# Appendix 4-EE

## Waste Rock Management Update - December 2018

# Crown Mountain
## Waste Rock Management Update

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Dr. Seth D'Imperio, Principal Microbiologist
Enviromin, Inc.

December 13, 2018

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## Outline

- 9:30 Safety Share and Introductions (sign in sheet)
- 9:45 Crown Mountain Waste Management Objectives
  - Nitrate and Selenium
  - Conceptual design of unsaturated dump to achieve suboxic conditions
- 10:00 Snapshot of Results
- 10:15 Biogeochemistry of Selenium and Nitrate Reduction in Mined Rock
  - What does it take to drive these processes
  - Case Study of Unsaturated Waste Rock from the Elk Valley
- 10:45 Tour of Enviromin Laboratory
- 11:00 Results and Discussion
  - Preliminary Modeling – proof of concept
  - How fast is oxygen consumed?
  - Nitrate and Se reduction rates under different $O_2$ exposure
- 11:30 Questions and Path Forward
- 12:00 Adjourn

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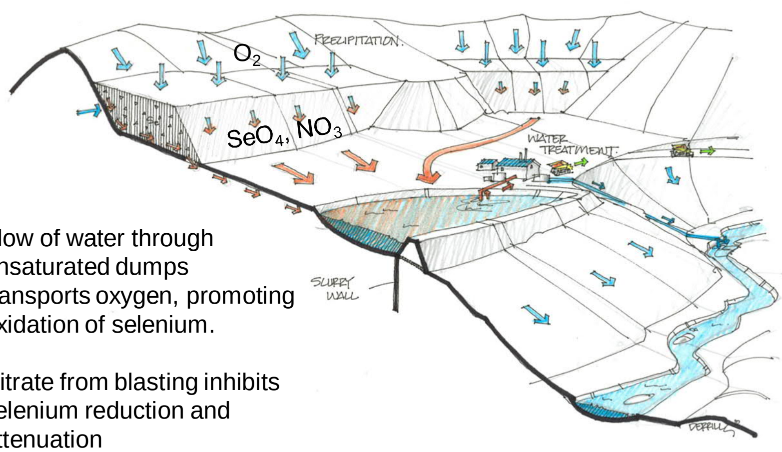
## Selenium Management




Flow of water through unsaturated dumps transports oxygen, promoting oxidation of selenium.

Nitrate from blasting inhibits selenium reduction and attenuation

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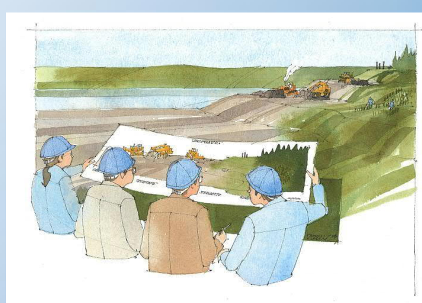
## Selenium Mitigation

- Water treatment
  - Treat mine effluent waters
- Water management
  - Reuse Se impacted water
  - Divert clean water around rock drains
  - Divert clean run-on water away from dumps
  - Reduce infiltration with dump covers
- Dump design to reduce $NO_3$ and Se loading
  - Selectively handle and encapsulate Se material
- *In situ* microbial source control
  - Interbed Coal Reject/tails with waste rock
  - Control oxygen, moisture, lithology (carbon) to affect reduction
- Mine planning
  - Change from surface to underground mining
  - Design facilities for *both* resource recovery and waste management through selective handling, sequencing, and placement



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## Crown Mountain Project Objectives

- Create conditions needed to drive $O_2$ to sub-oxic (<0.5 mg/L) levels required for nitrate and selenate reduction
  - Material characteristics
    - Water retention
    - Oxygen consumption
  - Material placement – built bottom up, layers, compaction
  - Gas and water flux to maintain sub-oxic zones
  - Support microbial community capacity to consume $O_2$ and reduce $NO_3$/Se
  - DOC availability – coal reject

- Design a waste rock dump that can achieve sub-oxic conditions in a zone with sufficient residence time to allow for denitrification and selenium reduction to occur using carbon from coal reject, or where needed, carbon amendment.

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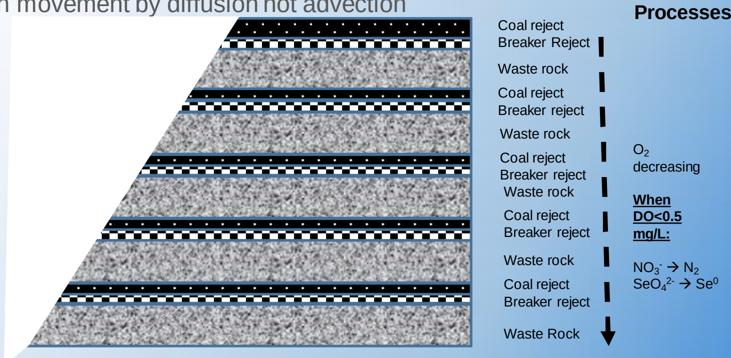
## Conceptual Model
## Selenium and Nitrate Attenuation in a Waste Rock Dump

Expected role of coal reject layers:

- Retain moisture retarding oxygen transport.
- Generate dissolved organic carbon to support biological reduction.
- Provide sub-oxic zones where reductive processes could occur.

