SHIELDING HIGH-ENERGY ACCELERATORS

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Summary of the Presentation

1. Introduction
2. Simple Approximations
   Point-source Line-of-sight models (Moyer Model)
3. Learning Physics with computers
4. Geometrical approximations
5. Scoring Quantities
1932

- J. Chadwick discovers the neutron in Cambridge UK.
- J. D. Cockroft and E. T. S. Walton build an accelerator at Cambridge UK.
- E. O. Lawrence and M. S. Livingstone build an accelerator at Berkeley USA.
The Cosmotron
The improvement programs for the Cosmotron at Brookhaven and the Bevatron at Berkeley made understanding of the stray radiation field and the design of efficient shielding fundamental necessities.

At the New York Conference on the Shielding of High-Energy Accelerators in 1957, Lofgren commented:

“I hope that the Cosmotron and the Bevatron are the last two large accelerators to be designed without shielding. I might just mention a few of the varied problems from our experience when shielding is added as an afterthought.

1. **Shielding foundation** had to be put in after the machine was completed, and this resulted in a serious interference with operation.

2. **Financing was inadequate** because it was not planned early enough in advance.

3. **Many components that were installed in areas of high radiation level** requiring shut-down for servicing might otherwise have been installed in low-level areas.

4. In some areas it was nearly **impossible to design a really good shield and also have access holes in the shield.**

5. **It was necessary to abandon an appreciable area** in the building which might have been used for offices and laboratories.”
Perhaps CERN should have remembered these comments when the first Antiproton Accumulator was designed without a shield in the early 1980s.

Plus ça change, plus c'est la même chose.
(Alphonse Karr)
Need for Accurate Shielding Calculations

- Accelerators such as the 7 GeV proton synchrotron NIMROD at the Rutherford Laboratory and the CERN PS were built originally with heavy roof-shielding.

- The development of extracted proton beams at these laboratories and the construction of accelerators on or near the surface of the ground such as the Brookhaven AGS, Stanford’s SLAC and the Fermilab proton accelerator, encouraged the development of the science of accelerator shielding.
An efficient shielding design should attenuate the high radiation intensities to levels that are acceptable to humans and other apparatus outside the shielding, at a reasonable cost and without compromising the utility of the particle accelerator for its designed purposes. This is achieved in three stages:

1. Specification of the source term(s).

2. Specification of the design levels for the radiological constraints.

3. Design of the actual shield on an optimum cost-effective basis and with readily available construction materials.

The first stage is difficult because no-one will agree on what the losses will be, but the maximum intensities and losses which form the basis of the shield design must be agreed upon by laboratory management and any national or regional radiation control authority before shield specification begins.
The second stage also needs the agreement of any national or regional radiation control authority, and is illustrated by considering the design constraints chosen for the LHC.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Full loss</th>
<th>Normal loss</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dose (mSv)</td>
<td>Dose Rate (mSv/h)</td>
</tr>
<tr>
<td>Controlled</td>
<td>50</td>
<td>–</td>
</tr>
<tr>
<td>Supervised</td>
<td>2.5</td>
<td>–</td>
</tr>
<tr>
<td>Non-designated</td>
<td>0.3</td>
<td>–</td>
</tr>
<tr>
<td>Any area</td>
<td>100 mSv/h</td>
<td>–</td>
</tr>
</tbody>
</table>

A review of aspects of the third stage is principal subject of this talk.
Two assumptions are often made in shielding calculations.

1. The source is approximated by a **Point Source**.
   *i.e.* it is localized in a geometrical region which is small in size compared with the other dimensions of the shielding situation.
   This means that the inverse square law of geometrical dilution will hold.

2. The dose as a function of position is described only in terms of the relative co-ordinates of the point source and the point of interest –
   This vector is the **Line of Sight**.
   *i.e.* there are no contributions from secondary sources.
In a pure point-source/line-of-sight model, the radiation field at P is affected only by particles travelling along the vector linking S to P and not from any other point.

\[ H(r, z) = H(\zeta, \theta) \]

\( H \) can be separated into a build-up/attenuation function and particle source term which is a function of polar angle.

\[ H(\zeta, \theta) = k Z(\zeta, \theta) \Theta(\theta) / R^2, \]

The function \( Z(\zeta, \theta) \) need not have \textit{a priori} any particular functional form and could have a build-up as well as an attenuation component.

