Basics of Shielding Design for Charged 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”
PTCOG REPORT 1: Shielding Design and Radiation Safety of Charged Particle Therapy Facilities
(http://ptcog.web.psi.ch/archive_reports.html)

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
Secondary Radiation

- Produced by interaction of particles with beam line components
- 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 stop
- Accelerators, beam transport line and treatment rooms require shielding
Secondary Radiation from Protons

• Interaction of protons (50 MeV - 1000 MeV) with matter results in the production of an intra-nuclear cascade (spray of charged and neutral particles)

• Intra-nuclear cascade is important for protons in therapeutic energy range of interest (67 MeV – 330 MeV)

• Five distinct stages
  – Intra-nuclear cascade
  – Production of muons
  – Electromagnetic cascade
  – Evaporation of nucleons and fragments
  – Activation
Intra-Nuclear Cascade

- Incoming hadron (p,n,..) interacts with individual nucleons in nucleus, producing spray of particles
- Pions and kaons are produced above ~ 135 MeV and ~ 495 MeV, respectively
- Large fraction of energy transferred to single nucleon

- This nucleon with E> 150 MeV propagates cascade
- Nucleons with energies between 20 -150 MeV transfer energy to several nucleons (~ 10 MeV/nucleon)
- Charged particles are quickly stopped by ionization
- Neutrons predominate
Evaporation and Activation

• After interaction with incoming hadron, remnant of original nucleus is left in an excited state
  • It de-excites emitting particles with typical energy < 30 MeV
• Particles include “evaporation nucleons” (protons and neutrons) and some fragments
  • Proton energy deposited locally
  • Evaporation neutrons travel long distances
  • Remaining excitation energy emitted as gammas
  • De-excited nucleus may be radioactive (activation)
Muons and Electromagnetic Cascade

- Charged pions decay to muons and neutrinos
- Muons are penetrating particles, and deposit energy by ionization, photonuclear reactions also possible
- Neutral pions decay to gammas which initiate electromagnetic (EM) cascade
- Attenuation length of EM cascade is much shorter than that for neutrons
- Neutrons are principal propagators of cascade with increasing depth
Unshielded Neutron Spectra for 250 MeV Protons Incident on Thick Fe Target (FLUKA)

# 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>

Characteristics of Shielded Neutron Field

- High-energy neutron component propagates cascade in shield and continuously regenerates 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-section at lower energy.
- Radiation field reaches equilibrium condition beyond a few mean free paths within shield.
- Typical neutron spectrum observed outside a thick shield consists of peaks at ~ few MeV and at ~ 100 MeV.
Carbon Ion Interactions

- Nuclear interactions occur by either grazing or head-on collisions
- In grazing collision, fragmentation of incident ion or target nucleus occurs
- Only segments of nuclei that interpenetrate undergo significant interaction and mutual disintegration
- Evaporated nucleons and light clusters are produced
Carbon Ion Interactions

• Head-on collisions are less frequent but large energy transfer occurs
• Projectile breaks into many small pieces and no high-velocity fragment survives (unlike in grazing collisions)
• Secondary particles are produced

Courtesy of Igor Pshenichnov
Relative Dose at 1 m (0° - 10°) from 430 MeV/u Carbon Ions Incident on ICRU Tissue

N.E. Ipe and A. Fasso, SATIF8, 2006
Neutron Spectra in Concrete from 430 MeV/u Carbon Ions Incident on ICRU Tissue

- Neutron energy: 340 MeV
- Neutron energy: 145 MeV
- Neutron energy: 2.3 MeV

Fluence (cm$^{-2}$ per carbon ion) vs. Neutron Energy (GeV)

- 0-10 degrees: Concrete Surface
- 80-100 degrees: Concrete Depth = 4.8 m
- 0-10 degrees: Concrete Depth = 4.8 m
- 80-100 degrees
Secondary Radiation Field

- Quite complex
- For shielding, neutrons are the dominant component
- Important to understand how neutrons interact
Neutron Energy Classification

- **Thermal:** \( \bar{E}_n = 0.025 \text{ eV at 20ºC} \)
  - Typically \( E_n \leq 0.5 \text{ eV} \)

- **Intermediate:** \( 0.5 \text{ eV} < E_n \leq 10 \text{ keV} \)