Breaker Reject capillary break

Oxygen movement by diffusion not advection

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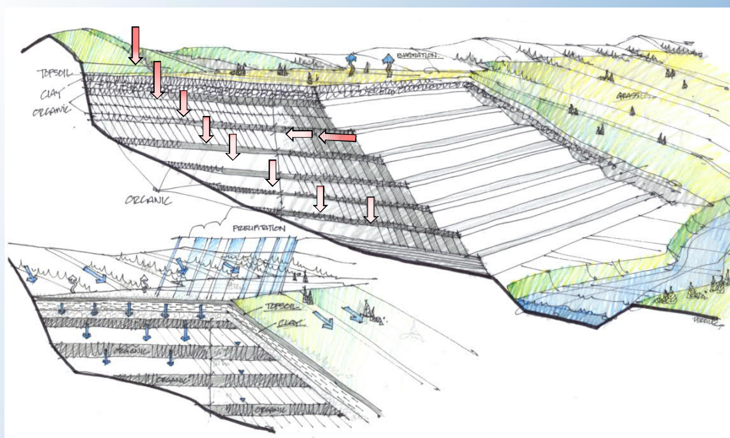
## Suboxic Waste Rock Dump Design

Progressive consumption of oxygen by reaction with sulfides and aerobic biotic activity within compacted coal reject layers to create sub-oxic conditions needed for nitrate and selenium reduction in lower zones



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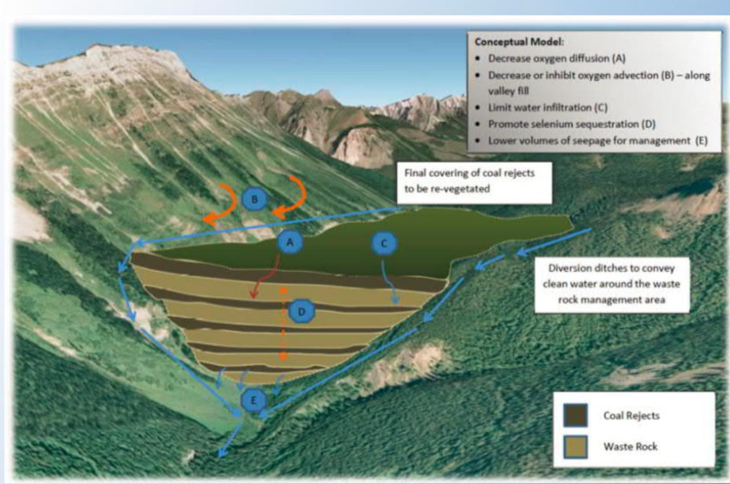
## Waste Rock Management: Layered Approach

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## RESULTS
## Preliminary $O_2$ Transport and Consumption Modeling

- Phase 1
- Preliminary 1D Findings (assuming compacted coal reject layers)
  - $O_2$ penetrates into waste rock, but consumption in pore spaces drives development sub-oxic conditions on the scale of years
- Provides proof of concept
  - The proposed approach can yield conditions that result in reduction of selenate and nitrate.
  - Results are consistent with observations of full-scale facilities.

- Phase 2
  - Working to develop a 2D model of a more specific spoil facility design based on Crown Mountain topography, hydrology, mass balance, waste sequence, improved material characterization etc.
  - Requires laboratory developed rates of oxygen, nitrate, and selenium reduction for the ROM waste and coal reject

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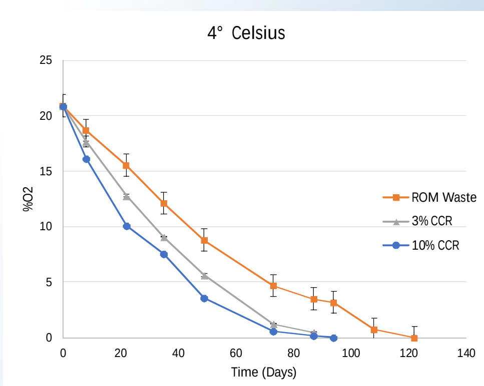
## RESULTS
## How fast is oxygen consumed - respirometry




T = 4, 10, and 25 °C
0, 3%, and 10% coal reject

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## Nitrate and Selenium Reduction in Columns
## 21%, 10%, 5%, and 0% oxygen at 10°C



## RESULTS – $NO_3$ and Se Removal Efficiency

$NO_3$-N

| | Aerobic | | | Microaerobic | | | Anaerobic | | |
|---|---|---|---|---|---|---|---|---|---|
| Sampling Location | Feed | CR | WR | Feed | CR | WR | Feed | CR | WR |
| Conc. (mg/L) | 99.8 | 3.96 | 2.88 | 100 | 4.93 | 2.77 | 101 | 4.66 | 2.80 |
| % Removal | - | 96 | 97 | - | 95 | 97 | - | 95 | 97 |

Selenium

| | Aerobic | | | Microaerobic | | | Anaerobic | | |
|---|---|---|---|---|---|---|---|---|---|
| Sampling Location | Feed | CR | WR | Feed | CR | WR | Feed | CR | WR |
| Conc. (mg/L) | 0.185 | .146 | .017 | 0.181 | .019 | 0.007 | 0.185 | .007 | 0.004 |
| % Removal | - | 20.8 | 90.8 | - | 89.5 | 96.1 | - | 96.2 | 97.8 |

