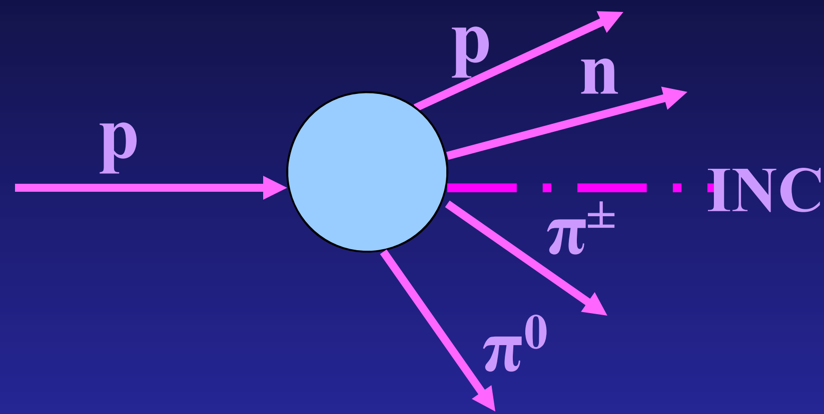
Secondary Radiation Production and Shielding Design for Proton Therapy Facilities



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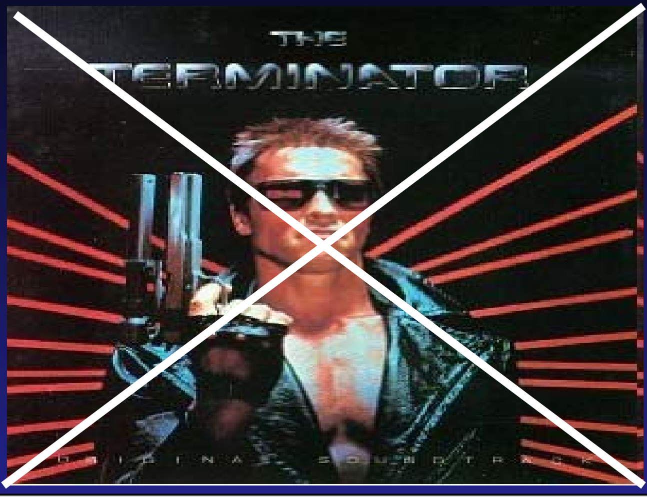
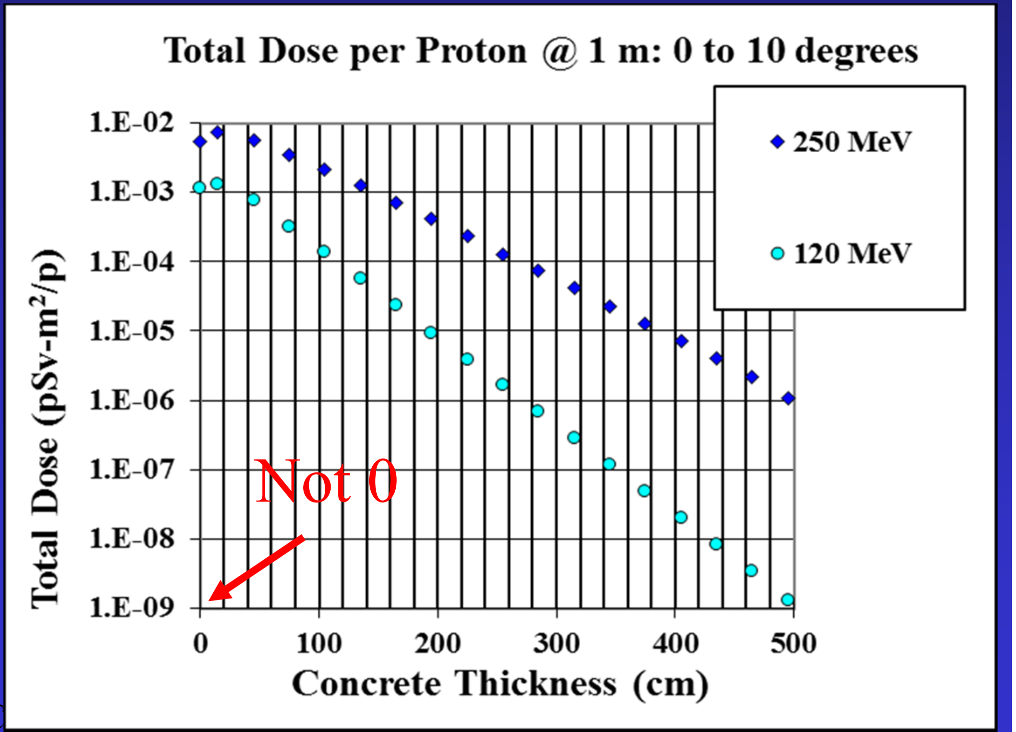
"Doing the right thing, doing it right"

Shielding Design

- **Shielding is NOT the TERMINATOR**
  - Radiation dose outside shielding cannot be made = 0
- **Shielding is the ATTENUATOR**
  - Primary purpose is to attenuate or reduce the radiation dose to levels below some regulatory or design limit <u>UNDER EXPECTED USAGE CONDITIONS</u>
- **Requires understanding of secondary radiation production, beam losses , nuclear and neutron interactions**
- **Knowledge of various other parameters**





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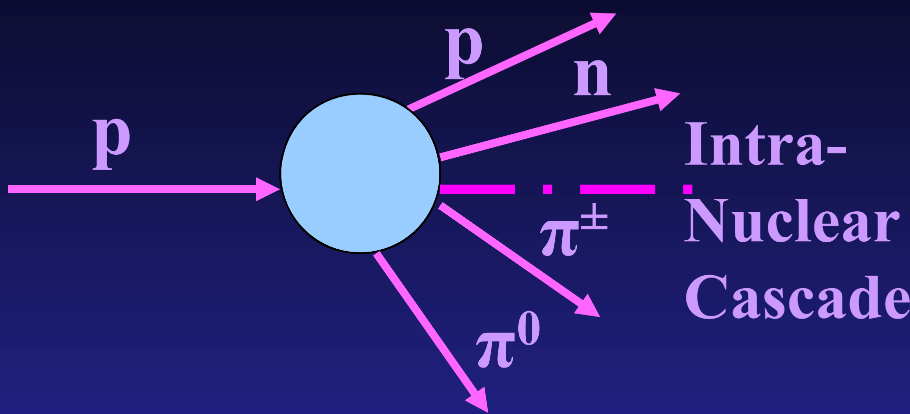
Secondary Radiation

- Produced by interaction of protons with any material
- Consists of:
  - Prompt radiation which is on only when the machine is on
  - Residual radiation from activation which remains even after the machine is turned off
- Produced at locations where there are beam losses or beam interception
  - In synchrotron and cyclotron during injection, acceleration and extraction
  - During energy degradation in cyclotron
  - During beam transport to treatment room
  - In beam-shaping and beam-modifying devices
  - In patient, dosimetric phantom and beam stopper
- Important to understand physics behind secondary radiation production

Physics: Intra-Nuclear Cascade (INC)



- The interaction of protons with matter results in an intra-nuclear cascade
- Important in shielding design for protons in the therapeutic energy range of 67 MeV - 330 MeV
- Similar to a water cascade, there is a succession of stages in an intra-nuclear cascade

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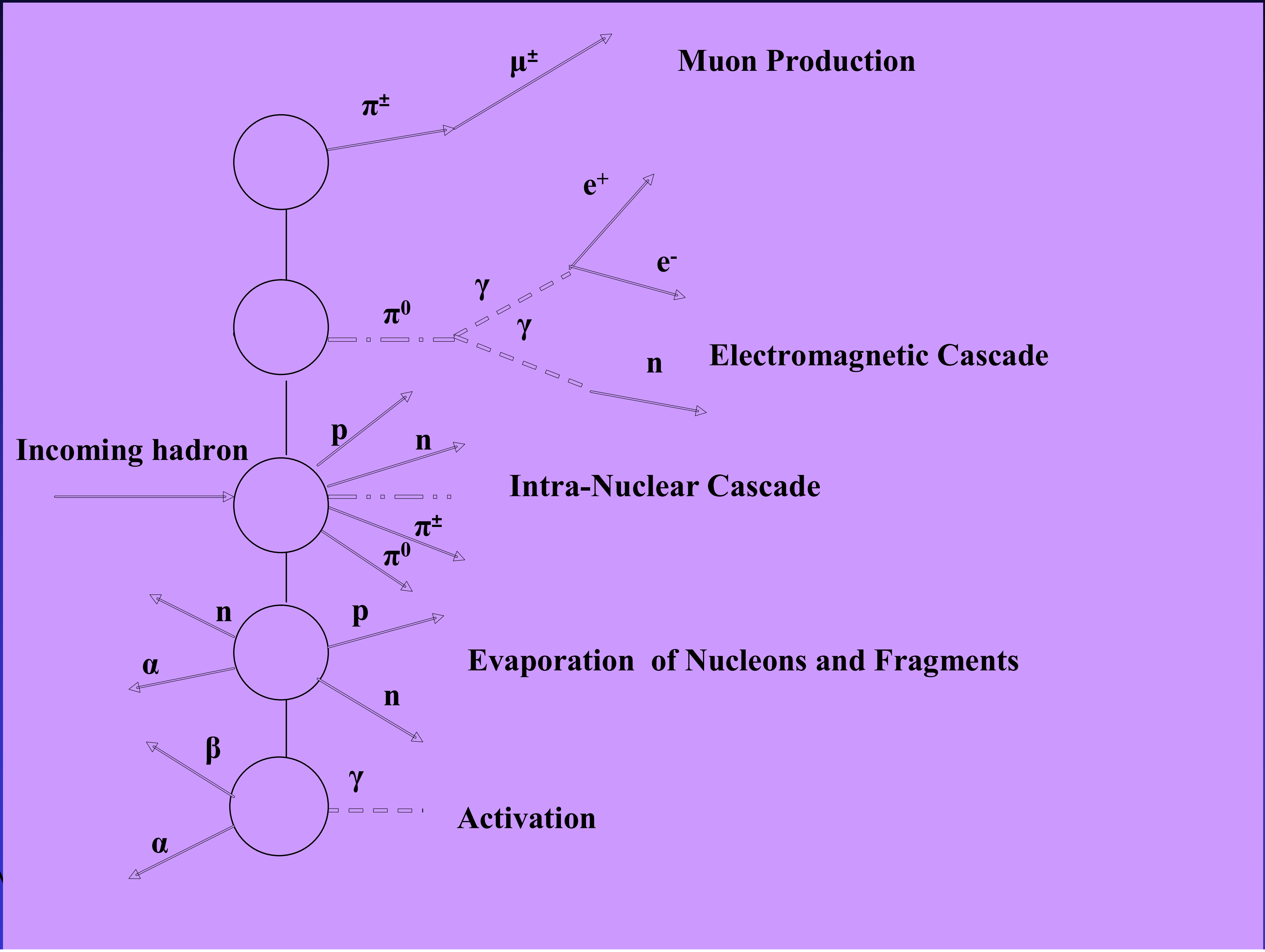
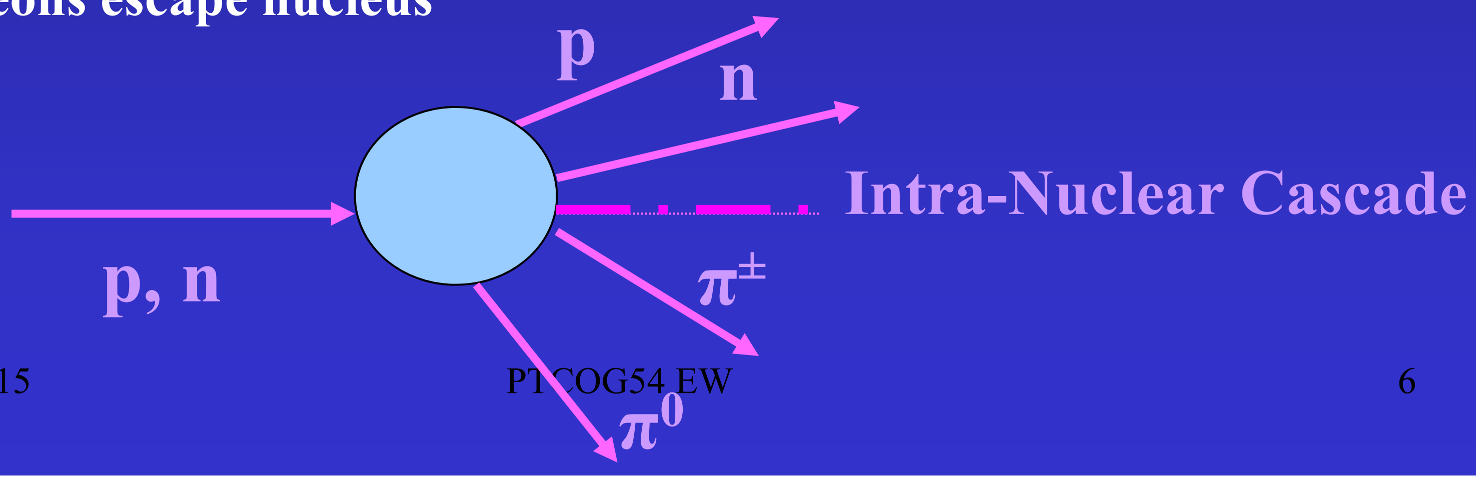
Stages: Intra-Nuclear Cascade



