Mine Closure - International Experiences

Mike O’Kane, P.Eng.,
O’Kane Consultants (Canada)
&
Steve Pearce, Sr. Geoenvironmental Scientist,
O’Kane Consultants (United Kingdom)

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Discussion Points

- Some Thoughts and Comments on Mine Closure Experiences
  - With a slight focus on cover systems
- Some Case Studies
  - Different climates
  - Different legacies
- Discussion on Aspects of a new Global Cover System Design Guidance Document
- Is there a Opportunity to Achieve a “Better Outcome”?
- Summary Discussion Points
Acknowledgements

- Boliden
- Aboriginal Affairs and Northern Development Canada
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- International Network for Acid Prevention (INAP)
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Acknowledgements

Professor of Civil and Geological Engineering
3B48 Engineering Building, University of Saskatchewan
57 Campus Drive, Saskatoon, SK.
Canada V8V 4Z8
lee.barbour@usask.ca

Integral Ecology Group

Justin Straker, M.Sc., P.Ag.
Forest Ecologist, Soil Scientist, Principal
PO Box 23012 Cook St. RPO, Victoria, BC
Canada V8V 4Z8
jstraker@integralecologygroup.com
Acknowledgements

Gord McKenna, PhD, PEng, PGeo
Senior Geotechnical Engineer
Suite 500 - 980 Howe Street
Vancouver, BC
Canada V6Z 0C8
gmckenna@bgcengineering.ca

Derrill Shuttleworth
Illustrator
956 Chichester Road
Gabriola Island, BC
Canada V0R 1X1
derrillshuttleworth@shaw.ca
A Suggested Design Approach

Define Cover System Design Objectives

- Site Identification
- Pre-Screen
- Cover System Alternatives
- Site and Hydrogeological Characterization
- Develop Cover System Design Alternatives
- Performance Predictions
- Water Quality Assessment
- Ecological Risk Assessment
- Establish Cover System Performance Criteria
- Cover System Water Balance Predictions
- Cover System Field Trials
- Landscape Design Considerations
- Review of Construction Costs & Schedule
- Risk Analysis of Cover System Design Alternatives
- MAEA

Decision (Select Cover System Design)

Alternatives Analysis

Post-Construction Monitoring & Maintenance

Permit Level Design

Develop Construction Drawings & Technical Specifications

Consultation w/ Stakeholders

Site Plan - Approval Process

MEND 2012
A Suggested Design Approach

1. Objectives
   - Holistic

2. Design Criteria
   - Could be very specific (e.g. Factor of Safety or Net Percolation)
   - Could be generalized guidelines
   - Developed from objectives

3. Design
   - To meet the criteria
   - Flexible
   - Holistic (embraces the inevitability of change / evolution)
   - Falls from criteria

4. Performance Criteria
   - Developed from criteria
   - Developed from design
   - Developed in concert with Site Wide Closure monitoring

Develop a “Base Case” Conceptual Design to Assist with Determining Closure / Design Criteria and Design
General Criteria

- The reclamation and closure of WRDs must guarantee the following:
  - Reclaimed WRDs shall support the end land-use, which is wildlife habitat.
  - Reclaimed WRDs must have a minimum 1.5 factor of safety against the Maximum Design Earthquake event.
  - Reclaimed WRDs shall possess a maximum elevation that is equal or lower than the highest elevation of natural landforms with 15 km of the WRD.
  - Final WRD slopes must possess a minimum overall gradient of 3H:1V with internal bench faces no steeper than 2.5H:1V.
  - Reclaimed WRDs must be able to safely convey peak flows generated from the 100-year, 24-hour duration design storm event.
  - Reclaimed WRDs must guarantee that post-closure seepage waters will not adversely affect the quality of surface water receptors.
  - Reclaimed WRDs shall possess a minimum topsoil thickness of 0.3 m for revegetation purposes.
  - Reclaimed WRDs must support the development of self-sustaining ecosystems.
Watch out for High-Risk Promises

- Promises that go against nature
  - *Wildlife can be kept from feeding on metaliferous vegetation*

- Promises with no definition
  - *Make the land better than it was before*

- Promises based on development of future technology
  - *Agreeing to develop new computer models for prediction*

- Promises with low probability of success
  - *Agreeing to create a maintenance-free landscape*

- Promises that are technically impossible
  - *The site will have no erosion*

- Promises based on complex numerical models
  - *Complex computer models that show certain end-pit lake performance far into the future under all conditions*

