Secondary Radiation and Shielding Design for Particle Therapy Facilities

Nisy Elizabeth Ipe, Ph.D., C.H.P.
Consultant, Shielding Design, Dosimetry & Radiation Protection
San Carlos, CA, U.S.A.
Email: nisy@comcast.net

“Doing the right thing, doing it right”
Shielding Design

• Shielding is NOT the TERMINATOR
  – Radiation dose 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 UNDER EXPECTED USAGE CONDITIONS

• Requires understanding of secondary radiation production, beam losses, nuclear and neutron interactions

• Knowledge of various other parameters

http://ecx.images-amazon.com/images/I/41QM6GC2P7L._SL500_AA300_.jpg
Secondary Radiation

- Produced by interaction of protons or ions 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 beam losses occur
  - In synchrotron and cyclotron during injection, acceleration and extraction
  - During energy degradation in cyclotron
  - During beam transport to treatment room
  - In beam shaping devices located in treatment nozzle
- Also produced in patient, dosimetric phantom and beam stopper
- Important to understand physics behind secondary radiation production
Carbon Ion Nuclear Interactions

Grazing Collisions
• Major interaction is fragmentation of incident ion or target nucleus
• Many secondary particles including nucleons (n, p) are produced
• Only segments of nuclei that interpenetrate undergo significant interaction and mutual disintegration
• Remainder of nucleus is uninvolved, but maybe highly excited

Head-On Collisions
• Less frequent but large energy transfer occurs
• Projectile breaks into many small pieces (nucleons, alphas, etc.)

The high-energy nucleons produced from above collisions interact further and generate nuclear cascades

Courtesy of Igor Pshenichnov
Physics: Nuclear Cascades

- Interaction of a hadron (p, n, pion) with a nucleus (A) results in a spray of forward-directed particles.
- These particles collide with other nuclei producing more particles.
- Process continues and results in development of extra-nuclear cascade.
- This is the primary cascade which feeds all other processes.
- Important in shielding design of carbon ions with energy > 200 MeV/nucleon.
- Similar to a water cascade, there is a succession of stages or levels in a nuclear cascade.
Six Levels of a Nuclear Cascade

NCRP Report
No. 144

<table>
<thead>
<tr>
<th>Level</th>
<th>Most Numerous Participants</th>
<th>Time Scale (s)</th>
<th>Typical Energy per Particle (MeV)</th>
<th>Percent of Energy Deposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muons</td>
<td>π⁻, K → μ⁻</td>
<td>10⁻⁸</td>
<td>any</td>
<td>10</td>
</tr>
<tr>
<td>Electromagnetic Cascade</td>
<td>π⁰ → e⁻γ</td>
<td>10⁻¹⁶</td>
<td>any</td>
<td>20</td>
</tr>
<tr>
<td>Intranuclear Cascade</td>
<td>p, n, π, K</td>
<td>10⁻²²</td>
<td>&lt;200</td>
<td>30</td>
</tr>
<tr>
<td>Extranuclear Cascade</td>
<td>p, n, π, K</td>
<td>10⁻²³</td>
<td>&gt;200</td>
<td>30</td>
</tr>
<tr>
<td>Evaporation of Nucleons and Fragments</td>
<td>p, n, d, α</td>
<td>10⁻¹⁹</td>
<td>&lt;30</td>
<td>10</td>
</tr>
<tr>
<td>Induced Activity</td>
<td>α, β, γ</td>
<td>seconds to years</td>
<td>&lt;10</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>
Intra-Nuclear Cascade

- Important in shielding design of protons (67 MeV to 330 MeV)
- Incoming hadron (p, n) interacts with individual nucleons in nucleus, producing a spray of particles
- 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 nucleon with E > 150 MeV is forward peaked 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

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Evaporation and Activation

- Energy of nucleons that do not escape nucleus is distributed among remaining nucleons
- Original nucleus is left in an excited state
- It 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
- Neutrons are principal propagators of cascade with increasing depth, since protons and pions (E < 450 MeV) have a high rate of energy loss
Calculated (FLUKA) Neutron Yield in Tissue for Various Ions

Neutron yield 0°-10°

Yield of neutrons per incident particle per steradian

Neutron energy [MeV]

P200 He202 Li234 B329 C400 N430 O468

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

More shielding is required in the forward direction

Ipe Data with FLUKA

More shielding is required in the forward direction

$pSV = 10^{-12} Sv$
Unshielded Neutron Spectra at Various Production Angles for 250 MeV Protons Incident on Thick Iron Target (FLUKA)

Characteristics of Shielded Neutron Field for Protons

- 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 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
- Radiation field reaches equilibrium condition beyond a few mean free paths 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 in the forward direction consists of peaks at $\sim 2$ MeV and at $\sim 100$ MeV
Neutron Spectra from 430 MeV/u Carbon Ions Incident on ICRU Tissue

N.E. Ipe and A. Fasso, Proceedings of SATIF8, 2006, Korea
Neutron Energy Classification and Interactions

• Thermal: $\bar{E}_n = 0.025$ eV at 20°C
  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
Thermal Neutron Capture

- Thermal neutrons diffuse about and are captured by the nucleus
- Excited nucleus emits capture gamma rays
- Capture cross section ($<1$ keV) decreases with increasing neutron energy
- 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 $\sim$10,000 x higher

Borated polyethylene is used instead of polyethylene for shielding maze doors

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)
- 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

Inelastic Scatter \((n, n')\)

- Kinetic energy is not conserved
- 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*

