Activation of soil and ground water outside the Beam Delivery System tunnel

- Production of radioactive nuclei outside the BDS concrete shielding wall is mainly due to neutron interaction with silicon and oxygen nuclei.
- $^3\text{H}$ and $^{22}\text{Na}$ produced in soil are dissolved in the water.
- There are various regulations with regard to the activity of radioactive nuclei in water.
- There are no limits for the maximum permissible activity concentrations in soil.
Reactions in the soil and water

<table>
<thead>
<tr>
<th>Element</th>
<th>Soil %</th>
<th>Water %</th>
<th>Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>55</td>
<td>89</td>
<td>$^{16}\text{O}(n,x)^3\text{H}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{16}\text{O}(n,2\alpha 2\text{n})^7\text{Be}$</td>
</tr>
<tr>
<td>Si</td>
<td>31</td>
<td></td>
<td>$^{28}\text{Si}(n,x)^3\text{H}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{28}\text{Si}(n,x)^7\text{Be}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$^{28}\text{Si}(n,\alpha\text{ P }2\text{N})^{22}\text{Na}$</td>
</tr>
<tr>
<td>Al</td>
<td>4</td>
<td></td>
<td>$^{27}\text{Al}(n,\alpha 2\text{n})^{22}\text{Na}$</td>
</tr>
<tr>
<td>Ca</td>
<td>1.2</td>
<td></td>
<td>$^{44}\text{Ca}(n,\gamma)^{45}\text{Ca}$</td>
</tr>
</tbody>
</table>
Calculation of saturation activity

- Used FLUKA to calculate the saturation activity of different radio-nuclide in soil.

- Cylinder slab geometry for the tunnel, magnets and other beam components.

- Electromagnetic and hadronic cascades initiated from the interaction of 500 GeV beam on a spoiler.
Source terms for 0.1% loss (10 kW)

<table>
<thead>
<tr>
<th>Location</th>
<th>E ± δE (GeV)</th>
<th>Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HZAB1</td>
<td>142.0 ±1.3</td>
<td>2.8</td>
</tr>
<tr>
<td>VTAB2</td>
<td>219.4 ±0.7</td>
<td>4.3</td>
</tr>
<tr>
<td>HZAB2</td>
<td>64.2 ±0.5</td>
<td>0.13</td>
</tr>
<tr>
<td>VTAB3</td>
<td>24.8 ±3.4</td>
<td>0.05</td>
</tr>
<tr>
<td>HZAB3</td>
<td>10.4 ±4.0</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Calculation of saturation activity-continued

- Folding the neutron fluence spectra calculated by FLUKA with experimental cross sections.
- Scoring directly residual nuclei produced in inelastic interactions with FLUKA.
- Using FLUKA to estimate the number of inelastic reactions by hadrons of $> 50$ MeV (star) in soil.
  - Use proportionality factors to convert the star density to activity concentration.
  - Widely used at hadron machines, should work outside thick shields in electron machines as well.
Activation cross section

\[ \sigma (\text{mb}) \]

\[ E \ (\text{GeV}) \]

\[ ^{16}\text{O}(n,X)^3\text{H} \]

\[ ^{28}\text{Si}(n,X)^3\text{H} \]
Neutron flux in soil per lost electron

Activity in soil per lost electron

$E \times d\Phi_n/dE$ (cm$^{-2}$)

$E \times dA_n/dE$ (Bq/cm$^3$)

$E$ (GeV)

$16\text{O}(n,X)^3\text{H}$

$28\text{Si}(n,X)^3\text{H}$

sum
Radionuclide concentration in soil (nuclei/cc/e)

<table>
<thead>
<tr>
<th></th>
<th>Fluence x cross section</th>
<th>Direct Isotope production</th>
<th>Star density</th>
</tr>
</thead>
<tbody>
<tr>
<td>3H</td>
<td>2.8 x10^{-9}</td>
<td>1.0 x10^{-9} (31%)</td>
<td>1.4 x10^{-9} (16%)</td>
</tr>
<tr>
<td>22Na</td>
<td>2.8 x10^{-9}</td>
<td>5.1 x10^{-10} (72%)</td>
<td>3.8 x10^{-10}</td>
</tr>
<tr>
<td>7Be</td>
<td>2.8 x10^{-9}</td>
<td>1.2 x10^{-10} (36%)</td>
<td>5.4 x10^{-10}</td>
</tr>
</tbody>
</table>
Saturation activity calculations in water

- Calculated saturation activity of different radioactive nuclei in soil
- Assumed 0.26 for fraction of water in soil
- Used (1 for $^3$H 0.15 for $^{22}$Na) extraction fraction from soil into water
- Density of water $= 1$ gm/cc
- Density of soil $= 2.1$ gm/cc
Saturation Activity of radionuclide in water immediately outside the shielding wall

- $^3$H  = 9,450 pCi/cc
- $^{22}$Na = 258  pCi/cc

- The calculated $^3$H saturation activity concentration for the SLC dump is 46,000 pCi/cc.

- The limits for activity concentration of $^3$H is the drinking water limit of 20 pCi/cc.
Shielding

- With site specific factors such as dilution due to the size of the well, distance of well to the shielding wall, the activity concentration in a drinking well could be lower by several order of magnitudes.
- Example: assume a dilution factor of 25.
- Need reduction by a factor of 20, or 4.3 HVLs.
- HVL for high energy neutrons is 14” in concrete and 4.8” in lead. Need 60” of extra concrete, or 21” of lead.
Conclusions

• Different methods using FLUKA to calculate the radio-nuclide activity concentration in soil are consistent.

• Preliminary results of calculations for the activity concentration for $^3$H in soil for the BDS collimation section is lower than the level calculated for the soil around the SLC dump.