*McKenna and O’Kane, 2011*
More High-Risk Promises

- Promises with-open ended timeframes and promises that cannot be tested in human time-scales
  - *Promises of good performance in the probable maximum precipitation event (PMP) or probably maximum flood (PMF)*
- Promises that are not self-sustaining or ignore natural ecological succession
  - *Creation of specific ecosystems at odds with soils or aspects*
- Promises that ignore economic reality
  - *Use salvage assets at closure to pay for remaining reclamation*
- Promises that ignore human nature
  - *Keeping fish from lakes and streams*
- Promises that may be conflicting
  - *Recreation and wildlife*

*McKenna and O’Kane, 2011*
Setting Simple Landscape Performance goals with Stakeholders, Regulators, and Shareholders

• Rather than setting lofty, unobtainable goals and failing
  • Set simple clear goals, and achieve them
• Ensure goals are clearly recorded and communicated, and that plans, designs, and performance are continually measured against these goals
• Ensure buy-in of goals from all parties
• Recognize there will need to be give and take in changing goals, but only until a landform is reclaimed

McKenna and O’Kane, 2011
Shuttleworth, 2011
Context for Cover Systems

- Groundwater and Surface Water
- Sulphide Oxidation
- Water Transport
- Gas Transport
  - Advection
  - Diffusion
- Example:
  - Net Percolation Rate?
- Example:
  - Oxygen Ingress Rate?
Cover System Objectives

- **Closure Objectives**
- **Cover System Design Objectives:**
  - Physical Stabilization
  - Chemical Stabilization

Meeting Land-use Expectations

“Less Engineered”

“More Engineered”

Straker and O’Kane 2014
Cover System Objectives

Cover Systems…
More than Net Percolation, Oxygen Ingress, and Erosion Management

In fact…..
Landuse can often be a Significant Driver for Determining Cover System Objectives

Social Expectations, Wildlife Habitat, Landuse, etc.

- Places, spaces, and infrastructure
- Food
- Commercial (e.g. Tourism)
- Energy (e.g. solar field)
- Museum / interpretive / historic
- Science, technology, and learning
- Recreational
- Permanent or post mining maintenance
- Traditional land use

McKenna 2012
Case Study… “Legacy Site”

Site: Ontario, Canada

Ayres et al 2012
Case Study... “Legacy Site”

- **Canadian Shield** – numerous bedrock outcrops and lakes
- **Open pit mining (nickel)** between 1988-91 & 1994-98
- **6.4 Mt of waste rock** on surface – 80% is mafic norite, avg. **S of 3%**
- **Several acidic seeps** developed
- **Semi-humid climate** – annual precip. of 900 mm (30% as snow) & potential evaporation of 520 mm
Case Study... “Legacy Site”

- **Open Pit**
  - Area 10 ha
  - Volume 3.2 Mm$^3$

- **WTP sludge storage**

- **NE Waste Rock Dump**
  - Area 13 ha
  - Volume 6.2 Mt

- **NW Waste Rock Dump**
  - Area 2 ha
  - Volume 0.2 Mt

Ayres et al 2012
Case Study... “Legacy Site”

• **Water Treatment Plant**
  - Lime treatment
  - Treats water from pit and seepage collection ponds
  - Capacity of ~100 m³/hr

• **Seepage Collection System**
  - Series of dams and ponds to collect acidic seepage from waste rock dumps
  - Significant pumping requirements (hydro costs)

Ayres et al 2012
Case Study… “Legacy Site”

- Minimal options for closure due to proximity of Lake
- Based on available data, Site decided to relocate all waste rock to open pit (with lime addition @ 2kg/tonne) and place a cover system

- Pit surface area ~ 10 ha

- Objectives of cover system:
  - Reduce ingress of atmospheric $O_2$
  - Reduce infiltration of meteoric $H_2O$
  - Growth medium for vegetation

Ayres et al 2012
Case Study… “Legacy Site”

- **Without cover system:**
  - ARD above phreatic surface
  - Poor pit water quality (pH, SO\(_4\), metals)

- **Alternate cover system scenarios:**
  - Control of ARD (except for “faulty cover” scenario)
  - Gradual decline in SO\(_4\) and metals

- **Alternate cover system scenarios evaluated:**
  - Thickness of barrier and growth medium layers

- **Key criteria evaluated:**
  - High / Low net percolation
  - High / low O\(_2\) diffusion

Control of oxygen ingress more critical than control of net percolation for cover system performance (recall GW inflow)

Ayres et al 2012
Case Study… “Legacy Site”

Cover System Field Trials:

TP#1

GCL (~1 cm)

N/C till (90 cm)

TP#2

Comp. sand-bentonite (45 cm)

