Integration of Field Investigations and an Innovative Modelling Tool in the Prioritization of Mitigation Strategies for an Abandoned Uranium Mine

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Site Location
Site Overview

- Langley Bay
- Under Water Tailings
- Uncontained Tailings
- Waste Rock
- Zeemel Bay
- Plant Site
- Open Pit
- Tailings Deposits
Uncontained Tailings

Dashed Outline represents Gamma readings > 1μSv/hr
Background - History

- Uranium Mine opened in 1955 with Open pit and went Underground in 1961
- Produced 6900 tons of U at a grade of 0.15%
- 3.5 Mm$^3$ of tailings
- 2.2 Mm$^3$ of waste rock
Background - History

• Mill Process – sulphuric acid leach (pH=1) – tailings NOT neutralized before discharge

• Sulphuric Acid produced on site using elemental Sulphur
Ground Fires Around the Sulphur Storage Pad
Background - Studies

- Detailed assessment in 1980s – *National Uranium Tailings Program (NUTP)*

- Environmental Impact Statement (EIS) studies for reclamation (2010)

- Risk assessment identified constituents of potential concern (COPC) in surface water as potential risks:
  - Uranium (eco-risk – Zeemel Bay)
  - Radium-226 (human and eco radiation dose – Langley Bay)
  - Arsenic (human food-chain risk)
  - Cadmium (aquatic risk)
Objectives of this Study

• Identify and quantify sources and pathways of COPCs

• Apply loadings model to assess current conditions and evaluate mitigation strategies
Waste Rock - Conceptual Model

- 50 Years of weathering
- Not acidic
- Assume Steady-State
East Waste Rock Pile

Flow Into Rock Pile

Catchment Area

Zeemel Bay

SP-1 Seep

Open Pit
Waste Rock Characterization – Conceptual Model

Characterization

Soluble Loads (Modified Shake Flask)

Pore Water

Grain Size Adjustments

Constant Solubility for Uranium

Loadings
Characterization Program – Waste Rock

- Test pits with excavator - 124 Samples
- 1m intervals to depths of about 5m
- Typical samples less than 75 mm (3”) grain sizes
- Select samples for grain-size assessment;
  - Less than 50 mm
  - 50 to 150 mm
  - Greater than 150 mm
Characterization Program – Waste Rock

**Laboratory analysis:**
- Metal contents
- Radiological content
- Leachable Mass – Shake Flask (modified SWEP)
- ABA

![Graph showing relationship between Leachable Mass (mg/kg) and Total Solid Content (mg/kg)]
Pore Water Concentrations in Waste Rock
## Pore Water Concentrations in Waste Rock

- Back calculation from shake flask results (mg/kg) and measured moisture contents

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radium-226</td>
<td>Bq/L</td>
<td>11</td>
<td>75</td>
<td>351</td>
<td>115</td>
<td>151</td>
<td>267</td>
<td>60</td>
<td>45</td>
<td>134</td>
</tr>
<tr>
<td>Sulphate (SO₄)</td>
<td>mg/L</td>
<td>392</td>
<td>1812</td>
<td>2765</td>
<td>1239</td>
<td>1294</td>
<td>2693</td>
<td>2190</td>
<td>3609</td>
<td>1924</td>
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<tr>
<td>Arsenic (As)</td>
<td>mg/L</td>
<td>0.03</td>
<td>1.72</td>
<td>2.46</td>
<td>0.74</td>
<td>0.73</td>
<td>1.50</td>
<td>1.29</td>
<td>1.39</td>
<td>1.22</td>
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<tr>
<td>Lead (Pb)</td>
<td>mg/L</td>
<td>0.18</td>
<td>0.86</td>
<td>2.22</td>
<td>1.10</td>
<td>0.77</td>
<td>6.03</td>
<td>1.73</td>
<td>3.26</td>
<td>1.91</td>
</tr>
<tr>
<td>Uranium (U)</td>
<td>mg/L</td>
<td>8.9</td>
<td>10.3</td>
<td>15.1</td>
<td>4.3</td>
<td>5.4</td>
<td>21.1</td>
<td>3.4</td>
<td>7.4</td>
<td>8.9</td>
</tr>
</tbody>
</table>
Grain Size Considerations

- Rock was 30 to 40% finer than 2"
- Typical decrease with increasing particle size

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ratio Leachable Content &lt;2-inch Dia. to &gt;6-inch Dia.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radium (Ra-226)</td>
<td>2.3</td>
</tr>
<tr>
<td>Sulphate (SO₄)²</td>
<td>3.6</td>
</tr>
<tr>
<td>Arsenic (As)</td>
<td>5.8</td>
</tr>
<tr>
<td>Lead (Pb)</td>
<td>5.5</td>
</tr>
<tr>
<td>Uranium (U)</td>
<td>4.6</td>
</tr>
</tbody>
</table>
Waste Rock Seepage – SP1 and SP 3