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# Biogeochemistry of Suboxic Nitrate and Selenium Reduction

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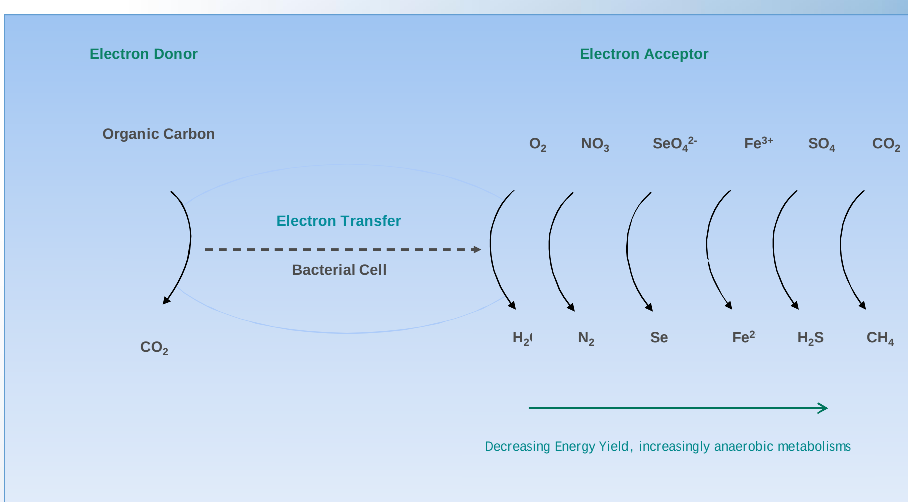
## Microbial Metabolism

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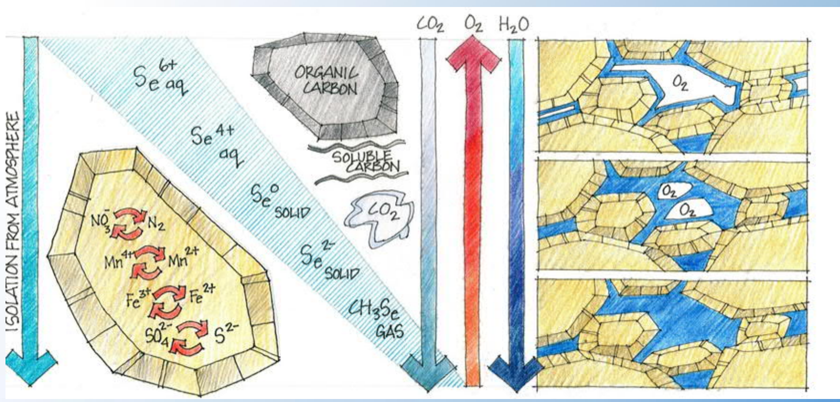
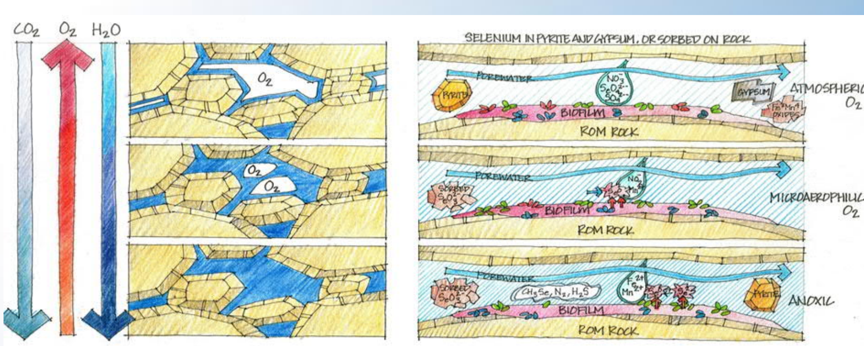
## Conceptual Selenium Biogeochemical Model




- $SeO_4^{2-}$ is released during sulfide oxidation
- Reduced $SeO_3^{2-}$, $Se^0$, & $Se^{2-}$ are less soluble than $SeO_4^{2-}$



## Conceptual Selenium Biogeochemical Model

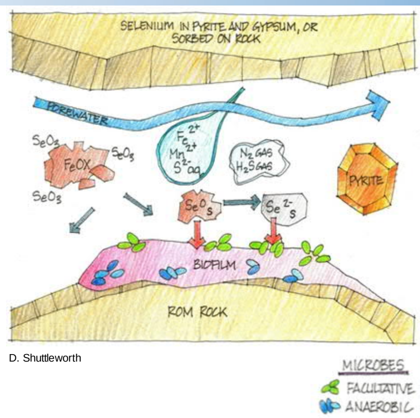



- Soluble $SeO_4^{2-}$ is associated with $O_2$ , $NO_3^-$, & $SO_4^{2-}$
- Microbial community changes with $O_2$ availability
- $O_2$ & $NO_3^-$ consuming microbes also promote Se reduction

