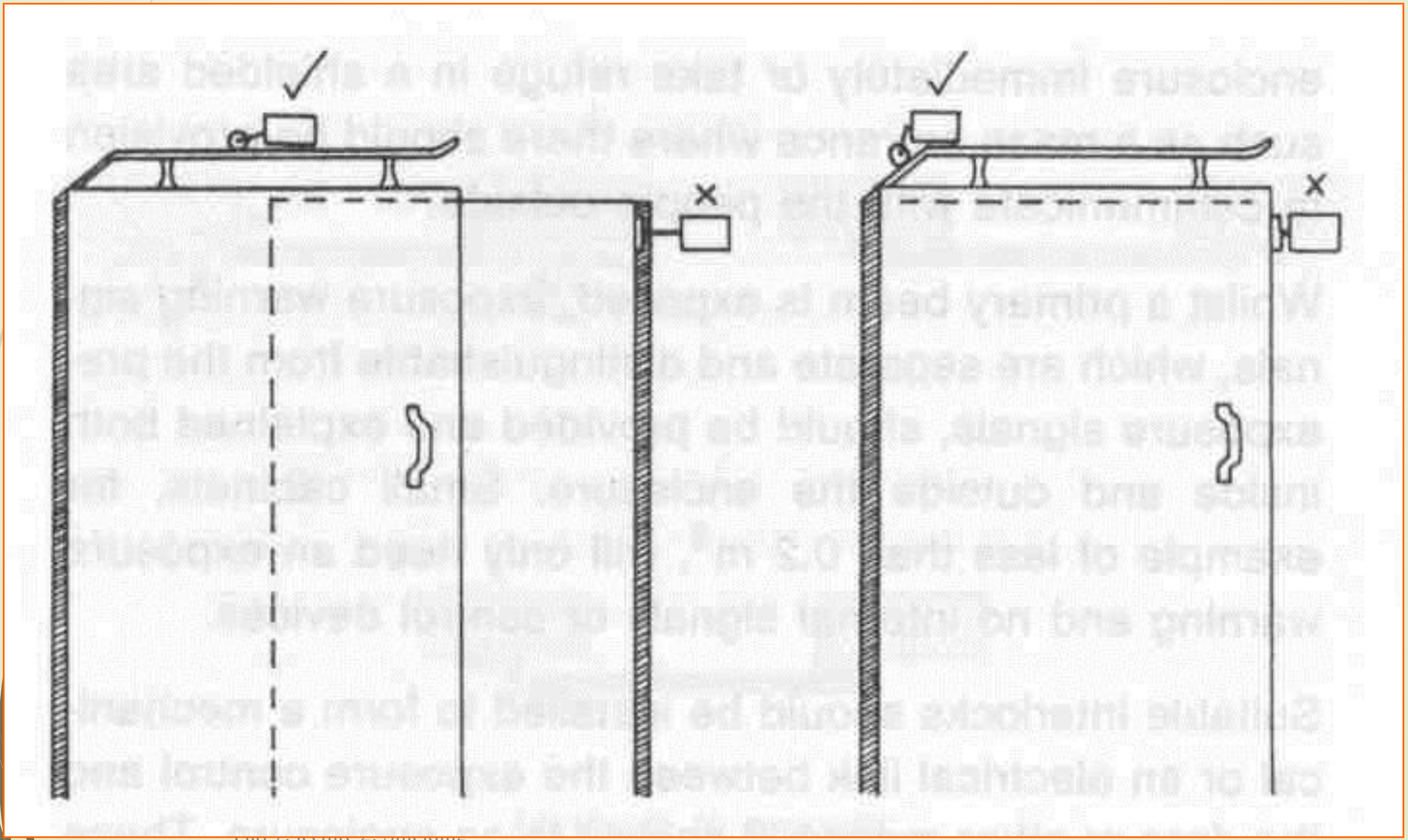
- Accelerators with an energy > 15 MV require considerations for neutron shielding and therefore a special door at the end of the maze.
- These neutron doors typically contain borated paraffin to slow down and capture neutrons
- A steel frame helps to attenuate tertiary photons from (n,gamma) reactions.

