Comparison of Radionuclide Activity in the NuMI Decay Pipe to Results from the MARS Monte Carlo

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Outline

• Introduction
• NuMI beamline
• Core sample results
• MARS simulation
• Nuclide distribution results
• Activity results
• Conclusions
Introduction

- Tritium is highly mobile.
  - Transfers from one medium to another

- Important to understand tritium production in beamline shielding.
  - Develop method of tritium inventory

- Difficult to assess tritium activity in solid samples
  - Need to extract the tritium first before measuring its activity.
    - Not guaranteed to extract the tritium.
  - Tritium is difficult to contain.

- Try MC methods to predict tritium production in shielding
  - Compare MARS output to activity from other radionuclides in core samples taken from the NuMI decay pipe shield at Fermilab.
NuMI Target Hall

120 GeV proton beam

Focus resultant pions and kaons

Graphite Target

120 GeV proton beam

Horn 1

Target/Baffle Carriage

Horn 2

Steel Shielding

Flowable Fill ρ = 2.2 g/cm³

Decay Pipe
NuMI Decay Pipe
675 m long

To Target Hall

Dolomite

2.9 m outer radius of shield
93 m
98 m

2 m diameter pipe

Decay Pipe Walkway

Neutrinos to MINOS in Soudan MN

To Absorber Hall

683 m

2.1 m outer radius

Pions and kaons decay to neutrinos and muons
Face of the NuMI decay pipe shield where the core samples were extracted.
Activity in Decay Pipe Shield

Tritium Activity
Dehumidifiers installed in target hall between 2006 and 2010

Fixed Radionuclide Activity
Maximum depth from surface: 30”
Comparison of $^{22}$Na Activity in solid sample to leachate

Leaching fraction for $^{22}$Na as a function of depth
MC Analysis of Nuclide Production

• Use MARS to predict nuclide distribution in the NuMI decay pipe shield.
  – Compare to fixed nuclide distributions such as $^7\text{Be}$ and $^{54}\text{Mn}$
• Simple model of NuMI target hall and decay pipe in MARS
• Detailed horns and target
• Idealised horn magnetic field
NuMI Target Hall in MARS

- Baffle
- Target
- Horn 1
- Horn 2
- Decay Pipe Entrance

Diagram showing the layout of the NuMI target hall in MARS with dimensions and labeling.
MC Analysis

- Core samples extracted at large radius.
  - $1.5 \text{ m} < R < 3.7 \text{ m}$
  - Inner radius of decay pipe shield: $1.0 \text{ m}$
  - Thick shielding problem.
  - Decay pipe shield has large volume.
- Use star densities with fine bins to extract spatial distributions.
- Use coarse radial bins for nuclide production.
  - Run MARS in MCNP mode
    - $E_{n,\text{th}} = 1 \text{ meV}$
Star Density per Proton in the Decay Pipe Shield

[Graph showing star density distribution with radius and Z-distance on the axes, and color scale indicating stars/cm³/s per proton]
Longitudinal Distribution Comparison

![Graph showing longitudinal distribution comparison with MARS data and labeled R = 2.1m.](image)
Radial Distribution Comparison

\[ \text{Radius (cm)} \]

\[ \text{\(^7\)Be Activity (pCi/g)} \]

\[ Z=93 \text{ m} \]
Radial Distribution Fits

• MARS Fit:
  – \( a_1 e^{-b_1 r} + a_2 e^{-b_2 r} \)
  – Identify first term with rapid drop-off at small radius
  – Identify second term with attenuation at large radius
  – \( b_1 = 0.077 \pm 0.002, \ b_2 = 0.024 \pm 0.001 \)

• Data Fit:
  – Core samples not deep enough to fit the first term
  – \( a_2 e^{-b_2 r} \)
  – \( b_2 = 0.0229 \pm 0.0011 \)
Nuclide Production Calculation

- Extract nuclide production per proton for R>1.7m
- Use DETRA to calculate activity $A_{tot}$.
  - Intensity based on NuMI POT data
  - Integrate over 375 days (300 day beam on, 75 day beam off) to compare to 2006 results
## Nuclide Activity Comparison