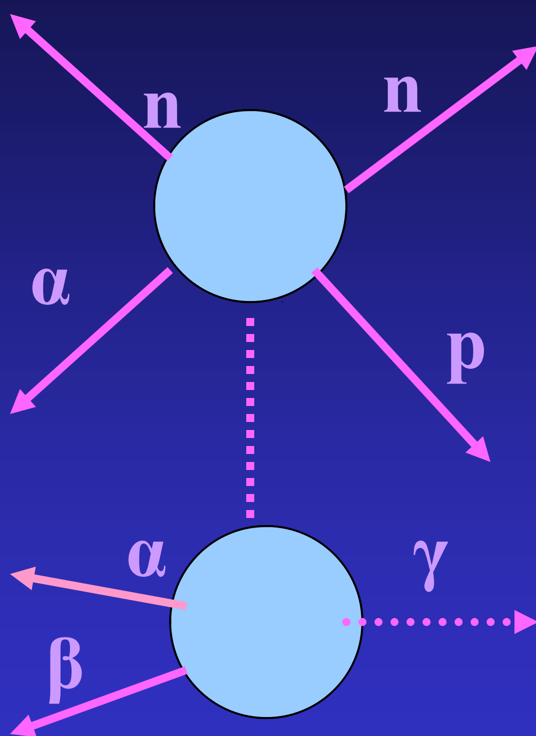
Intra-Nuclear Cascade

- Nucleus consists of nucleons, i.e., protons and neutrons
- Incoming hadron (p, n) interacts with individual nucleons in nucleus, producing a spray of particles
- Pions are produced above ~ 290 MeV
- Scattered and recoiling nucleons proceed through nucleus
- Each nucleon may interact with other nucleons leading to development of cascade
- Some nucleons escape nucleus
- Large fraction of energy is transferred to single nucleon
- This <u>nucleon</u> with E > 150 MeV is <u>forward peaked</u> and propagates the cascade
- Nucleons with energies between 20 and 150 MeV transfer energy by nuclear interactions to several nucleons (< 10 MeV/nucleon)
- Charged particles are quickly stopped by ionization
- Neutrons predominate at low energies



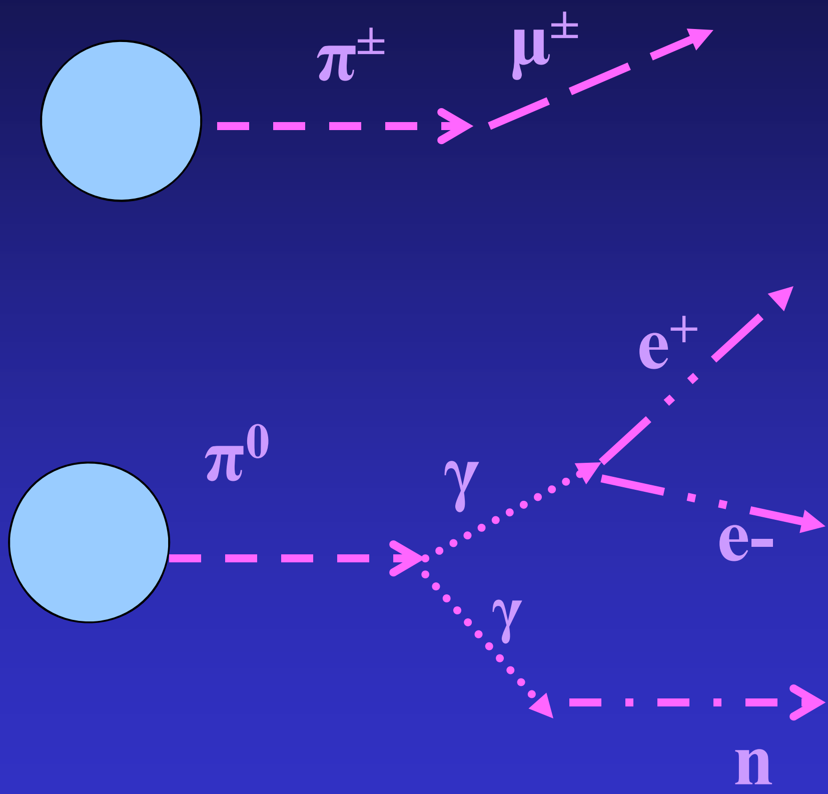
Evaporation and Activation

- Energy of nucleons that do not escape nucleus is distributed among remaining nucleons
- Some nucleons with considerable energy ("pre-compound") may be ejected
- Original nucleus is left in an excited state and de-excites by emitting "evaporation nucleons", alphas and fragments
- Low-energy charged particles deposit energy locally



- Evaporation nucleons are emitted isotropically
- Energy of evaporation neutrons extends to 8 MeV
- Neutrons travel long distances depositing energy continuously
- Remaining excitation energy emitted as gammas
- De-excited nucleus may be radioactive (activation)

Muons and Electromagnetic Cascade

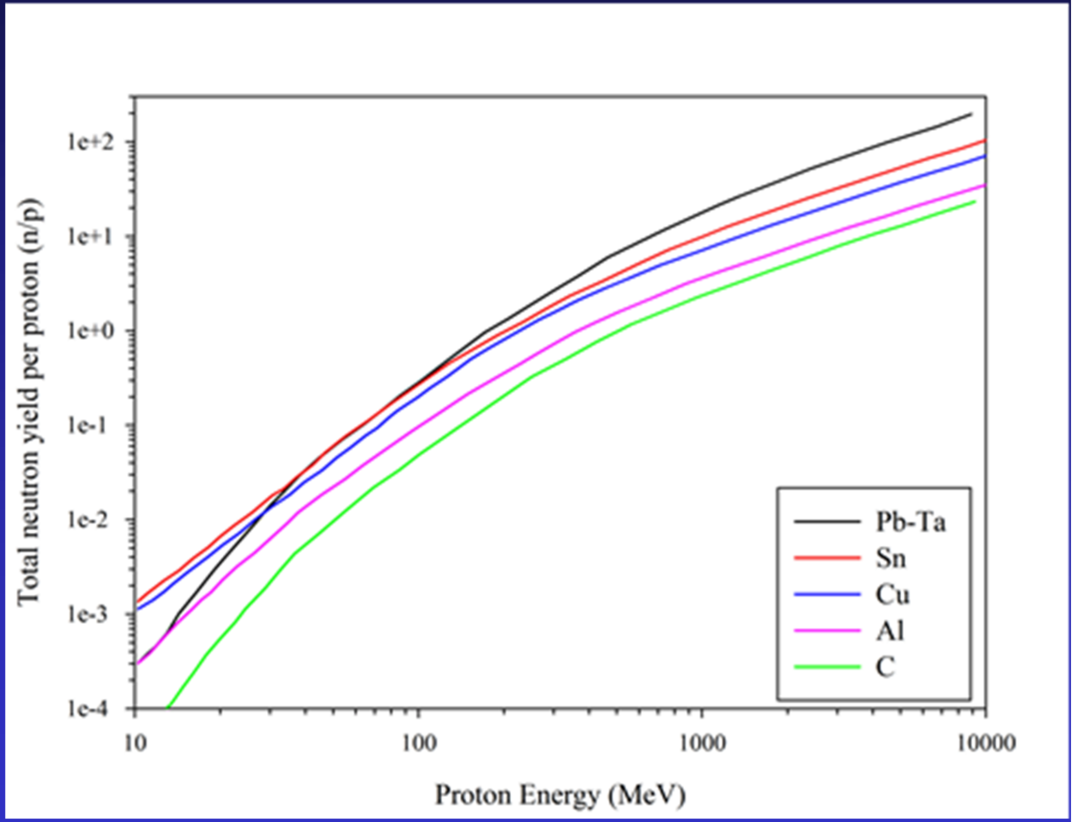


- Charged pions decay to muons
- Muons are penetrating particles and deposit energy by ionization; photonuclear reactions also possible
- Neutral pions decay to gammas which initiate electromagnetic (EM) cascades
- EM cascades do not contribute significantly to energy transport
- Protons and pions (E < 450 MeV) have a high rate of energy loss
- Neutrons are principal propagators of cascade with increasing depth in shielding

- Neutron yield = n/p
- Depends upon proton energy, target material and dimensions
- Thick target: Has thickness > proton range; yield is proportional to E_p^2 between 50 and 500 MeV
- Thin target: Has thickness <<< proton range; yield is proportional to target thickness; harder spectrum
- For shielding calculations, angular and energy distribution are more important than total yield!