Doors



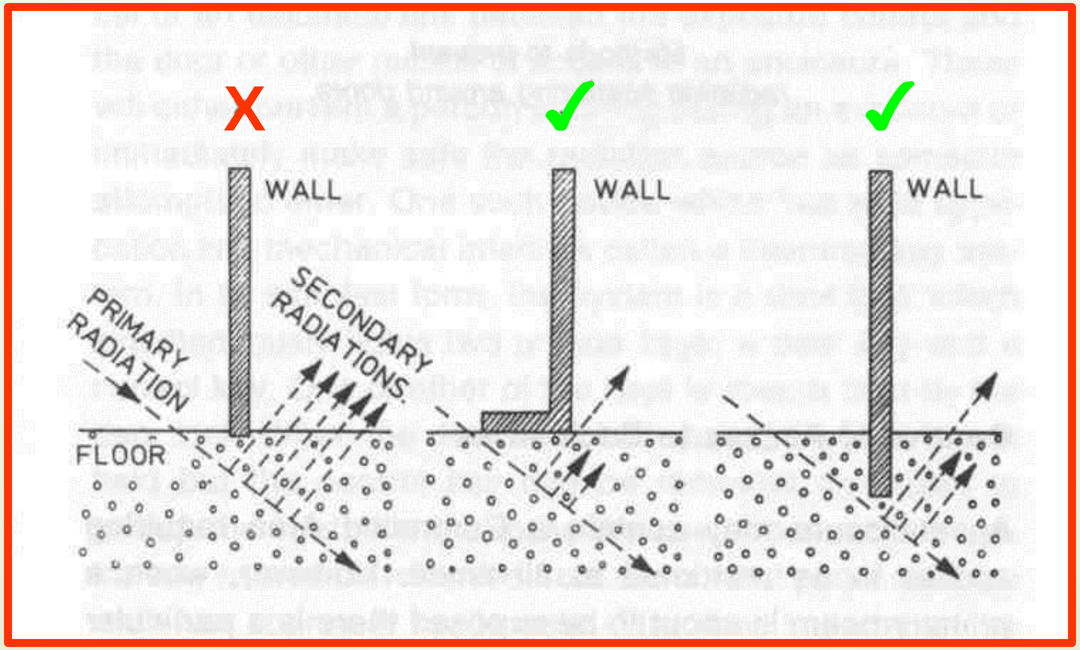
Be aware of leakage radiation

Interlocks



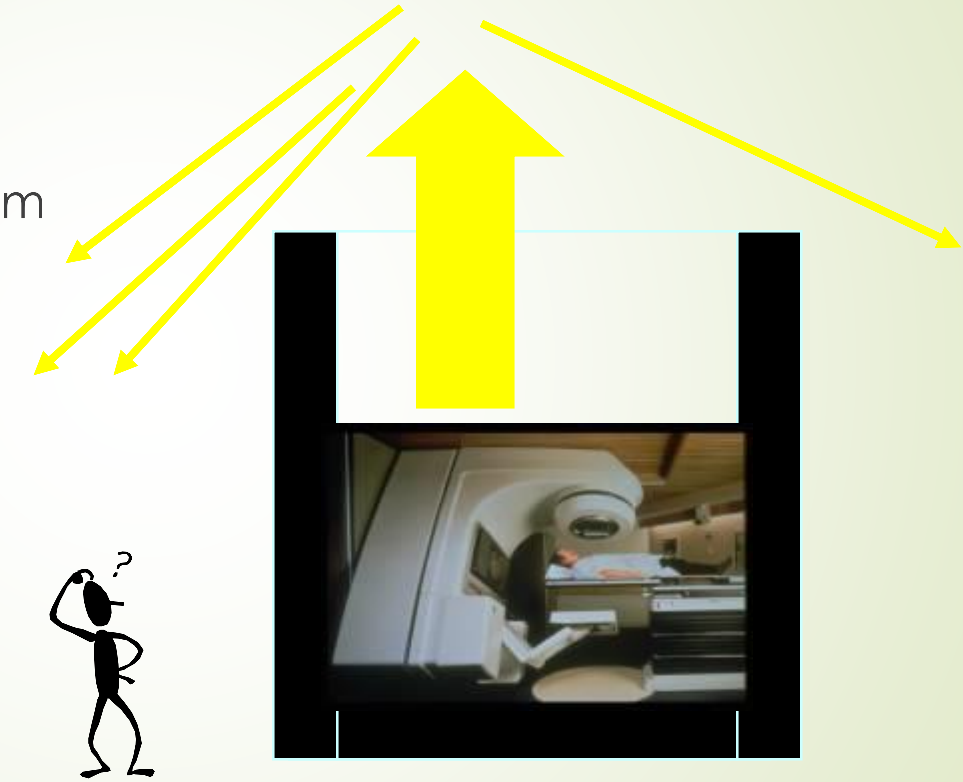
Some final shielding issues:

- When using a shielded wall consider scatter from under the shielding material

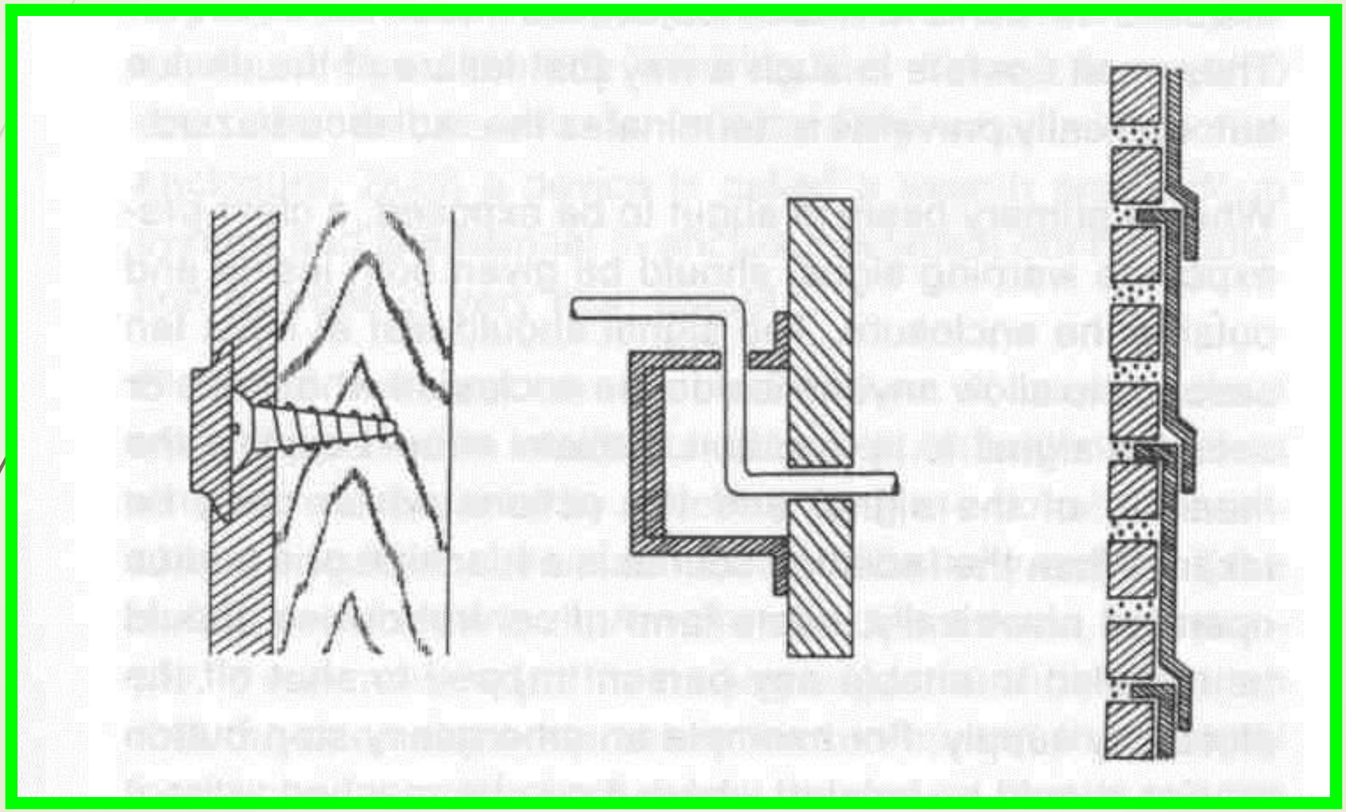


Sky shine ...

- Radiation reflected from the air above an insufficiently shielded room



Cover potential holes



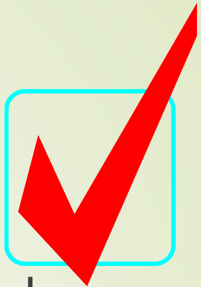
4. Verification and surveys

- It is essential to verify the integrity of the shielding during building (inspections by the RSO) and after installation of the treatment unit (radiation surveys)
- Flaws may not be in the design - they could as well be in the execution
- Assumptions used in the design must be verified and regularly reviewed.

Inspection During Building

- The building contract should specifically allow the Radiation Safety Officer (RSO) to carry out inspections at any time
- The RSO should maintain good communications with the Architect and Builders
- Room layout should be checked PRIOR to the installation of form work or wall frames
- Visual inspection during construction
  - ensures installation complies with specifications
  - may reveal faults in materials or workmanship

Inspection During Building



- Check the thickness of building materials
- Check the overlapping of lead or steel sheet
- Check the thickness of glass and the layout of windows and doors, to ensure that they comply with the specifications
- Examine the shielding behind switch boxes, lock assemblies, cable ducts, lasers etc that might be recessed into the walls
- Verify the dimensions of any lead or steel baffles or barriers
- Take a concrete sample and check its density

Inspection after Building Completion

- Ensure that the shielded areas conform to the plans
- Ensure that all safety and warning devices are correctly installed
- If a megavoltage unit, check that its position and orientation is as shown in the plan. No part of the radiation beam must miss the primary barrier

Radiation Monitors for Safety Survey

- Ionization chamber monitors with air equivalent walls. These have a slow response but are free from 'dead time ' problems