## Conditions Required for Microbial Se Reduction

- **Low $O_2$**
  - *Promotes the growth of anaerobic and facultative Se- reducing populations*
- **Available C**
  - *Is coal enough?*
  - *What's the longevity of C supply?*
- **Ideal $H_2O$ flux**
  - *Water brings food, takes away waste, but also brings $O_2$*
- **Nutrients**
  - *$NO_3^-$ & $PO_4^{3-}$ are necessary but also inhibitory*
- **Which microbes?**

**Leaky sub-oxic bathtubs with prolonged residence time**




D. Shuttleworth

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## Case Study in an Unsaturated System

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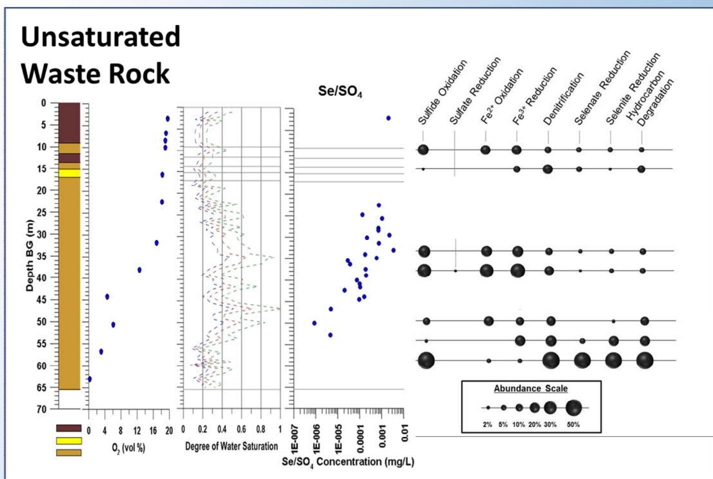
## Community Analysis Supports Geochemical Evidence




Skorupa et al, 2014

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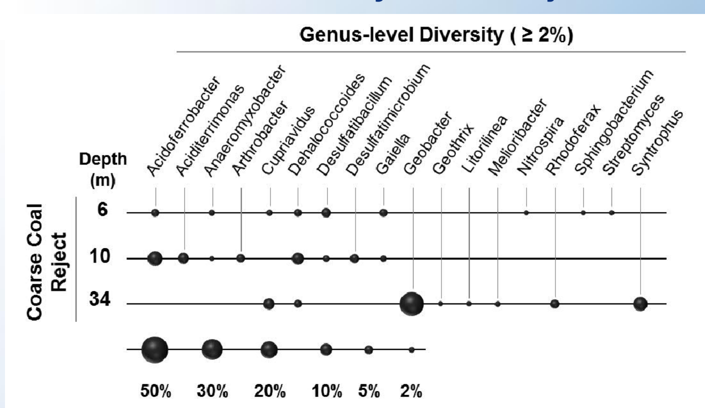
## Microbial Community – Coal Reject




- Anaerobic community in the processed waste
- *Geobacter* is rare in other waste, but dominant in the deep CCR
- Is an obligate anaerobe with strong capacity for metal reduction, including Se

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# Water and Gas Flux
# Preliminary Modeling Results

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# Preliminary Unsaturated Flow Modelling

| Thickness (m) | | | Cumulative Height (m) |
|---|---|---|---|
| 3 | Plant Rejects | Lift 6 | 188.5 |
| 0.5 | Breaker reject | | |
| 25 | RoM Waste | | |
| 5 | Coarse RoM Waste (due to segragation) | | |
| 1 | Plant Rejects | Lift 5 | 155 |
| 25 | RoM Waste | | |
| 5 | Coarse RoM Waste (due to segragation) | | |
| 1 | Plant Rejects | Lift 4 | 124 |
| 25 | RoM Waste | | |
| 5 | Coarse RoM Waste (due to segragation) | | |
| 1 | Plant Rejects | Lift 3 | 93 |
| 25 | RoM Waste | | |
| 5 | Coarse RoM Waste (due to segragation) | | |
| 1 | Plant Rejects | Lift 2 | 62 |
| 25 | RoM Waste | | |
| 5 | Coarse RoM Waste (due to segragation) | | |
| 1 | Plant Rejects | Lift 1 | 31 |
| 25 | RoM Waste | | |
| 5 | Coarse RoM Waste (due to segragation) | | |
| | Natural Ground | | |

Inputs

- Particle size of coal rejects (filter cake and coarse):
  - o PFS (Norwest, 2015)
  - o Analogous compacted tailings with similar particle size distribution (filter cake only).
- Particle size of waste rock: Literature for BC Coal deposits
- Breaker reject: Not included in intermediate layers due to low volume – evaluated as a final cover.
- Climate: Sparwood station scaled for elevation of site

Configuration

- Six 30 m high waste rock lifts, bottom 5 m assumed coarser (due to segregation).
- Material balance: PFS

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## Unsaturated Flow Modelling

- Model:
  - HYDRUS
- Sensitivities
  - Base case vs compaction
  - Effect of a cover on coal reject to reduce evaporative effects
- Findings
  - Raw coal rejects are not expected to retain sufficient moisture to limit oxygen entry
  - Compaction of rejects appear to achieve the desired characteristics.
    - No compaction of waste rock was modeled
  - 2 m ROM waste rock placed on reject helps with increasing moisture content in the coal rejects cap.