Neutron Yields from Thick Targets for Various Materials*

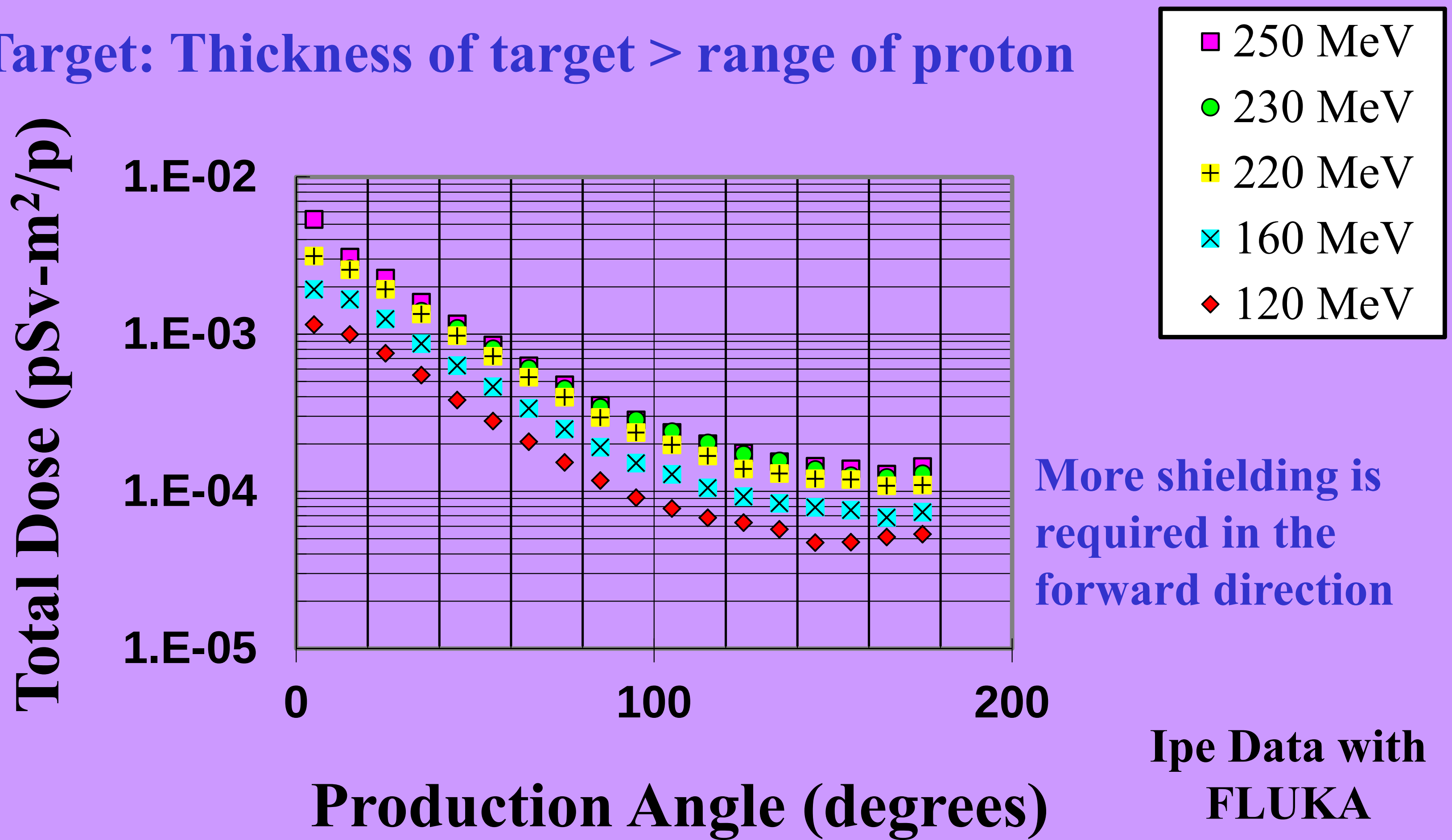
*except at highest energies



Tesch K. Radiat Prot Dosim1985;11(3):165–72

Angular Dose Profiles from Unshielded Thick Tissue Targets For Various Proton Energies

Thick Target: Thickness of target > range of proton

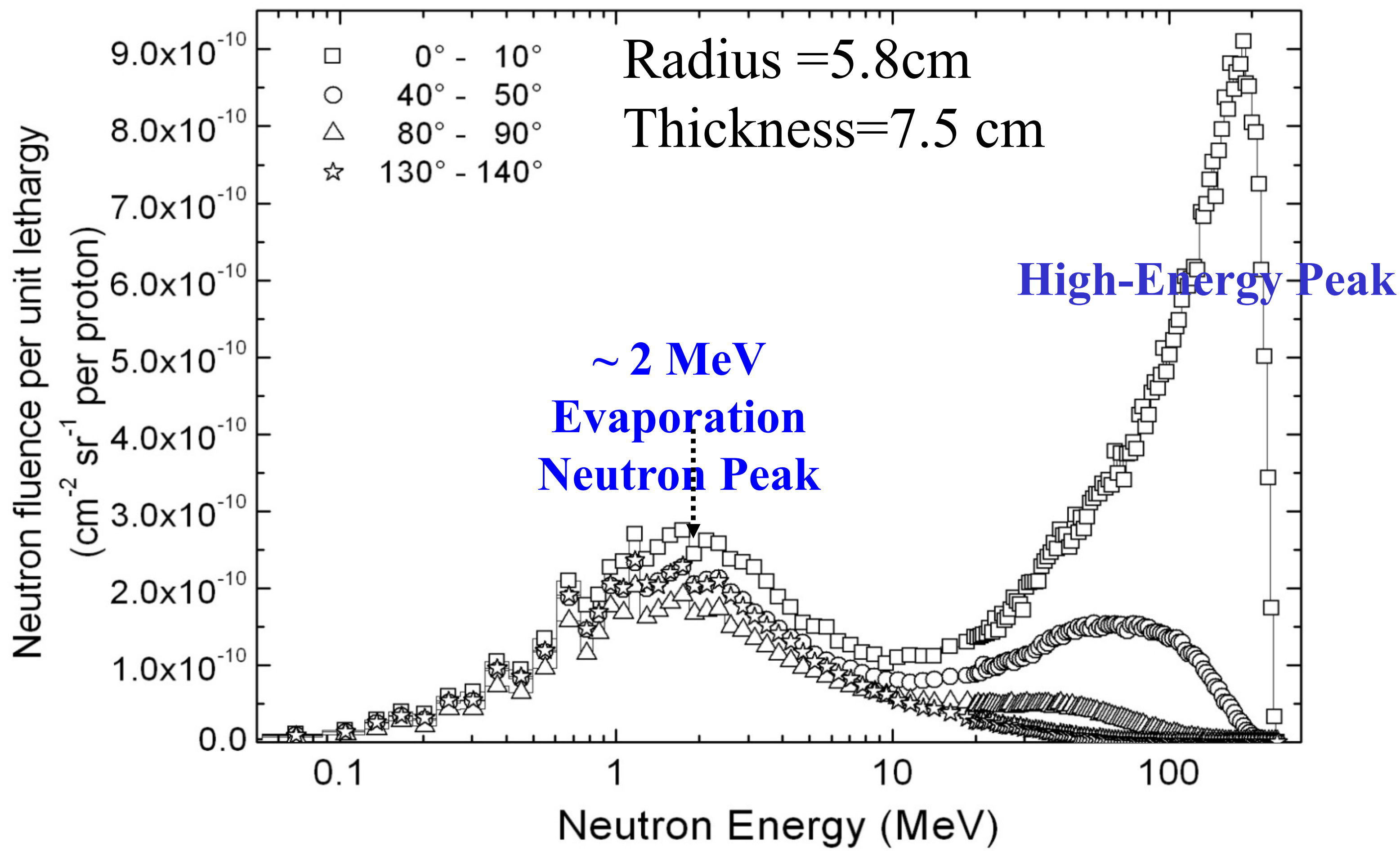


More shielding is required in the forward direction

Ipe Data with FLUKA

$1\ \text{pSv} = 10^{-12}\ \text{Sv}$

Unshielded Neutron Spectra at Various Production Angles for 250 MeV Protons Incident on Thick Iron Target (FLUKA)



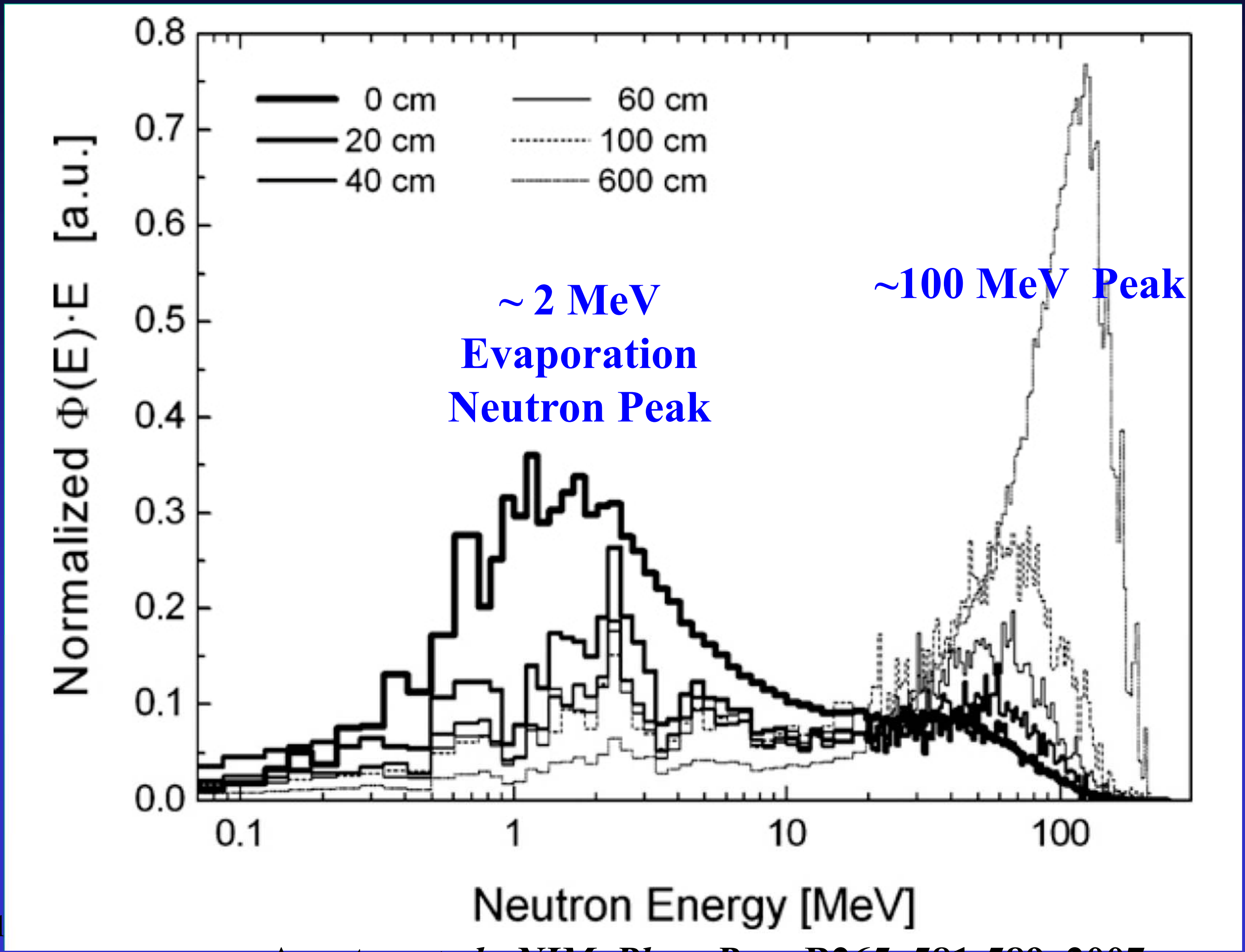
Agosteo *et al.*, *NIM Phys. Res.* B265, 581-589. 2007

Characteristics of Shielded Neutron Field

- High-energy cascade neutrons propagate cascade in shield
- Continuously regenerate lower-energy neutrons and charged particles at all depths in the shield via inelastic reactions
- Yield of lower-energy (and high-energy) neutrons increases as proton energy increases
- Greater yield of lower-energy neutrons is more than compensated for by greater attenuation in shield, because of higher cross-sections at lower neutron energies
- Eventually, radiation field reaches equilibrium condition beyond a few mean free paths (MFP) within shield
- Deep within shield, high-energy neutrons (E_n > 150 MeV) regenerate cascade; they are few in number, but, are accompanied by numerous low-energy neutrons
- Typical neutron spectrum observed outside a thick shield consists of peaks at ~ 2 MeV and at ~ 100 MeV

MFP = average distance between two consecutive interactions

Normalized Neutron Spectra in Transverse Direction at Various Concrete Depths, for 250 MeV Protons Incident on Thick Iron Target