- Geiger counters. These are light and easy to use with a fast response. They should be used with caution with pulsed accelerator beams due to possible significant 'dead time' problems

After Equipment Installation

- Before commissioning check that persons in the control area are safe:
  - scan the control area with the beam in 'worst case' configuration
    - maximum field size
    - maximum energy
    - pointing towards the control area if this is possible
  - check that the dose rates are within the designed limits

After Equipment Installation

- But before commissioning
  - with the field set to maximum and with the maximum energy and dose rate
  - point the beam, with no attenuator present, at the wall being checked
  - scan the primary shields using a logical scan pattern
  - especially concentrate on areas where the plan shows that joints or possible weaknesses may have occurred

After Equipment Installation

- But before commissioning
  - put scattering material in the beam which approximates the size and position of a patient
  - scan the secondary shields with the equipment pointing in typical treatment positions
  - if it is an accelerator room, then scan the maze entrance
  - after allowing for usage and positional factors, determine if the installation conforms to design conditions

After Equipment Installation

- Neutrons
  - if the equipment is an accel
    MV then the radiation scans should include a neutron survey, especially near the entrance to the maze
  - the survey instrument used for neutrons should be of a suitable type. See for example, AAPM report 19

Radiation Survey vs. Monitoring

- Radiation survey is the test that the area is safe for use (in particular the commissioning)
- However, one also needs to make sure that all assumptions (*e.g.* workload) are correct and continue to be so. This process is called monitoring and involves long time radiation measurements.