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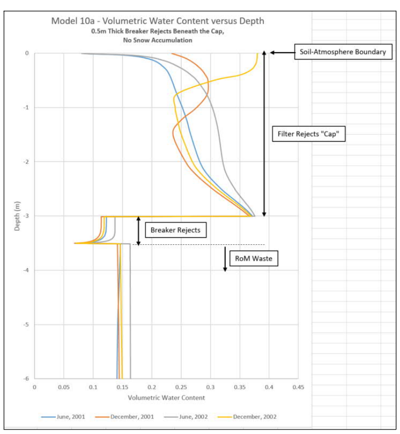
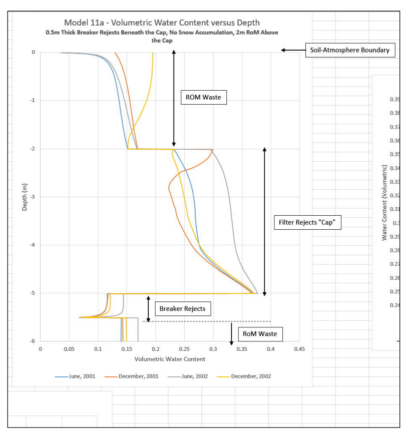
## Unsaturated Flow Modeling

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# $O_2$ Transport and Consumption Modeling

- Inputs
  - $O_2$ diffusion coefficient: Unsaturated flow model
  - Sulphide content: Crown Mountain data
  - Sulphide oxidation rates: Analogous file data
  - Carbon oxidation rate: No data, set to 0 (conservative).
- Model
  - FlexPDE (1D model, accounts for $O_2$ transport by diffusion, $O_2$ consumption by sulfides, Arrhenius temp dependence of oxidation rate, heat release due to sulfide oxidation)
  - Configuration
    - One lift (reject on waste rock)
    - No $O_2$ entry on edges

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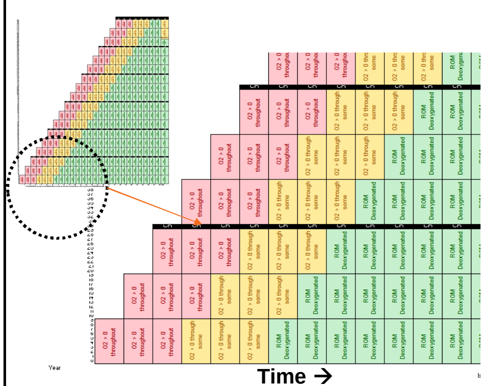
# Implications for Pile Performance




- Short-term
  - Performs as unsaturated.
- Intermediate
  - Parts of first lift become de-oxygenated.
- Long-term
  - First lift de-oxygenated.
- Need for water treatment determined by loading

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## Tour of Enviromin Laboratory

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## Laboratory Testing and Results

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## Oxygen Consumption Rates – Respirometry

- Sealed serum bottles
  - Ambient air in headspace
- 3 materials conditions
  - 100% Waste rock
  - 97% Waste rock + 3% coal reject
  - 90% Waste rock + 10% coal reject
- 3 Temperature conditions
  - 4 °C
  - 10 °C
  - 25 °C
- Oxygen concentration in headspace

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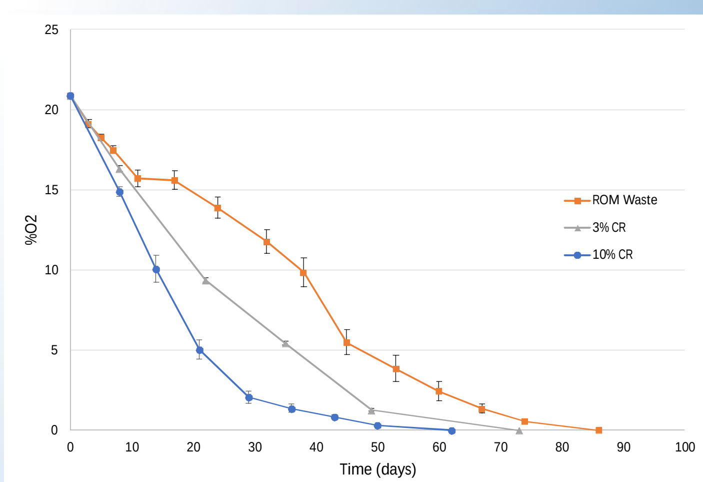
## Oxygen consumption curves 25° C

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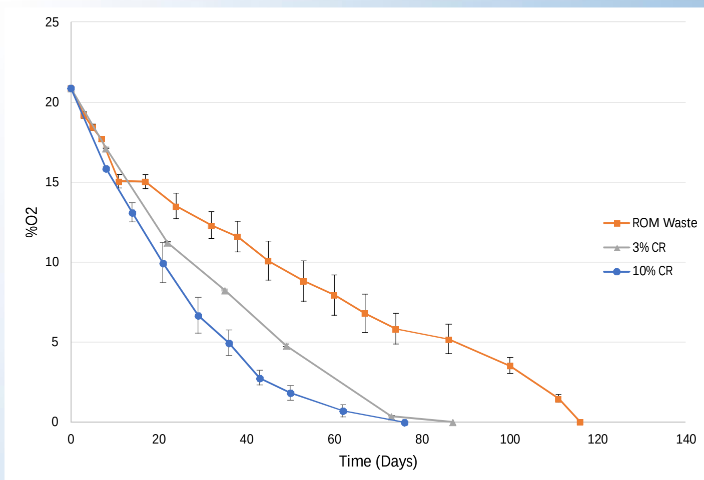
## Oxygen consumption curves 10° C