Flow into Rock Pile
U = 0.3 mg/L

SP1 Seep
U = 10 mg/L

SP3 Seep
U = 14 mg/L

SP1
SP3
Main Tailings – Conceptual Model

- 50 Years of weathering
- Not acidic
- Assume Steady-State

- Majority of precipitation reports as runoff
- Key loadings out of tailings:
  - surface flushing of upper 10(s) of cm of tailings
  - Subsurface (groundwater) flow
Gunnar Main Tailings – Solids Sampling

- Sampling by hand auger
- Depth intervals (bgs) of
  - 0-10 cm
  - 10-20 cm
  - 40-50 cm
  - 70-80 cm.
- Drive-point Piezos 1.5 mbgs
# Pore Water Concentrations in Gunnar Tailings

- Back calculation from SFE (mg/kg)
- Measured moisture content on each sample
- Sulphate over-estimated – artifact of Gypsum dissolution

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>Units</th>
<th>Main Tailings Area</th>
<th>Uncontained Tailings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Average</td>
<td>Minimum</td>
</tr>
<tr>
<td>Radium 226</td>
<td>Bq/L</td>
<td>80</td>
<td>18</td>
</tr>
<tr>
<td>Sulphate (SO₄)</td>
<td>mg/L</td>
<td>65,888</td>
<td>4,628</td>
</tr>
<tr>
<td>Arsenic (As)</td>
<td>mg/L</td>
<td>0.49</td>
<td>0.061</td>
</tr>
<tr>
<td>Lead (Pb)</td>
<td>mg/L</td>
<td>0.15</td>
<td>0.0019</td>
</tr>
<tr>
<td>Uranium (U)</td>
<td>mg/L</td>
<td>22.6</td>
<td>1.3</td>
</tr>
</tbody>
</table>
Uncontained Tailings – Conceptual Model

Generalized Cross Section

Drawing Not to Scale
Uncontained Tailings – Sampling

- Samples collected at 12 stations along drainage path
Uncontained Tailings – Flow Directions
## Pore Water Concentrations Uncontained Tailings

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>Units</th>
<th>Average</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radium 226</td>
<td>Bq/L</td>
<td>21.1</td>
<td>0.73</td>
<td>229</td>
<td>6.91</td>
</tr>
<tr>
<td>Sulphate (SO\textsubscript{4})</td>
<td>mg/L</td>
<td>3,464</td>
<td>40</td>
<td>62,359</td>
<td>565</td>
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<tr>
<td>Arsenic (As)</td>
<td>mg/L</td>
<td>0.054</td>
<td>0.002</td>
<td>0.42</td>
<td>0.020</td>
</tr>
<tr>
<td>Lead (Pb)</td>
<td>mg/L</td>
<td>0.50</td>
<td>0.005</td>
<td>8.97</td>
<td>0.068</td>
</tr>
<tr>
<td>Uranium (U)</td>
<td>mg/L</td>
<td>0.28</td>
<td>0.004</td>
<td>4.05</td>
<td>0.120</td>
</tr>
</tbody>
</table>

- Back calculation from SFE (mg/kg)
- Measured moisture content on each sample
Loadings Assessment

Waste Rock:
• Load = Porewater Concentration x Infiltration Rate
  » Corrected for grain size (except uranium)

Main Tailings:
• Load = Soluble Mass (top 10 cm) flushed each year
  + Deep Porewater flow x Concentrations

Uncontained Tailings:
• Load = Soluble Mass Flushed each year
Loadings Assessment - Median Concentrations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Waste Rock</th>
<th>Main Tailings (Runoff only)</th>
<th>Uncontained Tailings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radium (Ra-226)</td>
<td>MBq/a</td>
<td>2,718</td>
<td>202</td>
<td>349</td>
</tr>
<tr>
<td>Arsenic (As)</td>
<td>kg/a</td>
<td>17</td>
<td>2.4</td>
<td>1.0</td>
</tr>
<tr>
<td>Lead (Pb)</td>
<td>kg/a</td>
<td>27</td>
<td>0.1</td>
<td>3.4</td>
</tr>
<tr>
<td>Uranium (U)</td>
<td>kg/a</td>
<td>295</td>
<td>58</td>
<td>6.1</td>
</tr>
</tbody>
</table>
Integration Into Loadings Model

• Independent source term loadings estimates

• Combine with site flow rates

• Validate with extensive monitoring data
MineMod™

- Mine-Mod developed in house in C++ and Graphic interface

- Provides a real time platform to facilitate proactive closure planning, review reclamation options and to ensure the most appropriate strategies are implemented

- Valuable tool for the mine design process (provides a means to assess operational/management practices)
MineMod™

- Model is a combination of a database management system and calculation tool
- GIS-based in order to relate model and data components to geographical and site features
- User flexibility for the definition of source-term loading rates, site features and data import
- Time varied flows, loading rates, concentrations
- Real time processing of scenarios for round table meetings and regulator discussions/presentations
Model Inputs

• Loadings model combined the quantified releases from individual sources at the site with flows (surface and subsurface)

• Inputs included
  – Results from mine waste geochemistry
  – Groundwater monitoring data
  – Surface water monitoring data
  – Seepage data
  – Baseline surface water chemistry
  – Hydrology
  – Hydraulic exchange rate between the Lake and the Bays
Source Term Overview

- 4 surface tailings deposits and 1 submerged
- Uncontained (spilled) tailings and floodplain deposits in drainage creek
- Two large waste rock stockpiles, as well as fill material present throughout the property
- Flooded pit
Langley Bay

Ra-226 – Risk?