Such a model is directly applicable to the shielding of low-energy proton accelerators (< 400 MeV).

The source of radiation provided by the interacting protons is limited to a distance equal to the range of the protons, and this is small when compared with the usual dimensions of a shield. The effective source strength and the absorption length vary with the angle to the beam axis, but this variation can easily be described by analytic fits or tabular values.
Such a treatment was extended to proton energies in the GeV range by Moyer during the up-grade of the Bevatron shielding.

It was named the “Moyer Model” by De Staebler during the design of the SLAC accelerator.

In its present form the function $Z(\zeta, \theta)$ does not depend on the polar angle $\theta$ and is a pure exponential absorption term where the effective mean free path is independent of particle type and energy.

The angular dependence term includes any build-up effect along the line-of-sight and is approximated by a function of the form $\exp(-\beta \theta)$ where $\beta \approx 2.3 \text{ radians}^{-1}$.

$$H = \psi \times \exp(-\beta \theta) \exp(-\zeta/\lambda)/R^2,$$

where $\psi$ is a constant which depends on the energy of the incident protons as a simple power law with an exponent of 0.8.

The exponent is less than unity because the fraction of the incident proton’s energy leading to hadron production decreases as the proton energy increases.
• The model is only applicable to angles $\theta$ between 60 and 120°.

• The most appropriate form is that for $\theta = 90°$, where the above equation reduces to

$$H = H_0 \left( \frac{E_p}{E_0} \right)^{0.8} \frac{\exp\left(\frac{-\left( r - r_0 \right)}{\lambda} \right)}{r^2},$$

• $E_p$ is the proton energy in GeV,

• $E_0$ is 1 GeV,

• $H_0$ is $1.26 \times 10^{-14}$ Sv.m$^2$ per proton

• $\lambda$ is 118 g/cm$^2$ for concrete or earth and 164 g/cm$^2$ for iron.
• This model is also used to determine the lateral shielding required around targets and dumps at electron accelerators.

• Each of the three components of the radiation field, High-energy hadrons, Resonance neutrons and Bremsstrahlung, needs to be considered separately.

• In each case there is a linear dependence of $H$ on primary electron energy.

• The parameters in the above formula are:

<table>
<thead>
<tr>
<th>Radiation Component</th>
<th>$H_0$</th>
<th>$\lambda_{\text{concrete}}$</th>
<th>$\lambda_{\text{iron}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-energy hadrons</td>
<td>$2.0 \times 10^{-17}$</td>
<td>100</td>
<td>164</td>
</tr>
<tr>
<td>Resonance neutrons</td>
<td>$1.1 \times 10^{-15}$</td>
<td>42</td>
<td>130</td>
</tr>
<tr>
<td>Bremsstrahlung</td>
<td>$2.0 \times 10^{-15}$</td>
<td>46</td>
<td>50</td>
</tr>
</tbody>
</table>
ERRARE HUMANUM EST

To err is human

but to really foul things up needs a computer
Reflections on Flat Walls

Iron cylinder 20 cm radius
Total length 35 m
7 TeV protons enter at $z = 6$ m

Cut in the $xy$-plane through the flat wall geometry used in the simulations.
An iron target cylinder is centred at $x = y = 0$ and the walls are concrete.
Dimensions are given in cm.
Doses in pSv/proton averaged over the first 20 cm depth of the inner surface of the flat wall for a 35 m long magnet.
We expected these!

Doses in pSv/proton averaged over the first 20 cm depth of the inner surface of the flat wall for a 2 m long magnet.
The increase in dose with vertical distance must be linked with attenuation in the long iron target.

This is a point-source/line-of-sight model for a Moyer-type source ($\beta = 2.3\,\text{radians}^{-1}$) at the centre of an infinitely long iron cylinder of 20 cm radius whose axis is 2 m laterally away from the wall.

The contours are normalized to the dose at the same depth as before, 1 m downstream of the target in the $y = 0$ plane.

The $\lambda$s are 50 cm in the wall and 20 cm in the iron.

The Moyer-like model also shows that dose increases with vertical distance from the beam axis as in the FLUKA simulations.

The long cylinder of iron “shadows” the wall at small values of $\theta$.