N/C till (90 cm)

TP#3

Comp. silt/trace clay (60 cm)

N/C till (90 cm)

TP#4 (control)

Waste Rock

Ayres et al 2012
## Case Study… “Legacy Site”

<table>
<thead>
<tr>
<th>Barrier Layer Thickness</th>
<th>Growth Medium Layer Thickness</th>
<th>Simulation</th>
<th>Barrier Layer Deg of Saturation</th>
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<tbody>
<tr>
<td>30 cm</td>
<td>90 cm</td>
<td>Initial conditions</td>
<td>90%</td>
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<tr>
<td></td>
<td></td>
<td><strong>Dry year – run 1</strong></td>
<td><strong>78%</strong></td>
</tr>
<tr>
<td>45 cm</td>
<td>90 cm</td>
<td>Initial conditions</td>
<td>92%</td>
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<tr>
<td></td>
<td></td>
<td><strong>Dry year – run 1</strong></td>
<td><strong>82%</strong></td>
</tr>
<tr>
<td>60 cm</td>
<td>90 cm</td>
<td>Initial conditions</td>
<td>93%</td>
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<tr>
<td></td>
<td></td>
<td><strong>Dry year – run 1</strong></td>
<td><strong>85%</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Dry year – run 2</strong></td>
<td><strong>78%</strong></td>
</tr>
<tr>
<td>30 cm</td>
<td>120 cm</td>
<td>Initial conditions</td>
<td>93%</td>
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<tr>
<td></td>
<td></td>
<td><strong>Dry year – run 1</strong></td>
<td><strong>83%</strong></td>
</tr>
<tr>
<td><strong>45 cm</strong></td>
<td><strong>120 cm</strong></td>
<td>Initial conditions</td>
<td><strong>98%</strong></td>
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<tr>
<td></td>
<td></td>
<td><strong>Dry year – run 1</strong></td>
<td><strong>94%</strong></td>
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<tr>
<td></td>
<td></td>
<td><strong>Dry year – run 2</strong></td>
<td><strong>90%</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Dry year – run 3</strong></td>
<td><strong>86%</strong></td>
</tr>
</tbody>
</table>

Ayres et al 2012
Case Study… “Legacy Site”

Ayres et al 2012
Case Study... “Legacy Site”

Ayres et al 2012
Case Study… “Legacy Site”

Ayres et al 2012
Case Study... “Legacy Site”

Ayres et al 2012
Case Study... “Legacy Site”
Case Study... “Legacy Site”

Ayres et al 2012
Case Study… “Legacy Site”
Case Study… “Legacy Site”
Case Study... “Legacy Site”

Performance Monitoring

LEGEND:
- Pit backfill monitoring well (PBMW04–DX)
- Meteorological station
- Primary in situ cover monitoring site (P–OX)
- Secondary in situ cover monitoring site (S–XX)
- Weir structure (W–OX)
- Shed for lysimeter tipping bucket
- In situ temperature sensor (T–OX)
- CMT monitoring well
  (see Table 3 for details)

Ayres et al. 2012
Case Study... “Legacy Site”

Moisture Cycling in Barrier Layer

Ayres et al 2012
Case Study... “Legacy Site”

Oxygen Diffusion and Mass Flux

Ayres et al 2012
### Case Study… “Legacy Site”

#### Oxygen Diffusion and Mass Flux

<table>
<thead>
<tr>
<th>Year</th>
<th>P-01 $D_e$ (10^{-11} m^2/s)</th>
<th>P-02 $D_e$ (10^{-11} m^2/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>42</td>
<td>17</td>
</tr>
<tr>
<td>2007</td>
<td>36</td>
<td>3.9</td>
</tr>
<tr>
<td>2008</td>
<td>14</td>
<td>1.8</td>
</tr>
<tr>
<td>2009</td>
<td>14</td>
<td>1.8</td>
</tr>
<tr>
<td>2010</td>
<td>14</td>
<td>1.8</td>
</tr>
<tr>
<td>2011</td>
<td>6</td>
<td>1.9</td>
</tr>
</tbody>
</table>

*Minimum required 376*  

**Ayres et al 2012**
Case Study... “Legacy Site”

Thermal Cycling in Barrier Layer

Ayres et al 2012
Case Study… “Legacy Site”