Fast Neutron Interactions

- Neutrons can also be absorbed or captured: $(n, 2n)$, $(n, p)$, $(n, \alpha)$ or $(n, \gamma)$
- 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$^2$
Relativistic Neutron Interactions

- Relativistic neutrons arise from cascade processes in proton and ion accelerators
- Neutrons with $E_n > 150$ MeV
  - Propagate cascade through shielding
  - Continuously regenerate lower-energy neutrons and charged particles at all depths
  - Charged particles are stopped in thick shield
  - 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 and fragments
  – Activation

• Neutrons (20 MeV < $E_n$ ≤ 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
Calculational Methods

1. Monte Carlo (MC) Codes
   - FLUKA, MCNP, MCNPX, GEANT, etc.
   - Full computer simulation modeling the machine and room geometry can be performed
   - Full Monte Carlo simulation for specific room design is time consuming and not very cost effective during schematic design phase for determining bulk shielding
   - Should be used for all scatter calculations (maze scatter and penetrations)
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 angle of production, target material and dimensions, shielding material, density and composition, etc.

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

- \( H \) = dose at point of interest
- \( H_0 \) = dose at 1 m from source
- \( d \) = slant thickness of shield
- \( r \) = distance to shield
- \( \lambda \) = attenuation length
Attenuation Length

- Attenuation length ($\lambda$) is penetration distance in which intensity of radiation is reduced to 37% (1/e) of its value.
- Measured in cm, or in g-cm$^{-2}$.
- $\lambda$ changes with depth and reaches an equilibrium value.
- $\lambda$ increases with mass number $A$.
- Measured neutron attenuation lengths in concrete from various sources are shown below.

![Graph showing neutron attenuation lengths versus maximum source neutron energy.](image-url)
Calculation Methods

3. Computational Models

- Hybrid approach
  - Monte Carlo and Analytical Methods
- Source terms and attenuation lengths that are independent of geometry are derived using Monte Carlo
- Various parameters are considered
  - Particle energy, angle of production, target material, dimensions, shielding material, composition and density
- Computational models are particularly useful during schematic design phase for bulk shielding calculations
  - Facility layout undergoes several iterations
  - Are faster than full Monte Carlo calculations
Computational Models

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

Where:
- \( H \) is the dose equivalent at the outside the shield,
- \( H_0 \) is source term at an angle \( \theta \) 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
- \( d/g(\theta) \) is the slant thickness of the shield at an angle \( \theta \)
- \( \lambda_\theta \) is the attenuation length at an angle \( \theta \)
- \( g(\theta) \) is \( \cos \theta \) for forward shielding
- \( g(\theta) \) is \( \sin \theta \) for lateral shielding
- \( g(\theta) = 1 \) for spherical geometry
Dose in Forward Direction as a Function of Concrete Thickness for Protons incident on Tissue (FLUKA)

\[ y = 0.0166 e^{-0.0192x} \]

\[ H_0 = 0.0166 \text{ pSv-m}^2/\text{p} \]

\[ \lambda = 1/(0.0192) = 52 \text{ cm} \]

Shielding is the ATTENUATOR!
Shielding Thicknesses For Particle Therapy Facilities
(PTCOG Report 1)
Shielding Design Considerations

- Treatment and Beam Parameters
  - Particle type
  - 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 vary from facility to facility
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 facility dependent!*
Mazes

- Radiation at maze entrance consists of neutrons that scatter through the maze; and capture gamma rays
- Forward-directed radiation from target should never be aimed toward the maze opening
- Reducing maze cross-section area reduces dose at entrance
- As number of legs increases, the attenuation increases
- The legs should be perpendicular to each other
- At least two scatters are desirable
Beware of the Pseudo 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

No direct external radiation from source
1. Introduction – N. E. Ipe
2. Radiological Aspects of Charged Particle Therapy Facilities – N. E. Ipe
3. Shielding Design Considerations – G. Fehrenbacher & N. E. Ipe
4. Radiation Monitoring – Y. Uwamino & G. Fehrenbacher
5. Activation – Y. Uwamino
6. Monte Carlo Codes - S. Roesler
8. Safety Systems and Interlocks – M. Schippers

Advisors: A. Smith, A. Mazal and D. Jones
Consultants: S. Ban and H. Yashima
Thank You
Back Up Slides
# Neutron Yields for Protons Incident on a Thick Iron Target (FLUKA)

<table>
<thead>
<tr>
<th>Proton Energy, $E_p$ (MeV)</th>
<th>Range (mm)</th>
<th>Iron Target</th>
<th>Neutron Yield (n/p)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Radius (mm)</td>
<td>Thickness (mm)</td>
<td>$E_n$ &lt;19.6 MeV</td>
</tr>
<tr>
<td>100</td>
<td>14.45</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>150</td>
<td>29.17</td>
<td>15</td>
<td>30</td>
</tr>
<tr>
<td>200</td>
<td>47.65</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>250</td>
<td>69.30</td>
<td>58</td>
<td>75</td>
</tr>
</tbody>
</table>

Neutron Inelastic Cross Sections for Various Materials

- 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

ICRU Report 28
Skyshine and Groundshine

PTCOG Report 1
Relative Dose at 1 m (0°-10°) from 430 MeV/u Carbon Ions Incident on ICRU Tissue

Relative Dose Per Carbon ion @ 1 m: 0 to 10 degrees

Relative Dose

Shielding Thickness (cm)

- Neutron
- Proton
- Photon
- Charged Pion
Secondary Radiation Field

• Quite complex
• For structural (bulk) shielding, neutrons are the dominant component
• For mazes and penetrations, neutrons and capture gamma rays contribute to dose
• Important to understand how neutrons interact