- **Fast:** \( 10 \text{ keV} < E_n \leq 20 \text{ MeV} \)
  - Includes evaporation neutrons

- **Relativistic:** \( E_n > 20 \text{ MeV} \)
Elastic Scatter

- Kinetic energy and momentum are conserved
- Fast neutrons thermalized by elastic scatter
- 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
Inelastic Scatter

- 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

High-Z material used for shielding 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
Thermal Neutron Capture

- Thermal neutrons are captured by the nucleus.
- The excited nucleus emits capture gamma rays.
- Capture cross section ($< 1 \text{ keV}$) decreases with increasing neutron energy.
- $^1\text{H} \ (n,\gamma)^2\text{H} \ -2.2 \text{ MeV}$ (polyethylene & concrete).
- Boron has higher capture cross-section and lower capture gamma energy (0.478 MeV).

*Use borated polyethylene in maze door instead of polyethylene.*

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

PTCOG EW 2010, Nisy E. Ipe
Neutron Interactions ($E_n < 20$ MeV)

- Neutrons are uncharged and can travel long distances
- Almost all interactions are scatters (elastic or inelastic)
- Absorption important only at thermal energies and in a few resonances in keV region
Neutron Interactions ($E_n > 20$ MeV)

- Relativistic neutrons arise from cascade processes (proton) and nuclear and fragmentation processes (ion)
- Important in propagating cascade
- Neutrons in cascade have energies as high as the primary proton beam
- Neutrons from ion accelerators have maximum energy of \~2 \times \text{specific energy of ion} \ (860 \text{ MeV for 430 MeV/u carbon ion})
- High-energy neutron component ($E_n > 100$ MeV)
  - propagates neutrons through shielding
  - regenerates lower-energy neutrons and charged particles at all depths via inelastic reaction
  - charged particles are absorbed in the thick shielding
  - lower-energy neutrons undergo capture reactions giving rise to neutron-capture gamma rays
Neutron Interactions ($E_n > 20$ MeV)

- Low-energy component (50 MeV-100 MeV)
  - Intra-nuclear cascade
  - Evaporation nucleons
  - Activation
Calculational Methods

1. Monte Carlo (MC) Codes
   - FLUKA, MCNP, MCNPX, GEANT, etc.
   - Full computer simulation modeling accelerator, beam line and room geometry
   - Can be used to generate isodose curves, thus providing visualization of secondary radiation field
   - Can be used to derive computational models
   - Time consuming
Calculational Methods

2. Analytical Methods

- Most models are line-of-sight and assume point source
- Usually limited to transverse shielding and simple geometries
- Don’t account for changes in angle of production, target material and dimensions, shielding material, density and composition
- Example: Moyer Model derived for GeV proton machines

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

H = dose at point of interest
H\(_0\) = dose at 1 m from source
d = slant thickness
r = distance to shield
\(\lambda\) = attenuation length
Attenuation Length

- Attenuation length ($\lambda$) is the penetration distance in which the intensity of radiation is reduced by a factor of $e$.
- Measured in cm, or in g·cm$^{-2}$.
- $\lambda$ changes with depth and reaches an equilibrium value.

Calculational Methods

3. Computational Models

- Comprised of source terms and attenuation lengths as a function of angle
- Particle energy, angle of production, target material, dimensions, shielding material, composition and density are considered
- During schematic design phase, facility layout undergoes several iterations
- Full Monte Carlo simulations for specific room design is time consuming and not very cost effective
- Computational models are useful at this stage
Computational Models

\[
H(E_p, \theta, d/\lambda g(\theta))\frac{H_0(E_p, \theta)}{\lambda_0 g(\theta)} \exp\left(-\frac{d}{\lambda_0 g(\theta)} \frac{r^2}{-20 \theta}\right)
\]

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 \(\theta\)
- \(\lambda\) 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 From 430 MeV/u Carbon Ion Incident On 30 cm ICRU Tissue Sphere

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

- Vacuum
- Concrete
- 30 cm Fe + Concrete
- 60 cm Fe + Concrete
- 90 cm Fe + Concrete
- 120 cm Fe + Concrete

N.E. Ipe and A. Fasso, SATIF8, 2006
Computational Models for Composite Shield (Iron + Concrete) Thickness > 1.35 m