Agosteo *et al.*, *NIM Phys. Res.* B265, 581-589. 2007

Neutron Energy Classification and Interactions

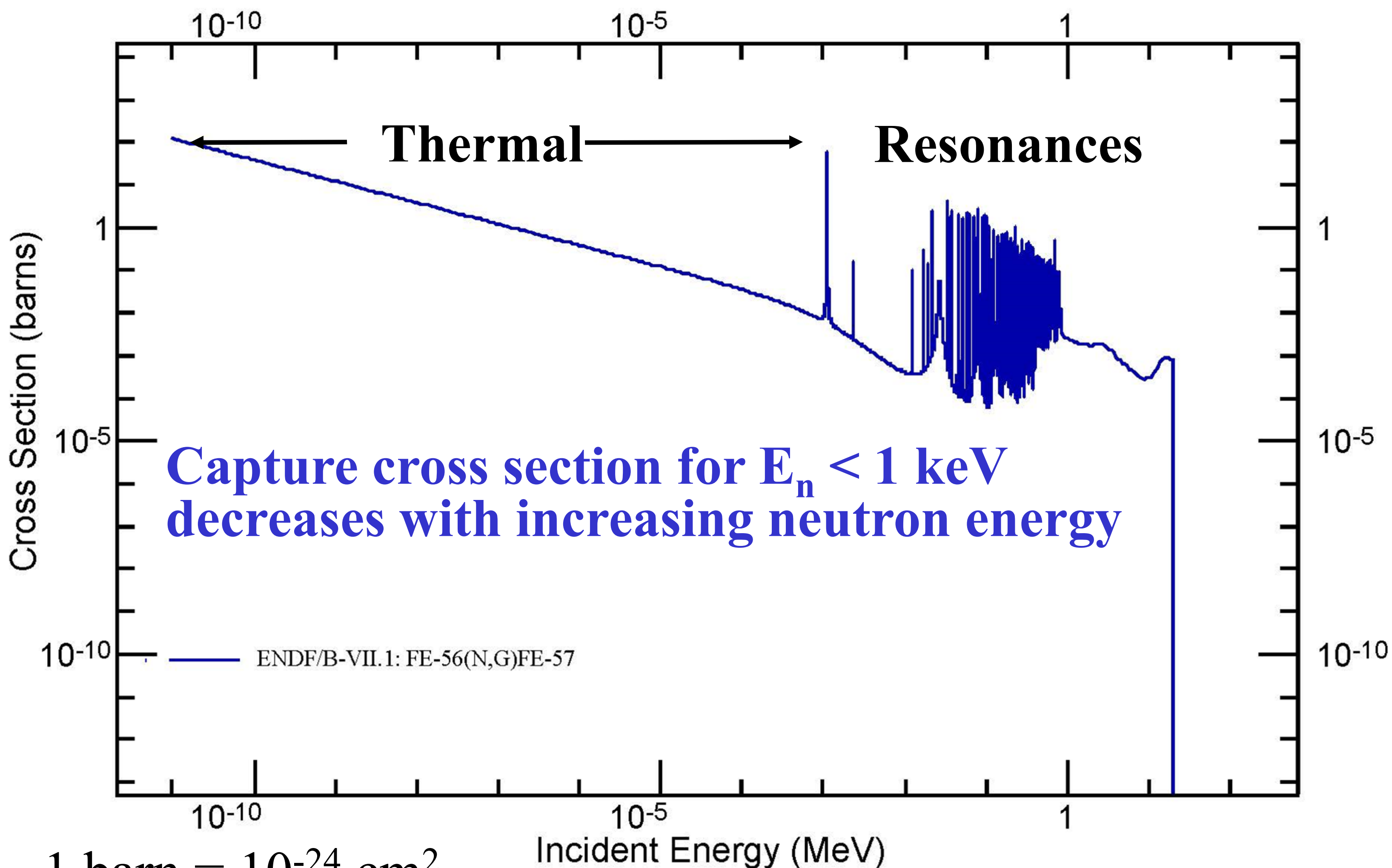
- Thermal: $\bar{E}_n = 0.025$ eV at 20ºC
  Typically $E_n \leq 0.5$ eV
- Intermediate : 0.5 eV $< E_n \leq 10$ keV
- Fast: 10 keV $< E_n \leq 20$ MeV
  - Include evaporation neutrons
- Relativistic $E_n > 20$ MeV
  - Include cascade neutrons

For $E_n < 20$ MeV, nearly all interactions are elastic or inelastic scatters

Absorption is important at thermal energies and at a few resonances in keV region

Resonances are peaks in the cross section which occur at energies where reactions with nuclei are enhanced

Absorption Cross Section for $^{56}Fe(n,\gamma)^{57}Fe$

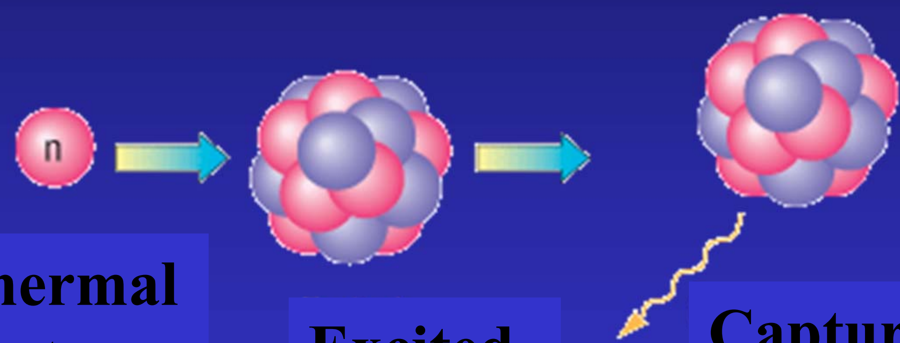


1 barn = 10^{-24} cm^2

Thermal Neutron Capture

- Thermal neutrons gain and lose only small amounts of energy through elastic scatter
- They diffuse about and are captured by the nucleus
- Excited nucleus emits capture gamma rays
- Energy of capture gamma from hydrogen is 2.22 MeV (polyethylene, concrete)
- Energy of capture gamma from boron is 0.478 MeV (borated polyethylene)
- Boron capture cross-section is ~10,000 x higher than hydrogen cross-section

Borated polyethylene is used instead of polyethylene for shielding maze doors



Thermal neutron

Excited Nucleus

Capture Gamma Ray

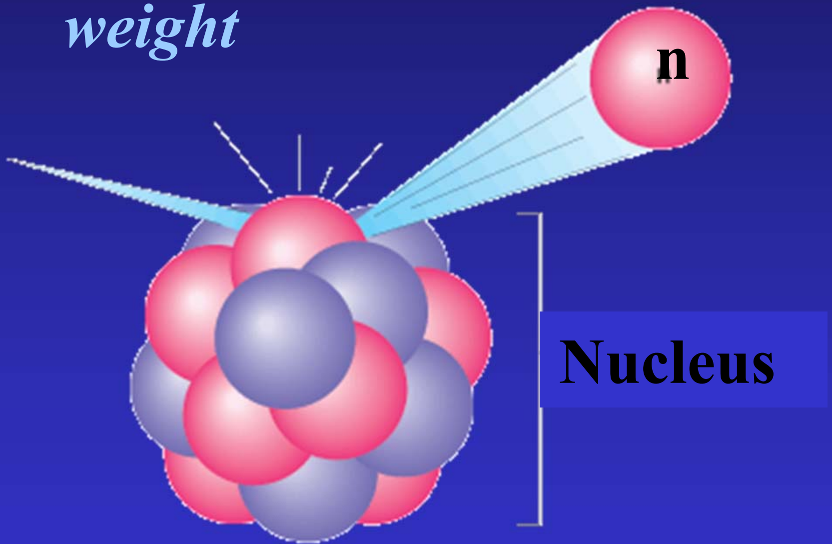
http://www.glossary.oilfield.slb.com/Display.cfm?Term=inelastic%20neutron%20scattering

Elastic Scatter

- Kinetic energy and momentum are conserved
- Fast neutrons lose energy by elastic scatter and become thermal neutrons
- Interaction with hydrogen is like a billiard ball collision
- Primary process of energy loss below 1 MeV in hydrogenous materials (concrete, polyethylene, etc.)
- Dominant interaction below 10 MeV for all materials

Hydrogenous materials are most effective for fast neutron shielding

Water content of concrete should be at least 5.5% by weight



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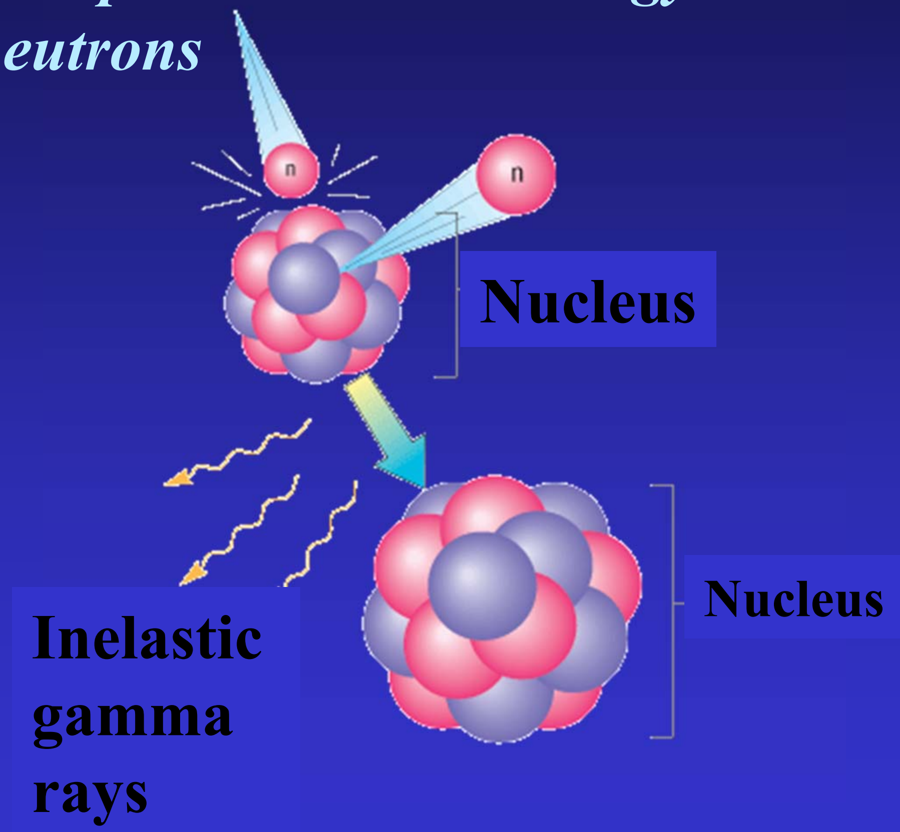
Inelastic Scatter (n, n/)

- Kinetic energy is not conserved
- Occurs only above lowest excited state in material (847 keV in ^{56}Fe)
- Nucleus absorbs energy and is left in an excited state
- De-excites emitting gamma rays
- Is dominant process above 10 MeV in all materials
- In high-Z materials, inelastic scattering reduces neutron energy, thus making hydrogenous material that follows more effective

Lead or steel must always be followed by a hydrogenous material because high-Z materials are transparent to lower energy neutrons