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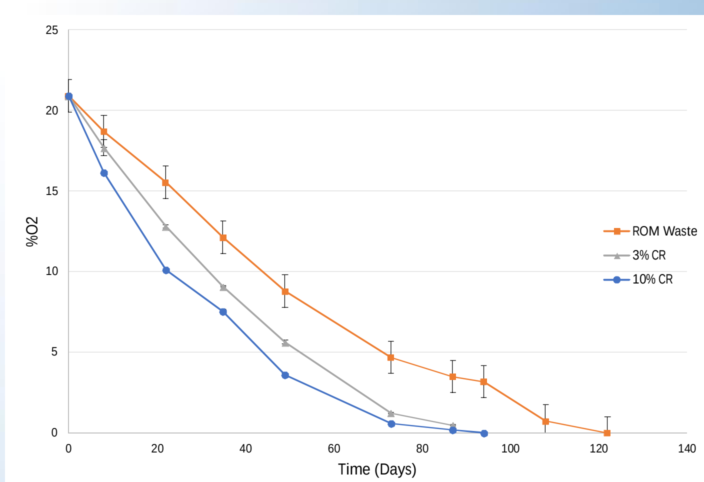
## Oxygen consumption curves 4° C

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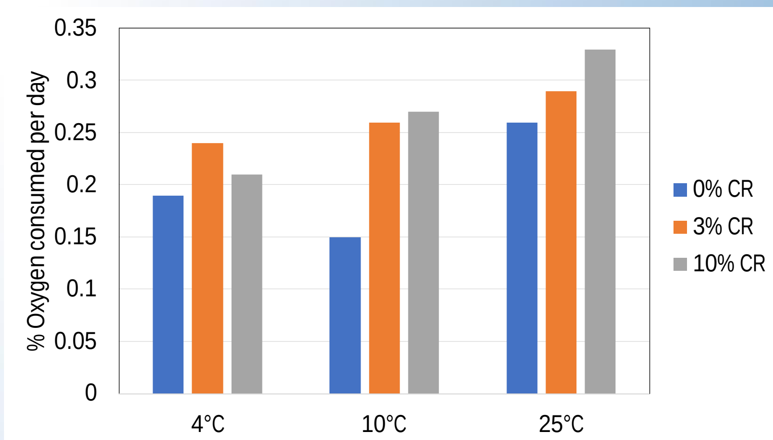
## Oxygen consumption rates are higher than rates of sulphide oxidation initially modeled




Oxygen consumption rates increase with increased temperature and increased coal reject fraction

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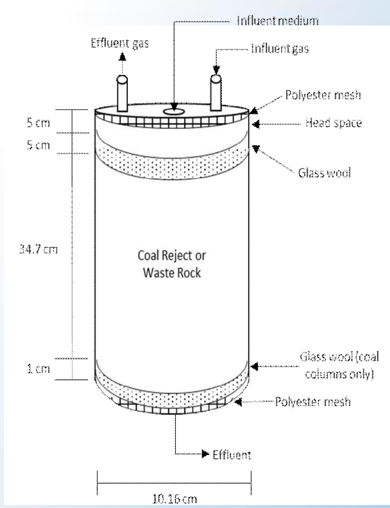
## Columns constructed for environment control




Flow rate controlled by volumetric pump

Water, $NO_3$, selenium added in-line

Headspace gas controlled by headspace replacement with custom mixed gas

Columns maintained at 10 °C

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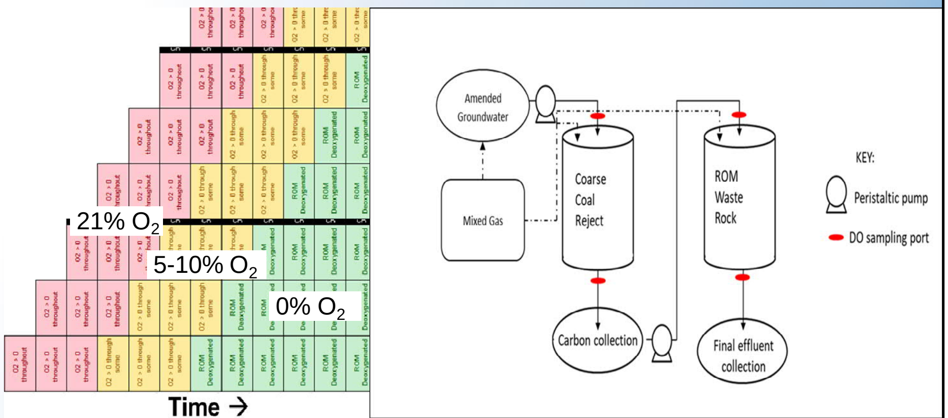
## Flow designed to mimic in-field conditions