Backfilled and Covered Pit Water Balance

<table>
<thead>
<tr>
<th></th>
<th>2006</th>
<th>2007</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation</td>
<td>765 mm</td>
<td>584 mm</td>
<td>809 mm</td>
<td>556 mm</td>
<td>728 mm</td>
</tr>
<tr>
<td>Runoff and interflow</td>
<td>62%</td>
<td>39%</td>
<td>40%</td>
<td>34%</td>
<td>38%</td>
</tr>
<tr>
<td>Evapo-transpiration</td>
<td>35%</td>
<td>57%</td>
<td>54%</td>
<td>68%</td>
<td>68%</td>
</tr>
<tr>
<td>Net percolation</td>
<td>3%</td>
<td>3%</td>
<td>1%</td>
<td>1%</td>
<td>5%</td>
</tr>
<tr>
<td>Change in storage</td>
<td>0</td>
<td>1%</td>
<td>5%</td>
<td>-2%</td>
<td>5%</td>
</tr>
</tbody>
</table>

Ayres et al 2012
Case Study... “Legacy Site”

Pit Overflow Water Quality

Ayres et al 2012
Meeting Performance Expectations

Common Cover System Failures

Or…. Six Ways to Fail your Cover System

From: INAP 2015
Meeting Performance Expectations

1. Poorly Defined, Unrealistic and/or Poorly Communicated Cover System Objectives

From: INAP 2015
Meeting Performance Expectations

2. Challenging Constructability and/or Inadequate / Inappropriate Construction QCA
Meeting Performance Expectations

3. Inadequate / Inappropriate Characterization

- Climate
- Materials
- Transfer of a specific design
Meeting Performance Expectations

4. Inadequate Appreciation for Influence of Basal Flow Conditions

From: INAP 2015
5. Surface Water Management

- Is it an engineering design that incorporates geomorphic principles?
- Reduction of Flow Capacity
  - Glaciation
  - Sediment
  - Vegetation
  - Beavers
6. Failure to Meet End Land-Use Objectives / Expectations
Case Study... a simpler cover system

20 km from Lake Victoria
Falls in Geita Forest Reserve

Dobchuk et al 2015
Case Study… a simpler cover system

Rainfall: 1016 mm
PE: 1370 mm

Average Monthly Rainfall (mm)

Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec

110 110 | 108 107 | 137 | 169 | 113 | 104 | 107 | 89 | 119 | 121 | 121 | 121

O’Kane Consultants
Integrated Mine Waste Management and Closure Services
Specialists in Geochemistry and Unsaturated Zone Hydrology

Dobchuk et al 2015
Case Study... a simpler cover system

- **Waste rock:**
  - Primary sulfide is pyrite
  - Carbonate mostly calcite
  - ~38% is potentially acid forming (PAF)

- **Tailings:**
  - 4% pyrite
- Only one seep of significance
- Downstream compliance points show some impact but quality meets discharge limits

Seep Location Pre-2010

Mtakuja River

WD1

NTSF
Case Study... a simpler cover system

- Mt Morgan
- Woodcutters
- Brukunga
- McArthur River
- Rum Jungle
- Kennecott Utah Copper

All with Similar Climate to Geita

Dobchuk et al 2015
Case Study... a simpler cover system

Encapsulation of PAF waste rock

Dobchuk et al 2015
Case Study... a simpler cover system

Dump PAF placement

Pit and dump walkovers by PAF team
Case Study… a simpler cover system

Crest berms and slope back towards natural hill slope

Clay layers and truck compaction of lift surfaces

Dobchuk et al 2015
Case Study… a simpler cover system

No Cover

Simple Cover
(NP ~ 15% of Rainfall)

Landform Design

Dobchuk et al 2015
Can we Quantify This...??

*Or in other words... can we use*

...“Quantitative Assessment Tools”... to inform on

...“Waste Placement Guidelines”...
What are we Quantifying?

End of Mining and cover waste from this point forward

Cumulative Acidity ($t\, H_2SO_4$)

- Acidity Produced
- Acidity Stored
- Acidity Mobilized
- Acidity Released (toe/basal seepage)

Years

Pearce et al 2015
What are we Quantifying?

Cumulative Acidity (t \( \text{H}_2\text{SO}_4 \))

Acidity Produced

Acidity Mobilized

Acidity Released (toe/basal seepage)

Acidity Stored

Years

 Pearce et al 2015
What are we Quantifying?

- Acidity Produced
- Acidity Stored
- Acidity Mobilized

Economic Benefit with Reducing Produced, Stored and Mobilized Acidity?

Reduce Produced, Stored and Mobilized Acidity

Pearce et al 2015
And... When we ask that Question

- We are not asking what is essentially the “Current Question” at most sites:
  - “What is the Shortest Haul to Place Waste?”
  - OR...
  - “Can we Build a WRD that limits Sulfide Oxidation?”