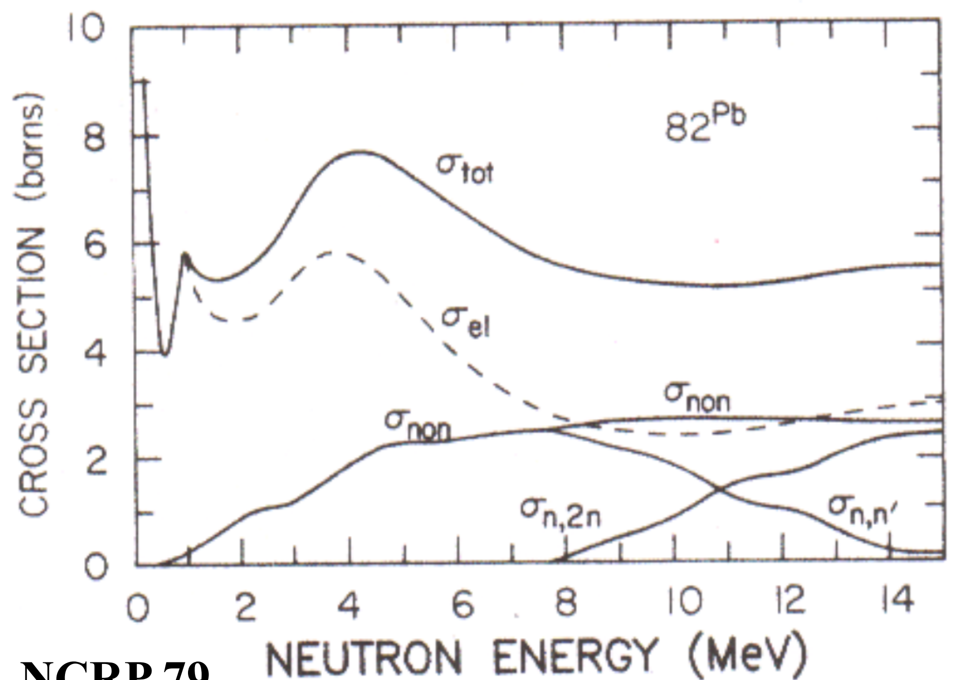


http://www.glossary.oilfield.slb.com/Display.cfm?Term=inelastic%20neutron%20scattering

Fast Neutron Interactions

- Neutrons can also be absorbed or captured in various reactions: (n, 2n), (n, p), (n, α) or (n, γ)
- Non-elastic cross-section is sum of inelastic (n, n') and (n, 2n) cross-sections for $E_n < 20$ MeV
- Inelastic reactions dominate at lower energies
- (n, 2n) reactions dominate at higher energies
- (n, 2n) reaction produces large number of lower-energy neutrons

Cross-Sections in Lead

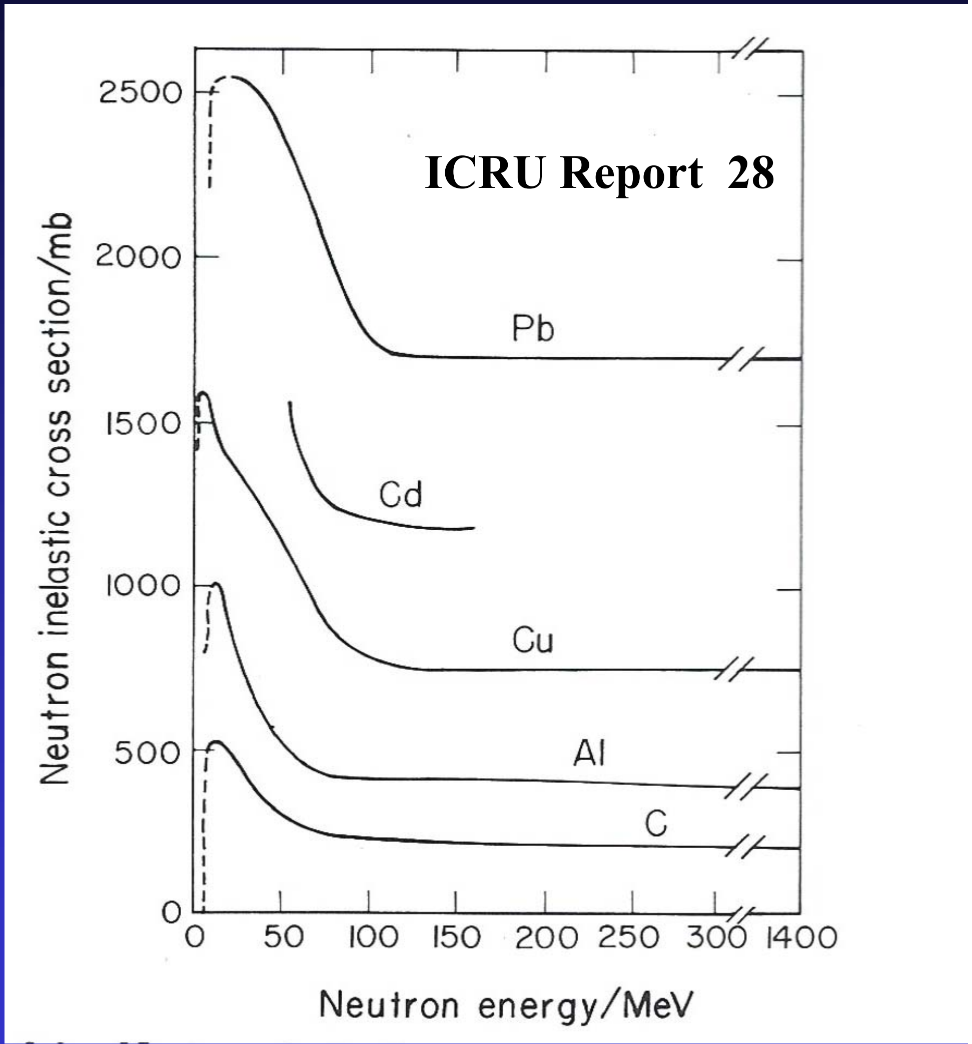


NCRP 79

1 barn = 10^{-24} cm^2

Neutron Inelastic Cross Sections for Various Materials

- **Inelastic cross sections increase with increasing mass number, A**
- **Cross sections decrease with increasing energy to a constant value above ~ 150 MeV**
- **Neutrons with E_n > 150 MeV will control radiation environment for E_p > 150 MeV**



Relativistic Neutron Interactions

- Relativistic neutrons (E_n > 20 MeV) arise from cascade processes in proton accelerators
- Neutrons with E_n > 150 MeV
  - Propagate cascade through shielding
  - Continuously regenerate lower-energy neutrons and charged particles at all depths via inelastic reactions
  - Low-energy neutrons undergo capture reactions resulting in production of capture gamma rays

Relativistic Neutron Interactions

- Neutrons (50 MeV < E_n <150 MeV)
  - Intra-nuclear cascade
  - Evaporation nucleons
  - Activation
- Neutrons (20 MeV < $E_n \leq$ 50 MeV)
  - Evaporation nucleons
  - Activation (not included in this talk)
    - Air, water, shielding material and beam line components can become radioactive
    - Cooling water in the vaults should be confined to a self-contained loop

Calculation Methods

1. Monte Carlo (MC) Codes

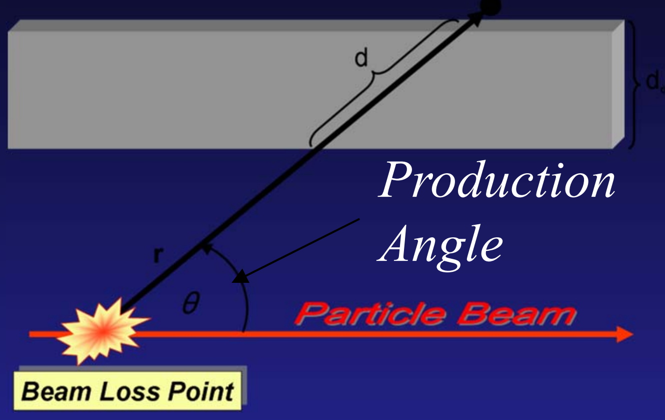
- Various MC codes are available for shielding calculations
- FLUKA and MCNP are well benchmarked and widely used
- Full computer simulation modeling accelerator, beam line and room geometry can be performed
- Requires use of <u>site-specific composition and density of shielding materials</u>
- <u>Total dose from all particles</u> should be calculated
- Should be used for maze and penetration-scatter calculations
- Be careful in using codes that only transport neutral particles; or that allow user to arbitrarily choose physics models
- Full MC simulations for specific room design are time consuming and not very cost effective during schematic design phase for determining structural shielding

Calculation Methods

2. Analytical Methods

- Most models are line-of-sight and assume point source
- Limited to transverse shielding and simple geometries
- Do not account for changes in production angle, target material/dimensions, shielding material, density and composition, etc.

PTCOG Report 1



$$H = \frac{H_0}{r^2} \exp\left[-\frac{d}{\lambda}\right]$$

H = dose at point of interest

H_0 = dose at 1 m from source

d = slant thickness

r = slant distance to shield

λ = attenuation length

Attenuation Length

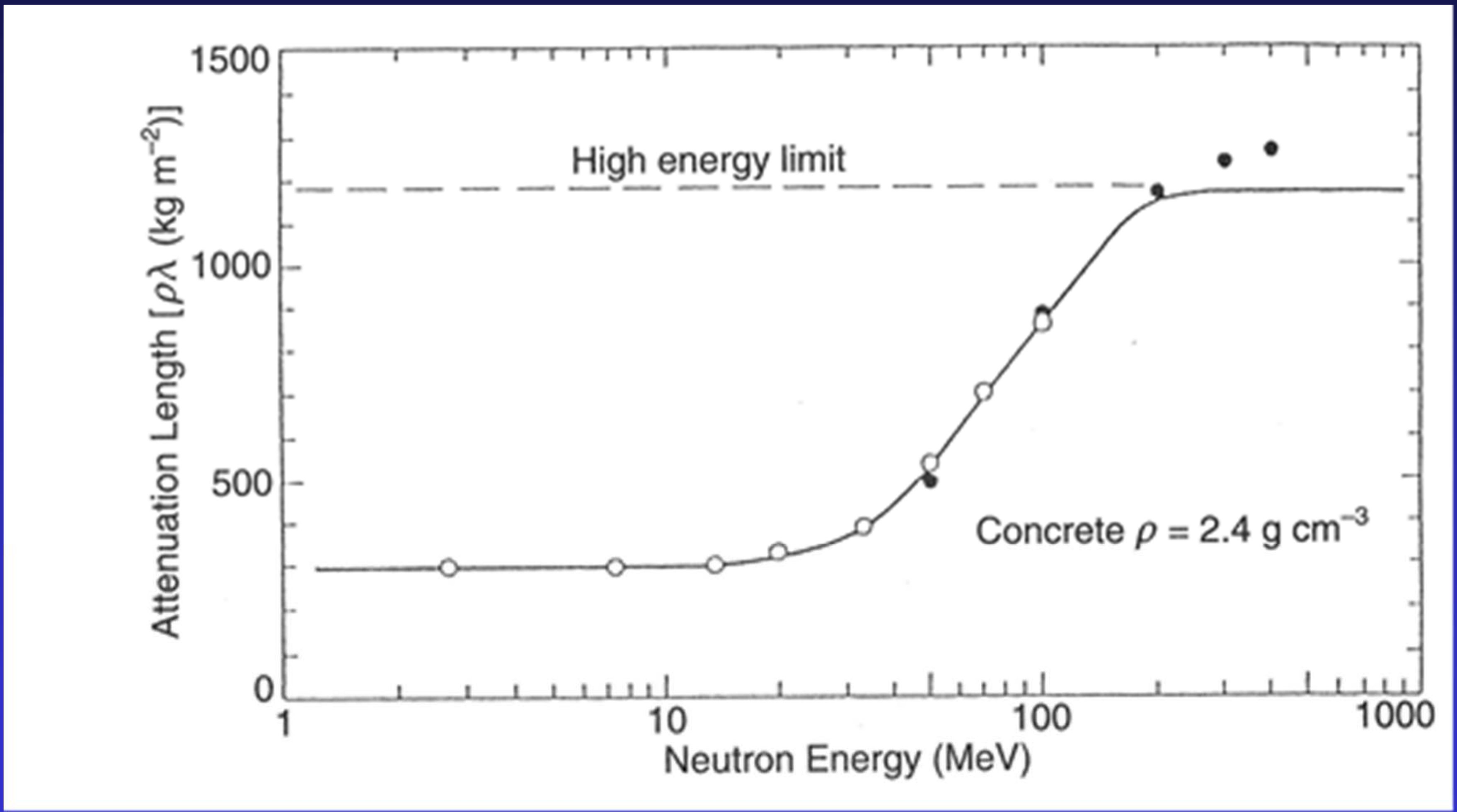
- **Radiation transmission is approximated by an exponential function over a limited range of shielding thickness**
- **Attenuation length is distance travelled through which radiation dose is reduced to 37% (1/e) of its original value.**
- **Neutron attenuation length, λ, is given by:**

$$\lambda = \frac{1}{\Sigma} cm$$

where Σ is the total neutron macroscopic cross section

- **It changes with depth as spectrum changes and eventually reaches an equilibrium value known as effective attenuation length**
- **Depends upon neutron energy, production angle, composition and density of shielding material**
- **Measured in cm or g /cm^2 (when multiplied by density)**