Regular Area Monitoring

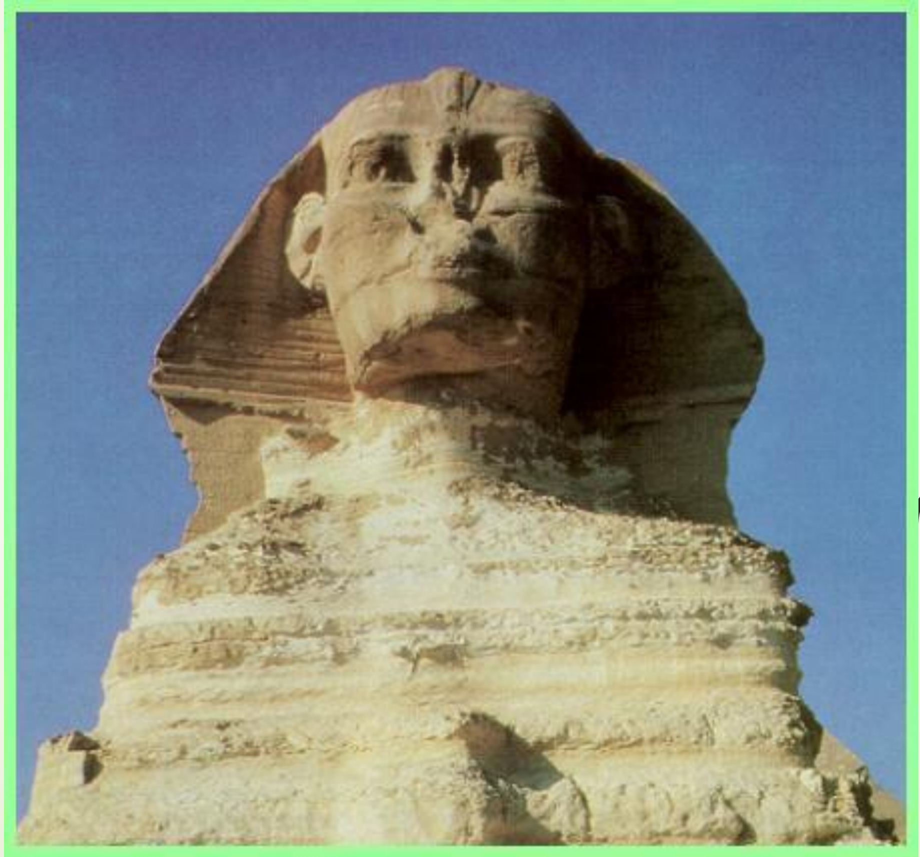
- Confirm the results of the radiation survey
- Radiation areas should be regularly checked in case the shielding integrity has changed
- This is especially important for rooms shielded with lead or steel sheet, as they may have moved and any joins opened up
- An area should be checked after any building works

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

Where to Get More Information

- IAEA TECDOC 1040
- NCRP report 151
- NCRP report 51
- McGinley P. Shielding of Radiotherapy Facilities. Medical Physics Publishing: Madison 1998.



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QUICK TEST

Please give a rough estimate of the required wall thickness of concrete required for a) 192-Ir HDR, b) LDR brachytherapy, c) superficial radiation, d) linac primary beam, e) Cobalt teletherapy scatter and leakage

Very rough estimates using common assumptions:

a) 192-Ir HDR - 70cm

b) LDR brachytherapy - 50cm

c) superficial radiation - 50cm (could be done more efficiently using lead)

d) linac primary beam - 200cm

e) Cob... d leaka...

Please note these are NOT recommended values for any particular installation!

Acknowledgements

- John Drew, Westmead Hospital Sydney