  - Rather, it is a Question of:
    - How do we Sequence the Development of the Open Pit(s) so we can Optimize the Haul
    - AND...
    - Construction of the Waste Rock Dump?”

- At the very least we should strive to improve our understanding when we can’t change dumping practices
Noting that...

- **The “OR” Question:**
  - Drives us to be *Compliant* and *Efficient*

- **The “AND” Question:**
  - Drives us to be *Effective* and *Sustainable*

- In the end, it will always be an *Economic Decision*

- **But... Using the “AND” Question:**
  - Allows us to *Fully* develop an *Economic Analysis* taking into account *Uncertainties* and *Risk* associated with characterization, long-term ML/ARD management (covers, water collection, water treatment etc.)

- Now... let’s focus on illustrating the tools to undertake the quantitative assessment of the “AND” Question
Why a Quantitative Approach

Complex and interrelated factors require a Quantitative method

1) Climate

2) Sulfide Content

3) Physical Characteristics

4) Structure of WRD due to Placement Method

5) Closure Measures (covers, treatment, etc.)

Pearce et al 2015
Why a Quantitative Approach

Complex and interrelated factors requires Quantitative method

• We typically can only “control” # 4) and # 5)

• Relative benefit of optimizing # 4) Can be assessed to determine how to reduce ML/ARD risks more effectively (technical and economic) than relying solely on # 5)

Pearce et al 2015
Quantitative Model

- Analytical model that has **algorithms** to determine:
  1. Internal heating of waste
  2. Acid production
  3. Seepage rate (and acid load)
  4. Gas generation (e.g. CO$_2$)

- Produces numerical output so waste placement techniques can be compared quantitatively

  *For Example:* How much less acid do we get if we end tip at 5m vs 30m?
Quantitative Model

- Lift height
- "Waste rock management factor" for lift
- Dump geometry (height/volume)
- PAF:NAF ratio and Waste Schedule
- Pyrite oxidation rate of PAF
- ANC (availability of ANC in waste material)
- External air temperature
- Sulfide grade of PAF
- Gas flow characteristics of waste (air permeability, diffusion)

All of these inputs can be derived from typical studies undertaken at site. This model is therefore easy to implement as part of planning.
Quantitative Model

Segregation Factor

Pearce et al 2015
Quantitative Model

Segregation Factor

10m lifts

Oxygen

5
10
15
20
25
30
35
Depth (m)

Aug-14
Sep-14
Oct-14
Nov-14
Dec-14
Jan-15
Feb-15
Mar-15

Lift 3
Lift 2
Lift 1/ Compacted Clay layer

30m lift

Oxygen (%): 14 15 16 17 18 19 20 21

0
5
10
15
20
25
30
35
Depth (m)

Nov-13
Dec-13
Jan-14
Feb-14
Mar-14
Apr-14
May-14
Jun-14

High oxygen ingress in base of lift in “rubble zone”

Pearce et al 2015
Quantitative Model

Compaction Factor

Pearce et al 2015
Quantitative Model

Structure Effect on Air Flow

1 x 10^{-1} \text{m}^3/\text{m}^2\text{s}

1 x 10^{-4} \text{m}^3/\text{m}^2\text{s}

1 x 10^{-6} \text{m}^3/\text{m}^2\text{s}

Pearce et al 2015
Field Verification of Model Approach

Field oxidation rates are influenced by scale
- Climate…
- Structure…
- Segregation…
- Texture…
- Temperature…
- etc.

Pearce et al 2015
Summary Discussion Points

- **Climate has an overarching influence on closure planning**
  - e.g. Cover systems
  - It is our first “filter” for design
  - It must be site-specific
  - We must account for climate change
Summary Discussion Points

- Setting Achievable Objectives and Communicating these Objectives is Paramount to “Good” Closure Planning

- From Achievable Objectives come Design Criteria and Designs that can be Permitted
While Challenging... with robust design and construction, we can create cover systems that manage oxygen ingress to levels that meet design criteria and allow for meeting closure objectives.
Summary Discussion Points

• **To be Effective…**

• A Closure Plan Must be Aligned with the Mine Plan, otherwise one could argue we are “creating Legacy Sites”

• **We can make our Closure Plans Very Effective…**

• If this Alignment occurs from the Beginning

McKenna 2011
Summary Discussion Points

• **Field Performance Monitoring** is Vital to Enhancing and Building **Trust** with respect to Closure Plans, and
• **For Developing further Understanding for Risk**
Thank You!

O'Kane Consultants
Rainbow of Hope for Children, and Habitat for Humanity Initiative El Salvador