Attenuation Lengths for Monoenergetic Neutrons Normally Incident on Concrete (NCRP 144)



Shielding Calculations

3. Computational Models

- Hybrid approach
  - Monte Carlo and Analytical Methods
- Site-specific source terms and attenuation lengths that are independent of geometry are derived using Monte Carlo
- Various site-specific parameters are considered
  - Particle energy, production angle, target material/dimensions, shielding material, composition and density
- They are particularly useful during schematic design phase
  - Facility layout undergoes several iterations
  - They are faster than Monte Carlo calculations
- *Published source terms/attenuation lengths should not be used since they assume thick targets; and theoretical concrete composition/density*

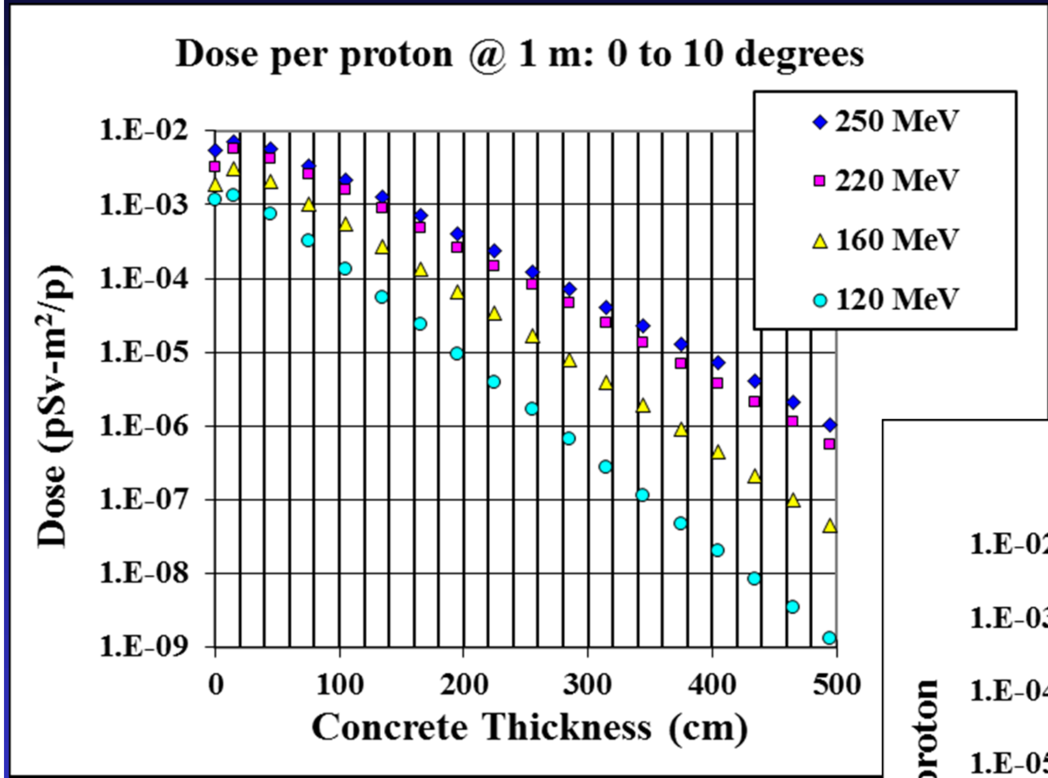
$$\frac{H_0(E_p,\theta)}{r^2}\exp\left[-\frac{d}{\lambda_\theta g(\theta)}\right]$$

Computational Models

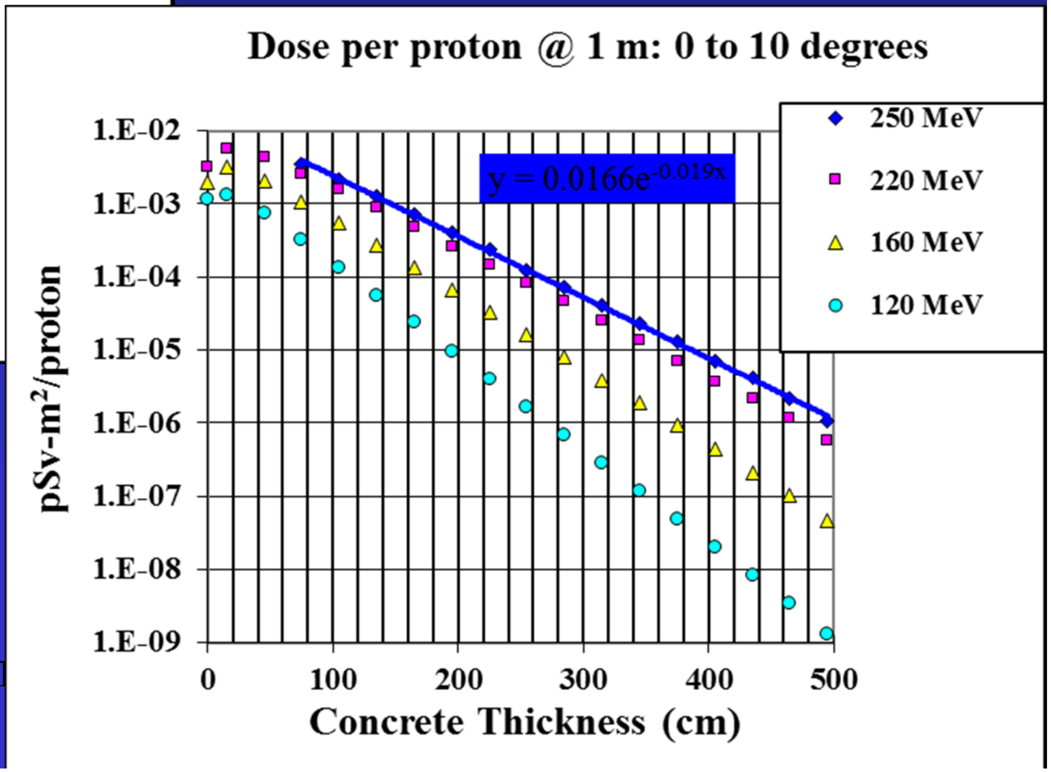
$$H(E_p, \theta, d/\lambda(\theta)) = \frac{H_0(E_p,\theta)}{r^2}\exp\left[-\frac{d}{\lambda_\theta g(\theta)}\right]$$

Where:
H is the dose equivalent at the outside the shield,
H_0 is source term at an angle θ with respect to the incident beam, and is assumed to be geometry independent
r is the distance between the target and the point at which the dose equivalent is scored,
d is the thickness of the shield
d/g(θ) is the slant thickness of the shield at an angle θ
λ(θ) is the attenuation length at an angle θ
g(θ) is cosθ for forward shielding
g(θ) is sinθ for lateral shielding
g(θ) = 1 for spherical geometry

Dose Attenuation in Forward Direction for Protons Incident on Tissue (Ipe Data: FLUKA)



H_0 = 0.0166 pSv-m2/p
$\lambda = 1/(0.019) = 52$ cm



Shielding is the attenuator!

Shielding Design Considerations

- **Treatment and Beam Parameters**
  - **Beam shaping and delivery *(scanning vs. scattering, etc.)***
  - **Energy per fraction**
  - **Dose delivered per fraction**
  - **Current at each energy to deliver a certain dose rate**
  - **No. of patients/year**
  - **No. of fractions/patient at each energy**
  - **Beam-on time**
  - **Beam/field size**
  - **Beam losses and locations**
  - **Target materials and dimensions**

Parameters are site-specific

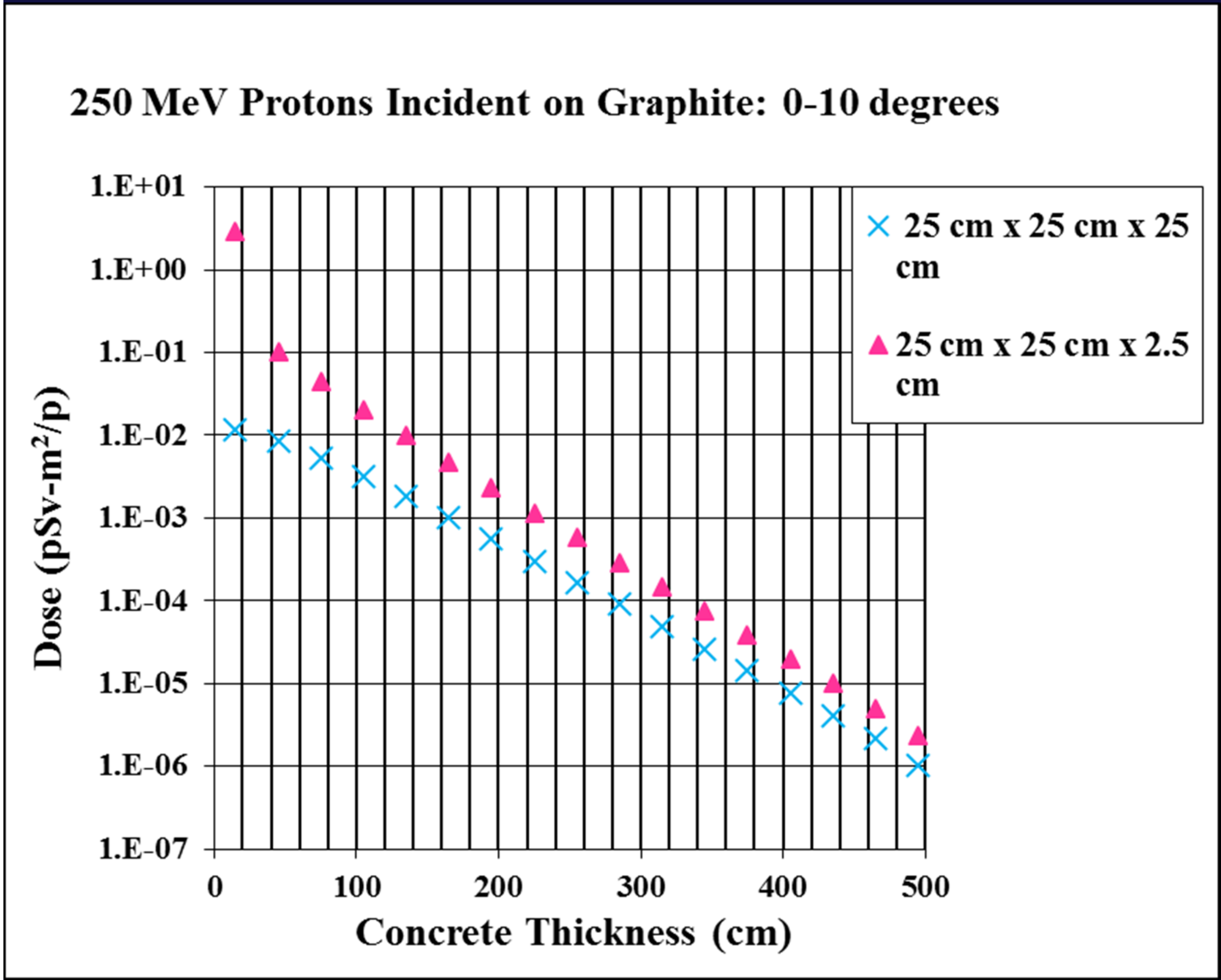
Typical Beam Currents Required for Dose Rate of 2 Gy/min in Water Target (1 liter) for Various Beam Delivery Techniques (With permission from IBA)