This anomaly would not have been detected in a cylindrical simulation: it needed a full three-dimensional FLUKA simulation to make it evident.
The FLUKA simulation for the flat wall provides good data for testing the validity of line-of-sight models. For several values the space angle, $\theta$ (20, 40, 60 and 80$^{\circ}$), one can look at the value of the dose equivalent as a function of distance along the line-of-sight and as a function of the azimuthal angle, $\phi$ (0, 15, 30 and 45$^{\circ}$). The point source was assumed to be at a distance of 50 cm downstream of the point of impact of the protons.
Attenuation along the line of sight for various polar angles, $\theta$, for a 20 cm radial thickness target.

Closed circles – $\phi = 0^\circ$, Open circles – $\phi = 15^\circ$, Closed triangles – $\phi = 30^\circ$, Open triangles – $\phi = 45^\circ$. 
Attenuation along the line of sight for various polar angles, $\theta$, for a 2 cm radial thickness target.

Closed circles – $\phi = 0^\circ$,  
Open circles – $\phi = 15^\circ$,  
Closed triangles – $\phi = 30^\circ$,  
Open triangles – $\phi = 45^\circ$. 
Effective mean free paths (cm) in the concrete wall for different values of $\theta$ at various proton energies

<table>
<thead>
<tr>
<th>Proton Energy</th>
<th>$\theta = 80^\circ$</th>
<th>$\theta = 60^\circ$</th>
<th>$\theta = 40^\circ$</th>
<th>$\theta = 20^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r = 20$ cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 TeV</td>
<td>49</td>
<td>57</td>
<td>74</td>
<td>88</td>
</tr>
<tr>
<td>1 TeV</td>
<td>51</td>
<td>57</td>
<td>69</td>
<td>91</td>
</tr>
<tr>
<td>100 GeV</td>
<td>52</td>
<td>59</td>
<td>72</td>
<td>99</td>
</tr>
<tr>
<td>10 GeV</td>
<td>50</td>
<td>57</td>
<td>73</td>
<td>98</td>
</tr>
<tr>
<td>$r = 2$ cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 TeV</td>
<td>46</td>
<td>56</td>
<td>70</td>
<td>111</td>
</tr>
</tbody>
</table>
For short or laterally thin targets, the cascade does not fully develop in the target and high-energy secondaries generate their cascades in the shield-walls. The dose at the point P is assumed to come from the secondary sources $S'$ in the initial layers of the shield, and sideways build-up/attenuation dominates over line-of-sight contributions.

This has been known for low-energy neutron and photon shielding for some considerable time, however it is not evident that this model should be applicable at high-energies.

The secondary source strength is a function of $R$ and $\theta$, but the attenuation in the wall is now a function of $d$ only.

The dose at P is an area integral of the form $\exp(-s/\lambda)/s^2$ where $s$ is the distance of the elemental area of wall source from the point P.
It has been shown that for a thin target in cylindrical geometry, the propagation of the cascade in the shield behaves in a similar way to the radiation from a line source situated on the inner surface of the shield.

The variation with depth $d$ is given by the Moyer-Integral:

$$D = \frac{k}{d} \int_{0}^{\pi} \exp(-\beta \theta) \exp(-d/\lambda \cos \theta) d\theta$$

In the case of a flat wall it is to be expected that the source will approximate rather to a uniform plane source distributed over the surface of the shield wall rather than to a simple line source.
All Sources are Point Sources

The attenuation of an isotropic source through a flat shield-wall.

All curves are normalized at a depth of 10 m.

All source types behave as a simple point source since the negative exponential of distance effectively removes all contributions other than those closest to the source.
Attenuation perpendicular to the wall (20 cm radial thickness target).

The dashed curves are for a wall-source model where the source strength for the surface integral is given by the simulated star-density distribution underneath the point of interest in the first 20 cm bin of the shield. An almost exact agreement, shown by the solid curves, can be obtained on an absolute basis by normalizing the 20 cm depth point of the model calculations to the 30 cm depth point of the FLUKA simulations.
Attenuation perpendicular to the wall (2 cm radial thickness target).

Closed circles – $\phi = 0^\circ$,
Open circles – $\phi = 15^\circ$,
Closed triangles – $\phi = 30^\circ$,
Open triangles – $\phi = 45^\circ$. 
A normalization uncertainty is to be expected since the source for the model calculations is not a surface source but is distributed in depth over the first few tens of centimetres of the shield.