Flow rate: 66.4 ml/week – Very low – but higher than annualized rainfall average

10 mg/L $NO_3$-N

0.2 mg/L $SeO_4$-Se

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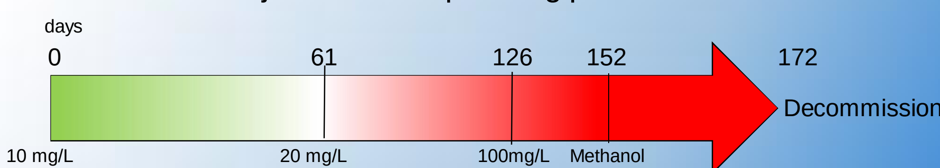
## Essential parameters measured during study

- In-House
  - Dissolved oxygen
  - $NO_3$-N
  - pH
  - ORP
- External Lab
  - Dissolved metals
  - Ammonia
  - Total selenium

Timeline of adjustment to operating parameters:

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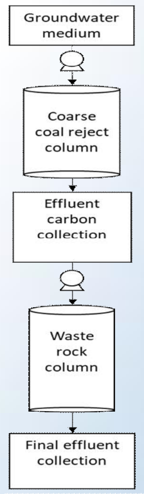
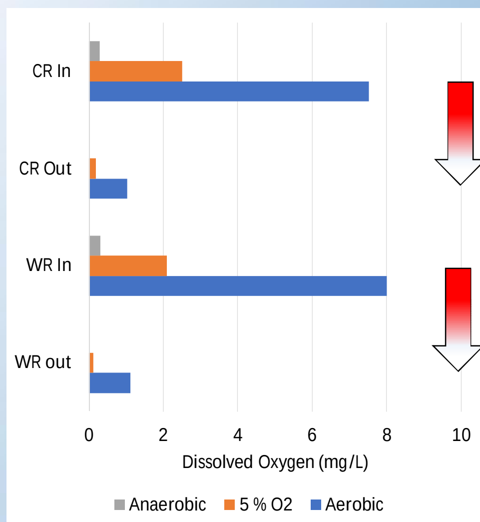
## Anoxic conditions created by materials

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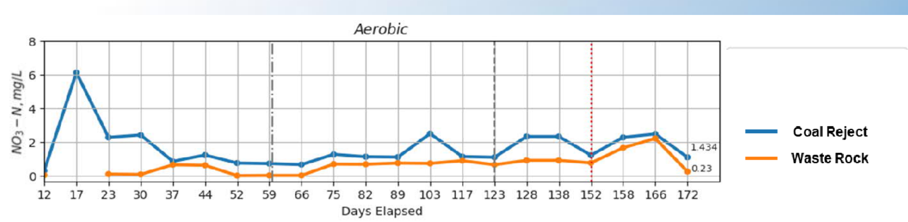
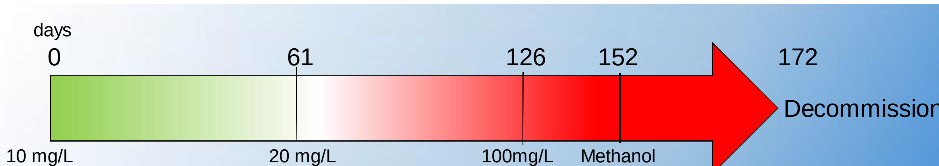
## Denitrification: Aerobic




Both coal reject and waste rock columns capable of denitrification
84% nitrate removed even with aerobic headspace

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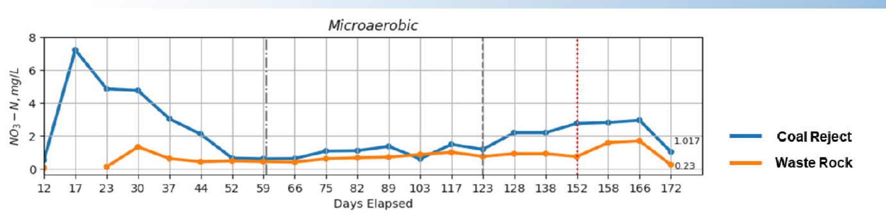
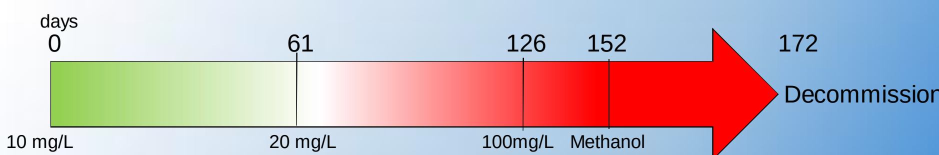
## Denitrification: Microaerobic