	Passive Scattering (PS)			Uniform Scanning (US)			Pencil Beam Scanning (PBS)		
Distal Energy (MeV)	Icyclo (nA)	Inozzle (nA)	Loss (nA)	Icyclo (nA)	Inozzle (nA)	Loss (nA)	Icyclo (nA)	Inozzle (nA)	Loss (nA)
160	130	11	119	22.5	2.6	19.6	17.36	0.493	16.87

Currents and current loss higher for PS compared to US and PBS

More secondary radiation production for PS compared to US and PBS

Effect of Target Thickness on Dose Attenuation in Forward Direction (Ipe Data: FLUKA)



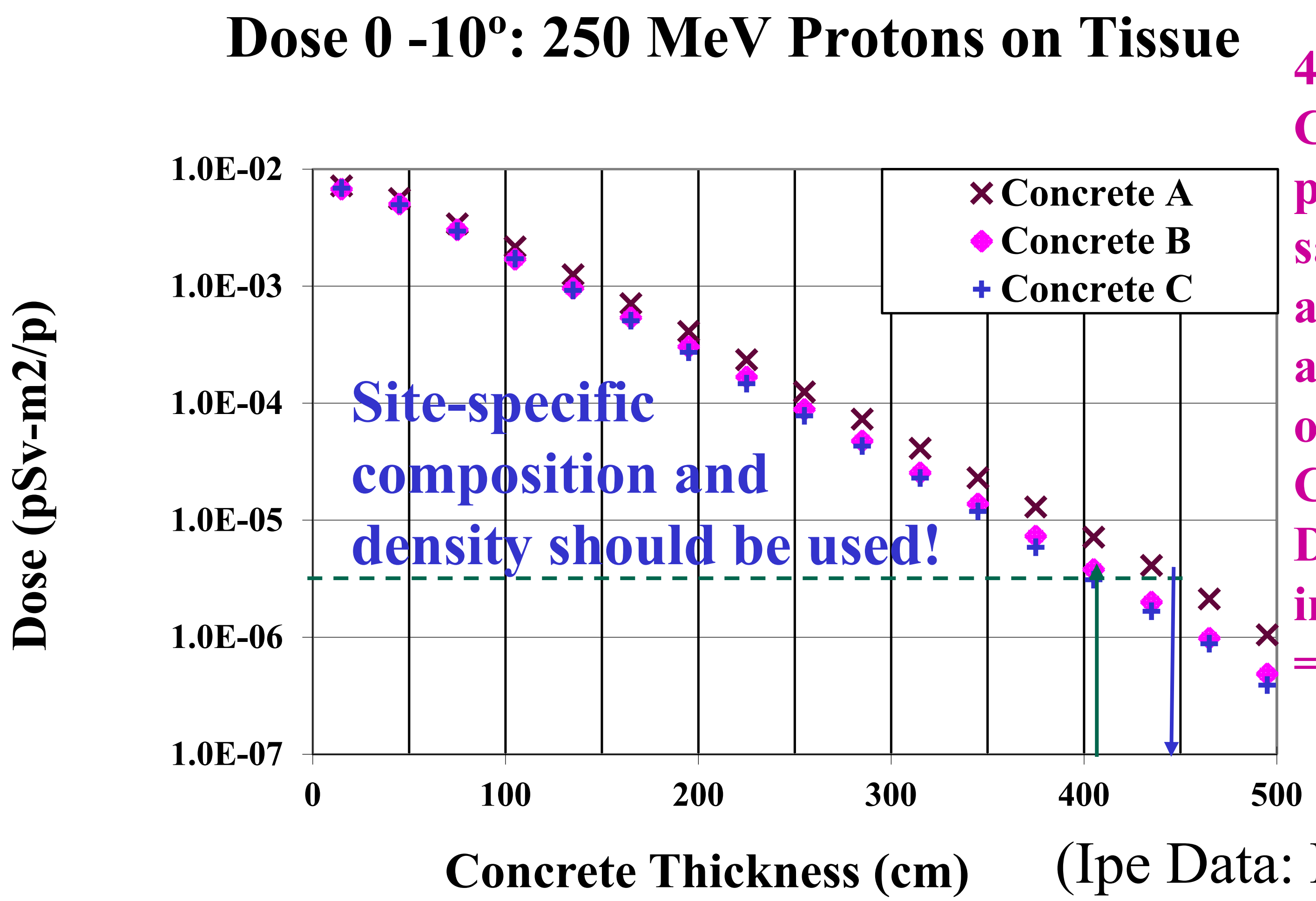
- Use of thick targets is <u>not</u> conservative in the forward direction
- Actual target thickness should be used

Shielding Design Considerations

- **Accelerator Type**
  - Synchrotron
  - Cyclotron
- **Shielding Material**
  - Composition
  - Density
  - Water content
- **Facility Layout**
  - Adjacent occupancies
  - Type of Area (Controlled, Public, etc.)
  - Above ground, underground..
- **Country/State Specific Regulatory Dose Limits**

Shielding design is site dependent!

Dose Attenuation of Concretes with Different Compositions but Same Density



448 cm of Concrete A provides same dose attenuation as 405 cm of Concrete C

Difference in thickness = 43 cm!

(Ipe Data: FLUKA)

Variation in Shielding Thicknesses For Different Proton Facilities (PTCOG Report 1)

Shielding thicknesses vary for three proton facilities with different machines, usage assumptions, regulatory limits and shielding materials

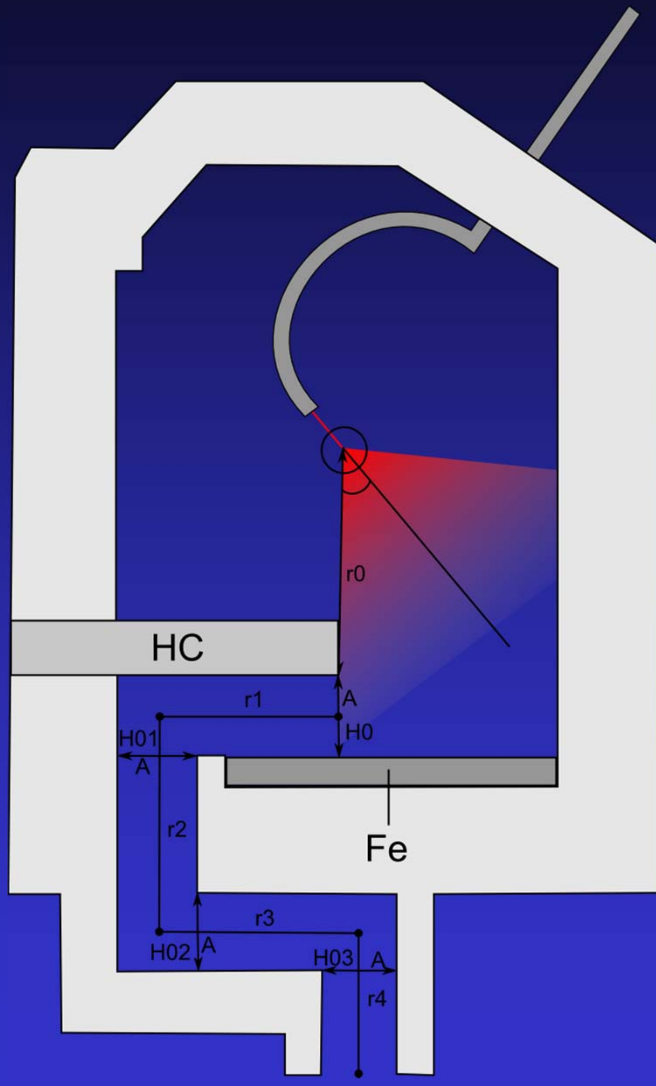
NCC, Korea: IBA 230 MeV Cyclotron

Loma Linda, CA: Optivus 250 MeV Synchrotron

Rinecker, Germany: Varian 250 MeV Cyclotron

Mazes

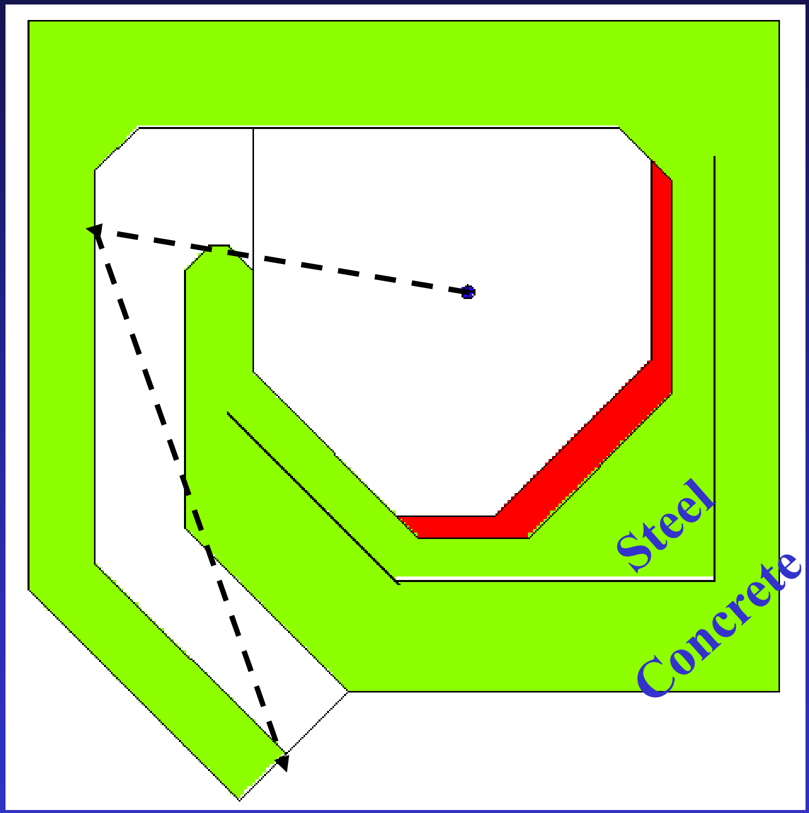
- Radiation at maze entrance consists of neutrons that scatter through the maze; and neutron capture gamma rays
- Forward-directed radiation from target should never be aimed toward the maze opening
- Dose at maze entrance can be reduced by:
  - Reducing maze cross-sectional area
  - Increasing maze length
  - Increasing number of legs
- Maze legs should be perpendicular to each other
- At least two full scatters to the entrance are desirable