The overall agreement suggests that, even for the thick radial target case, the dose is more affected by the radiation coming perpendicularly through the shield than that coming along the line-of-sight from the primary target to the point of interest.

This can be confirmed by inserting a “black hole” in the inner layers of the shield downstream of the proton entry point to absorb the component coming perpendicularly through the wall.
Attenuation along the line of sight for a polar angle $\theta = 40^\circ$, for a 20 cm radial thickness target, without and with a black-hole in the wall.

No Black Hole
$\lambda = 74$ cm

Black Hole
$\lambda = 47$ cm

Closed circles – $\phi = 0^\circ$, Open circles – $\phi = 15^\circ$, Closed triangles – $\phi = 30^\circ$, Open triangles – $\phi = 45^\circ$. 
Determination of Transverse Shielding for Proton Accelerators Using the Moyer Model*

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“Teach us to delight in simple things”
from Christmas in India
Rudyard Kipling

Abstract—The historical development of the Moyer Model—an empirical method used in the design of high energy proton accelerator shielding—is described. With the improvements in the understanding of high-energy radiation phenomena which have occurred during the past 20 yr it is now possible to lay a more satisfactory theoretical basis for this model. Several measurements at various high energy proton accelerators now make it possible to improve the parameters used in the model and consequently to increase its accuracy. An example of the use of the model to calculate transverse shielding for an extended uniform line source is given and comparison made with calculations by O’Brien.
• The distance from the target to the observer, $P$, is the same in Case (a) and Case (b); so the Moyer Model indicates that the dose in both cases is identical.

• Secondaries leaving the target at angles $\theta < 90^\circ$ interact in the shield and contribute to the dose at $P$.

• Since $x_2 > x_1$ then the exponential absorption in Case (b) is much stronger than in Case (a).

• Thus the dose when the shield is near to the target is greater than when the shield is far away from the target.

• The Moyer Model was built from experiments where $a \approx 2$ m.
This is the situation presented previously here. It was recognized when the SPS was being built but did not become obvious until the large flat walls of the LHC shield were being studied.
The CERN Reference Field irradiation facility (CERF) was set up for the intercomparison of detectors used in radiation protection around high-energy accelerators.

It is sponsored by the Commission of European Communities for use in assessing the radiation exposure of civil aircrew.

The facility consists of 48 exposure locations behind 40 cm thick iron or 80 and 160 cm thick concrete shields alongside copper targets bombarded by beams of hadrons of energies greater from 100 to 200 GeV.
The spatial arrangement of the target and these roof-shields gives approximately uniform fields over a surface of $2 \times 2 \text{ m}^2$.

This area is divided into individual elements of $50 \times 50 \text{ cm}^2$ and measurements are made at the centre of these elements which are 50 cm high.

There are also two side-shielding locations behind concrete shields.

Alongside the iron roof-shield, the concrete shield is 160 cm thick whereas alongside the concrete roof-shield the side-shield thickness is the same as that of the roof viz. 80 cm.
The Real Geometry

Cross-section through the “Concrete” Target Position

Plan View of Detector Array
Consider two rays at identical azimuthal angles. Since \( d_1 > d_2 \), the dose rate at A is less than the dose rate at B. Because of this, the dose rate just above C is also less than the dose rate just above D, due to the irradiation by the shield surface.
Comparisons for CERF

Ratio of dose in Cartesian or Cylindrical approximation to the dose in the “real” geometry.

<table>
<thead>
<tr>
<th>Position</th>
<th>T13</th>
<th>T14</th>
<th>T15</th>
<th>T16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cartesian</td>
<td>0.94</td>
<td>0.93</td>
<td>0.92</td>
<td>0.96</td>
</tr>
<tr>
<td>Cylindrical</td>
<td>1.11</td>
<td>1.05</td>
<td>1.05</td>
<td>1.11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Position</th>
<th>T9</th>
<th>T10</th>
<th>T11</th>
<th>T12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cartesian</td>
<td>0.97</td>
<td>0.97</td>
<td>0.91</td>
<td>0.98</td>
</tr>
<tr>
<td>Cylindrical</td>
<td>0.93</td>
<td>0.89</td>
<td>0.84</td>
<td>0.92</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Position</th>
<th>T5</th>
<th>T6</th>
<th>T7</th>
<th>T8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cartesian</td>
<td>1.03</td>
<td>1.01</td>
<td>0.98</td>
<td>1.03</td>
</tr>
<tr>
<td>Cylindrical</td>
<td>0.98</td>
<td>0.93</td>
<td>0.91</td>
<td>0.97</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Position</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cartesian</td>
<td>1.02</td>
<td>1.00</td>
<td>1.00</td>
<td>0.94</td>
</tr>
<tr>
<td>Cylindrical</td>
<td>1.20</td>
<td>1.13</td>
<td>1.14</td>
<td>1.09</td>
</tr>
</tbody>
</table>