Zeemel Bay

U – Risk?
Basecase Scenario

- Primary objective to evaluate loading rates to key receiving waterbodies
- Basecase developed for the status quo and used as a benchmark for sensitivity analyses
- Used the 50th percentile of loadings values
- Validated using extensive monitoring data for the site
- Reasonable prediction of observed water quality when independently derived sources incorporated

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Water Quality Guideline</th>
<th>Site-specific Remedial Objective</th>
<th>Minimum</th>
<th>Geometric Mean</th>
<th>Median</th>
<th>Maximum</th>
<th>Predicted</th>
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</thead>
<tbody>
<tr>
<td>Arsenic (As)</td>
<td>0.005</td>
<td>0.1</td>
<td>0.0002</td>
<td>0.00027</td>
<td>0.0003</td>
<td>0.0003</td>
<td>0.0002</td>
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<tr>
<td>Cadmium (Cd)</td>
<td>0.000014</td>
<td>0.0003</td>
<td>0.0001</td>
<td>0.000037</td>
<td>0.0001</td>
<td>0.001</td>
<td>0.0001</td>
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<tr>
<td>Lead (Pb)</td>
<td>0.0010</td>
<td>0.013</td>
<td>0.002</td>
<td>0.000017</td>
<td>0.0001</td>
<td>0.002</td>
<td>0.0001</td>
</tr>
<tr>
<td>Radium-226 (Ra-226)</td>
<td>0.11</td>
<td>-</td>
<td>0.090</td>
<td>0.12</td>
<td>0.12</td>
<td>0.17</td>
<td>0.11</td>
</tr>
<tr>
<td>Sulphate (SO₄⁾</td>
<td>100</td>
<td>-</td>
<td>6</td>
<td>7</td>
<td>7</td>
<td>14</td>
<td>7</td>
</tr>
<tr>
<td>Uranium (U)</td>
<td>0.015</td>
<td>0.09</td>
<td>0.0006</td>
<td>0.001</td>
<td>0.001</td>
<td>0.002</td>
<td>0.001</td>
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</tbody>
</table>
Basecase Scenario
Comparison of Predicted Results to Measured SW Values

[Sulphate graph]

[Sulphate graph]

[Map with locations]
Basecase Scenario
Comparison of Predicted Results to Measured SW Values
Basecase Scenario
Comparison of Predicted Results to Measured WR Seepage
Several scenarios developed to investigate the under-estimation of uranium in surface water down-gradient from the WRPs.

Loading rates from the WRP’s were adjusted using:

- 10th percentile porewater concentrations
- 90th percentile porewater concentrations
- Arithmetic average porewater concentrations
- 50th percentile porewater concentrations, *no grain size correction*
- 10th percentile porewater concentrations, *no grain size correction*
- 90th percentile porewater concentrations, *no grain size correction*
Sensitivity Scenarios
Waste Rock Piles – Loading Rates

90th percentile
Average
Basecase
10th percentile

EcoMetrix Incorporated
Sensitivity Scenarios
Waste Rock Piles – Grain Size Correction

90th percentile
50th percentile
Basecase
10th percentile

Uranium

Concentration (mg/L)

May-11 Jul-11 Sep-11 Nov-11 Jan-12 Mar-12 May-12 Jul-12 Sep-12
Results indicate that upper bound loading rates are required to resolve measured surface water values.

Uranium may be controlled by an equilibrium reaction within the WRP.

Solubility of uranium is not expected to be a function of particle size.
Several *additional scenarios* were developed to investigate sources of uranium in surface water down-gradient from the WRPs:

- Upper bound SW flow rates reporting to the WRP
- Upper/Lower bound loading rates from the Acid Plant area
- Surface water flow pathway from the Main Tailings
- Upper bound GW flow rate from the MT to the AP

Could not reconcile missing uranium concentrations
Summary

• Loadings model was able to reasonably predict the observed concentrations of COPCs in receiving waterbodies when independently derived sources incorporated.

• Provides a path forward in assessing potential remediation strategies and subsequent trade off studies.

• However, data suggest that there may be uranium loadings that are unaccounted for in the recognized sources on site.

• The uranium load from the WRP’s is likely underestimated by the median porewater concentrations.

• Potential solubility control and/or source within or up-gradient of the footprint of the WRP.
Recommendations

- Flows reporting to the seepage locations surrounding the WRP’s be further quantified
- Flow originating from the catchment up gradient of the WRP be investigated
- Acid Plant site be further investigated wrt flow direction and chemistry

~200,000 m$^3$/a report to the WRP from Catchment above
Conclusions

• Appropriate data collection and interpretation is necessary to characterize mine sources

• Holistic approach to site wide loadings allows for focus on priority sources and closure measures

• Becomes a useful communication tool when evaluating site aspects with regulators/industry
Thank you for your attention!

Questions?