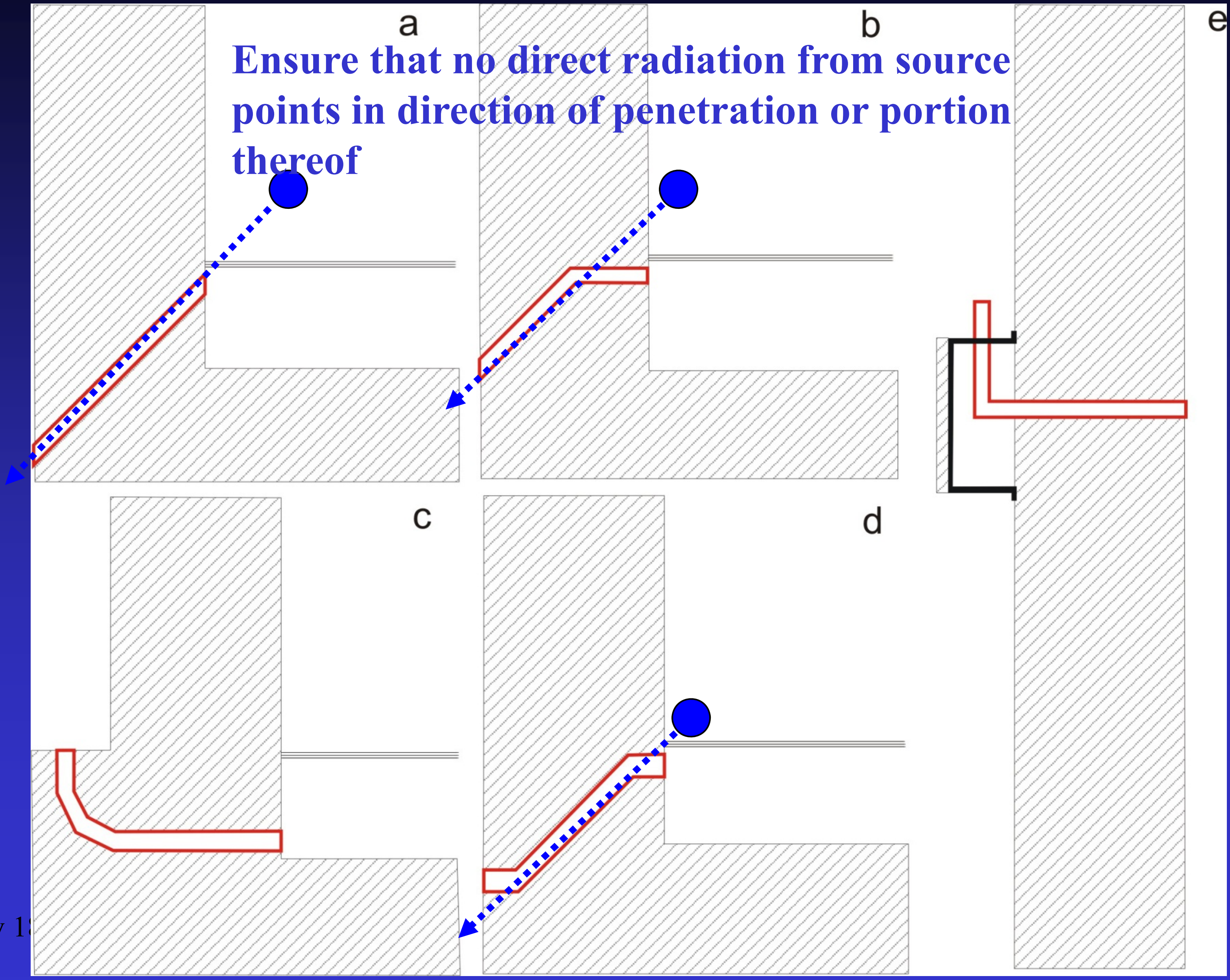
PTCOG Report 1

Example of an Ineffective Maze

- Maze appears to have two legs
- Legs are not at 90 degrees to each other
- Single scatter from source reaches maze entrance with very little attenuation
- Ineffective design

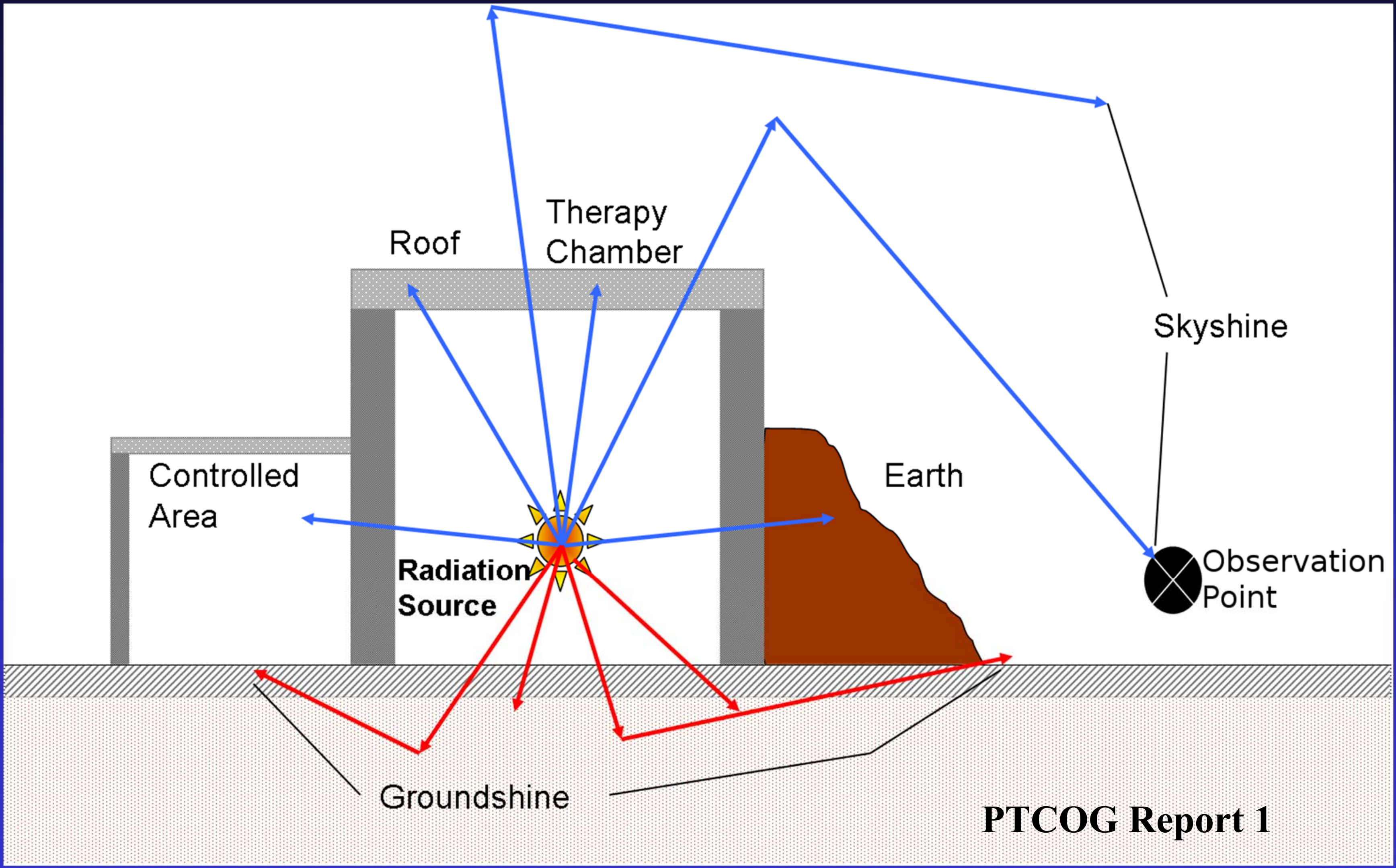


Design of Penetrations

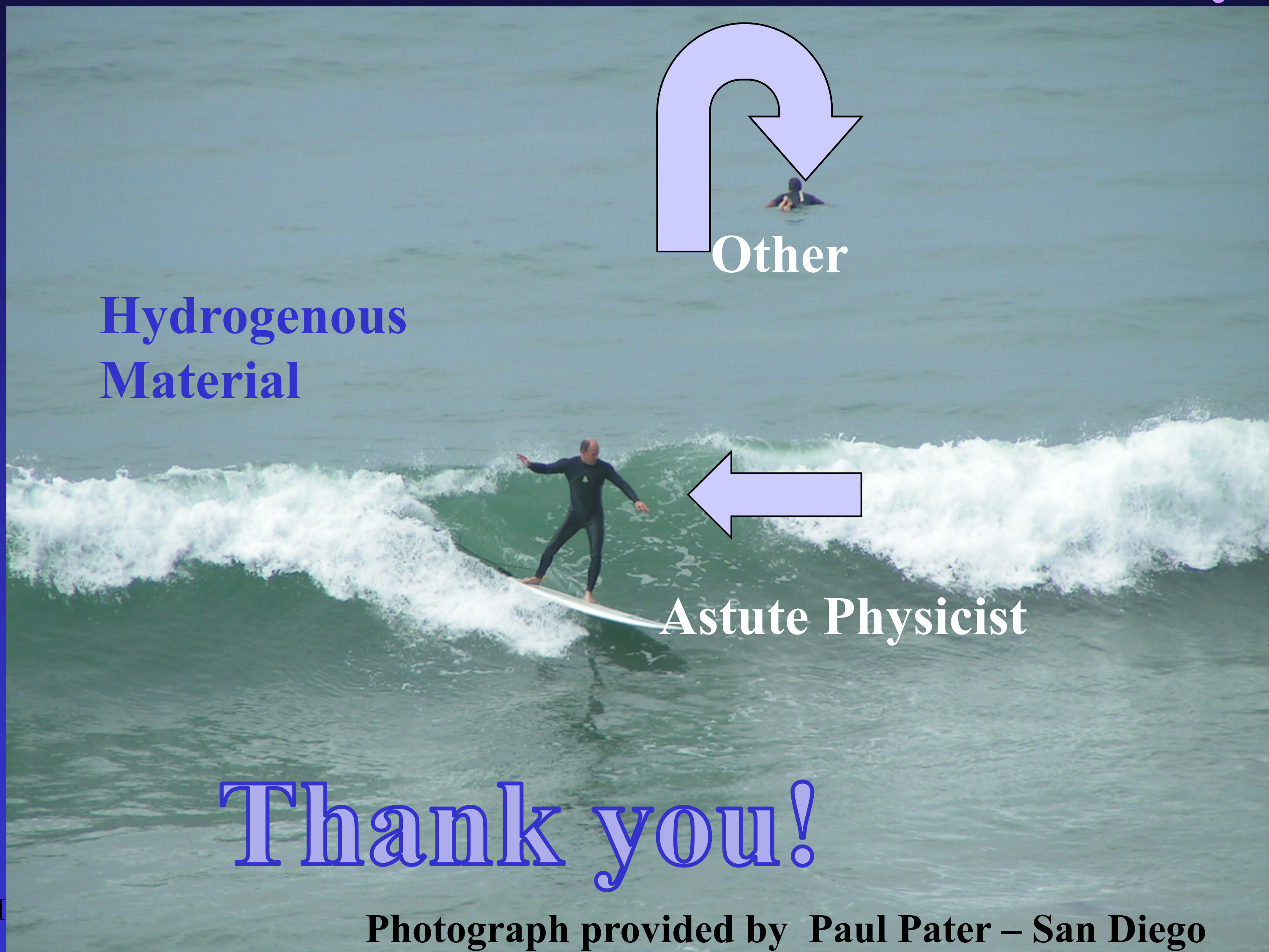


Ensure that no direct radiation from source points in direction of penetration or portion thereof

Skyshine and Groundshine



The astute physicist surfs the shielding wave undaunted, while the other flees away!



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