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>MARS Activity (pCi/g)</th>
<th>DATA Activity (pCi/g)</th>
<th>MARS Ratio $^7$Be/X</th>
<th>Data Ratio $^7$Be/X</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^7$Be</td>
<td>454±91</td>
<td>346±52</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$^{22}$Na</td>
<td>111±22</td>
<td>78.7±11.9</td>
<td>4.1±0.7</td>
<td>4.4±0.9</td>
</tr>
<tr>
<td>$^{54}$Mn</td>
<td>25.1±5.0</td>
<td>19.7±3.0</td>
<td>18.1±3.4</td>
<td>17.6±3.7</td>
</tr>
<tr>
<td>$^3$H</td>
<td>229±46</td>
<td>57.9±0.9</td>
<td>2.0±0.4</td>
<td>6.0±0.9</td>
</tr>
</tbody>
</table>

The activity at $R=2.1$ m and $Z=93$m (from Horn 1) in the NuMI decay pipe for 300 days of beam on followed by 75 days beam off.

- Activities for $^7$Be, $^{22}$Na, and $^{54}$Mn agree with the activity seen in the core samples.
- Ratio of $^7$Be/$^{22}$Na, $^7$Be/$^{54}$Mn agree very well with data.
- MARS reports greater activity for tritium
  - Tritium underreported in data as a single leach cycle does not collect all of the tritium
Tritium Leaching Predictions from MARS

• Unknown value for leaching fraction $L_{3H}$
  – Lower bound of 0.10 from $^{22}\text{Na}$ data.
  – Upper bound of 0.88 from the assumption that all of the tritium is collected in two leachings.

• Use ratio of $^{7}\text{Be}/^{3}\text{H}$ in MARS to predict $L_{3H}$
  \[
  L_{3H} = \frac{(^{7}\text{Be}/^{3}\text{H})_{\text{MARS}}}{(^{7}\text{Be}/^{3}\text{H})_{\text{DATA}}}
  \]
## Predicted Leaching Fraction

<table>
<thead>
<tr>
<th>Location from Horn 1</th>
<th>Year</th>
<th>Radius</th>
<th>$^{7}\text{Be}/^{3}\text{H from Data}$</th>
<th>Estimate $L_{3\text{H}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>93 m</td>
<td>2006</td>
<td>2.1 m</td>
<td>6.0</td>
<td>0.33±0.09</td>
</tr>
<tr>
<td>683 m</td>
<td>2006</td>
<td>1.5 m</td>
<td>8.0</td>
<td>0.25±0.07</td>
</tr>
<tr>
<td>93 m</td>
<td>2010</td>
<td>2.1 m</td>
<td>2.9</td>
<td>0.41±0.11</td>
</tr>
<tr>
<td>98 m</td>
<td>2010</td>
<td>3.0 m</td>
<td>1.8</td>
<td>0.66±0.17</td>
</tr>
<tr>
<td>249 m</td>
<td>2010</td>
<td>3.0 m</td>
<td>2.9</td>
<td>0.41±0.11</td>
</tr>
<tr>
<td>693 m</td>
<td>2010</td>
<td>1.5 m</td>
<td>3.0</td>
<td>0.40±0.10</td>
</tr>
</tbody>
</table>

**Ratio of $^{7}\text{Be}/^{3}\text{H from MARS}$:**
- 2006: 2.0
- 2010: 1.2
Conclusions

• Activity in samples taken from the NuMI decay pipe shielding in 2006 and 2010 demonstrate the mobility of $^3$H.
• Fixed nuclides like $^7$Be and $^{22}$Na can be used to benchmark Monte Carlo codes used for radionuclide production in shielding.
  – MARS prediction of nuclide distributions match data.
  – Predicted activity of fixed nuclides agree with data.
• Comparison of tritium activity predicted by MARS to the activity seen in the samples implies that only 41% of the tritium collected in the deep samples.