<table>
<thead>
<tr>
<th>Iron (cm)</th>
<th>0-10°</th>
<th>10-30°</th>
<th>40-60°</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$H_0$ (pSv-m²/ion)</td>
<td>$\lambda$ (g/cm²)</td>
<td>$H_0$ (pSv-m²/ion)</td>
</tr>
<tr>
<td>0</td>
<td>3.02 ± 0.04</td>
<td>123.81 ± 0.48</td>
<td>4.81 ± 0.06 x1.E-01</td>
</tr>
<tr>
<td>30</td>
<td>1.25 ± 0.02</td>
<td>123.12 ± 0.38</td>
<td>2.44 ± 0.03 x1.E-01</td>
</tr>
<tr>
<td>60</td>
<td>6.05 ± 0.03 x1.E-01</td>
<td>120.32 ± 0.46</td>
<td>1.11 ± 0.04 x1.E-01</td>
</tr>
<tr>
<td>90</td>
<td>2.77 ± 0.09 x1.E-01</td>
<td>119.58 ± 1.25</td>
<td>5.27 ± 0.29 x1.E-02</td>
</tr>
<tr>
<td>120</td>
<td>1.33 ± 0.05 x 1.E-01</td>
<td>117.68 ± 0.91</td>
<td>2.48 ± 0.24 x1.E-02</td>
</tr>
</tbody>
</table>

Ipe & Fasso, SATIF8, 2006
Total Dose Equivalent Transmission Curves For 430 MeV/u Carbon Ion Incident On Tissue

0 to 10 degrees

Transmission vs Shielding Thickness (cm)

- Concrete
- 30 cm Iron + Concrete
- 60 cm Iron + Concrete
- 90 cm Iron + Concrete
- 120 cm Iron + Concrete
- Iron
- ProShield Ledite 300
- Ledite 293
- Ledite 247

N.E. Ipe, ICRS11, 2008
PTCOG EW 2010, Nisy E. Ipe
Shielding Design Considerations

• Accelerator Type
  – Synchrotron
  – Cyclotron
  – Self shielding effects of beam line components

• Type of Shielding Material
  – Composition
  – Density
  – Water content

• Facility Layout
  – Adjacent occupancies
  – Type of Area (Controlled, Public, etc.)
  – Above ground, underground..

• Country/State Specific Regulatory Dose Limit

*Shielding design is facility dependent!*

PTCOG EW 2010, Nisy E. Ipe
Shielding Design Considerations

- **Treatment**
  - Particle type (*proton*, *carbon ion*, …)
  - Energies
  - Current or intensity at each energy
  - Beam shaping and delivery (*scanning vs. scattering*, etc.)
  - No. of patients/year
  - No. of fractions/patient at each energy
  - Dose delivered per fraction
  - Beam-on time
  - Beam losses and locations
  - Target materials and dimensions

*Treatment parameters vary from facility to facility*
Fixed Beam Room Shielding Considerations

- Horizontal and 45 ° vertical beams
- Use Factor = 1/2 for each beam, or 2/3 and 1/3
- Neutrons from carbon ions dominate shielding in forward direction
- Neutrons from protons dominate at large angles and at maze entrance when proton intensity is higher
- No shielded door at maze entrance
- Consider contributions from adjacent areas

Courtesy of Siemens Medical Solutions U.S.A, Inc.
Gantry Room Shielding Considerations

- Beam rotates around patient
- Beam stopper is asymmetric and rotates with beam
- Ceiling, lateral walls and floor see forward radiation
- Walls in forward direction thinner than Fixed Beam Room because of lower Use Factor (1/4)

Courtesy of Siemens Medical Solutions U.S.A, Inc.
Skyshine and Groundshine (PTCOG Report 1)
Ducts/Penetrations (PTGOG Report 1)

- Extension of Duct Length
- Curved Bend
- One Bend
- Two Bends
- Shadow Mask Shield
Architect’s 3-D Rendition of an SRS Monarch 250 Single-Room Facility

Courtesy of The Benham Companies, An SAIC Company, Oklahoma City, Oklahoma
CONCLUSIONS

“One Size Fits All” Approach to Shielding
DOES NOT WORK

Shielding is facility specific

PTCOG EW 2010, Nisy E. Ipe
Thank You