- The Cartesian in a good approximation.
- Cylindrical overestimates on T1–T4 and T13–T16.
- There is leakage in the “real” geometry to T13–T16.
Which Estimator: BDX or TRKL?

<table>
<thead>
<tr>
<th>Type</th>
<th>Estimator</th>
<th>Cartesian</th>
<th>Cylinder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume</td>
<td>Track-length</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Surface</td>
<td>Boundary crossing</td>
<td>1.46</td>
<td>1.38</td>
</tr>
</tbody>
</table>
Which Estimator – continued

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One-way Two-way

Concrete

100 GeV protons

z

r

z = 150 cm

0.209

0.326

Star density

0.223

0.297

0.611

0.803

z = 200 cm

0.255

0.338

r = 80 cm

0.193

0.284

r = 60 cm
Direction is important

One-way

Reduced One-way

Two-way

\[ D_A > D_B \quad \text{but} \quad D_A < D_C \]
• In the early 1970s, the execution time of a problem gave the longest delay times, often measured in weeks, whereas the geometry set-up required only several hours of a programmer’s time.

• The geometrical set-up now requires weeks of work, but the execution time still requires several days because of the increased statistical accuracy now required in viable solutions.

• Once established however, the same geometrical description can be used for many purposes other than shielding studies: e.g. radiation damage to machine components, radioactivity in the accelerator components, radioactivity in the surrounding rock, radioactivity in the air inside the accelerator caverns etc.

• It is best to make use of the available computing power by simulating such problems in full three-dimensional detail using programs such as FLUKA.
## Which Geometry?

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Realistic</th>
<th>Idealistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Un-symmetrical</td>
<td>Symmetrical (cylindrical)</td>
<td></td>
</tr>
<tr>
<td>Long (1 month)</td>
<td>Short (1 hour)</td>
<td></td>
</tr>
<tr>
<td>days/weeks</td>
<td>hours</td>
<td></td>
</tr>
<tr>
<td>Enormous</td>
<td>Short (1 line)</td>
<td></td>
</tr>
<tr>
<td>Months</td>
<td>Days</td>
<td></td>
</tr>
</tbody>
</table>

### Problem “solved” in

- Realistic: Months
- Idealistic: Days
• These studies exemplify the care that must be taken in predicting lateral shielding requirements in the forward region.

• Dose contours in flat walls are severely affected by the attenuation in magnet strings.

• At very-forward angles, this leads to an increase of dose at the wall surface with increasing vertical distance from the beam axis.

• As a consequence, detailed magnet structures and realistic shields are de rigeur when estimating doses in the forward direction.

• This is in contrast to the simplifications which can be accepted when estimating lateral doses.
• The transmission of radiation in flat-wall shields can be better represented by a **wall-source model**, where the effective source is the distribution of secondary interactions in the initial layers of the shield wall, rather than by a **point-source/line-of-sight model** where the point source is concentrated around the initial interaction point of the protons.

• Great care must be taken in predicting lateral shielding requirements in the very-forward region, especially when the loss of protons occurs in thin or short objects.
• There is no reason to maintain the simplification of a cylindrical geometrical representation of the problem, it can be dangerously misleading.

• In a real shield, the thickness is always a function of azimuth.

• Details of accelerator construction close to the beam-line and which require an azimuthally asymmetric representation can be important as secondary sources of radiation.

• These cannot be represented correctly in cylindrical geometry.
• The dose at the shield wall boundary is not the dose to which a person will be exposed.

• Make sure that the distance of a person from the shield wall is correctly taken into account.

• There is sometimes a big difference between the one-way and two-way dose (fluence).  
  One-way for shield-walls that end in air.  
  Two-way for small underground caverns.  
  Track-length always works!
Above all

THINK!