Similar performance to aerobic columns
Improved denitrification in coal reject

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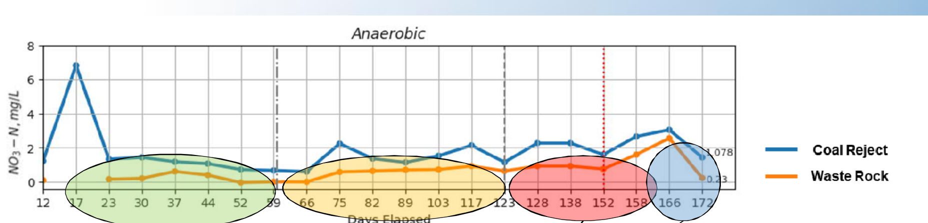
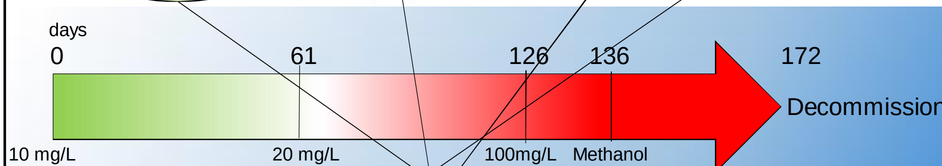
## Denitrification: Anaerobic




Addition of carbon increases $NO_3$ removal capacity
Very short lag time to complete denitrification
No other nutrients added
mass is removed

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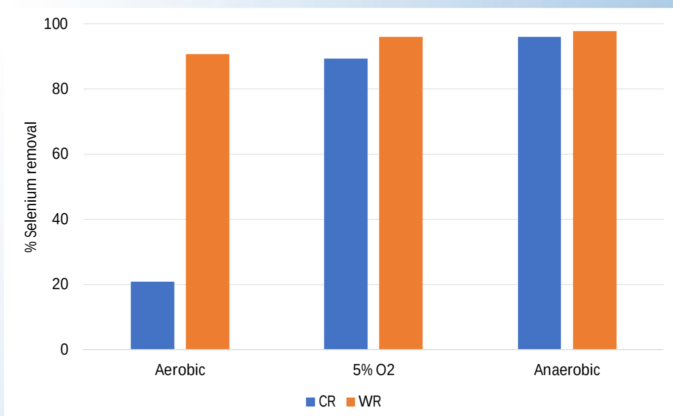
## Selenium removal at 10 mg/L $NO_3$-N




Near-complete selenium removal under anoxic and anaerobic conditions

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## Laboratory Study Conclusions

- Coal reject and ROM waste materials are capable of nitrate and selenium removal from affected waters
  - Coal reject provides sufficient carbon for these metabolisms
- Oxygen concentration affects rates and extent of denitrification and selenium reduction.
- Oxygen consumption rates observed in respirometry studies are much higher than those included in the initial model
  - Incorporating these rates of $O_2$ consumption will decrease time expected to achieve denitrification and selenium reduction in a full-scale system.
- Variable nitrate concentrations could be treated with the addition of an external carbon source
- These laboratory rates will be included in next phase of 2D modeling.

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## What does this mean?

- Significantly faster rate of net oxygen consumption was measured in respirometry than was included in preliminary modeling, even at lowest temp.
  - Preliminary 1-D model showed proof of concept for development of suboxic conditions in 6+ years, but this number will drop significantly using respirometry data
  - This needs to be evaluated in a 2D model
- Nitrate and selenium reduction was efficient and near complete in columns under controlled gas conditions (5% and 0% $O_2$)
  - in both coal reject and waste rock
  - At lowest N, reduction was complete
  - Under increasing nitrate load with addition of carbon
  - Without nutrient amendment
- The observed nitrate and selenium reduction rates under different gas conditions need to be assessed under flow numerically in a 2D model.
  - integrate more recent mine planning, material balance, material characterization and lab data into the prediction of oxygen consumption, nitrate reduction, and selenium reduction.

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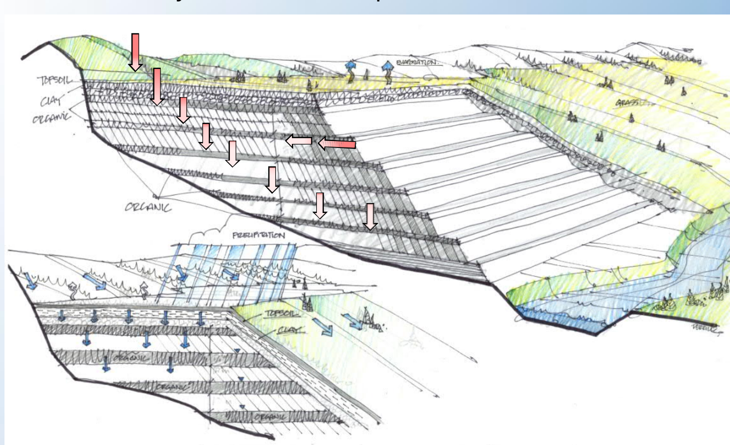
## Suboxic Waste Rock Dump Design

Updated 2D model to test various options for construction and monitoring during startup, incorporating lab data, topography, construction sequence, material balance, layer thickness, compaction, carbon amendment, etc.

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## Path forward

- Do we have a solution for selenium management in unsaturated spoil?
  - The lab results are very promising.
  - The next step is to update the model and determine how to scale up the lab results to real-world design.
- How long will it take to develop suboxic and reducing conditions in spoil?
  - Preliminary 1D modeling conservatively predicted it would take 6+ years to establish a sub-oxic zone in the spoil pile, but could not quantify nitrate and selenium reduction.
  - Inclusion of lab rates should reduce this time period in the updated model, perhaps significantly. This model can be used to evaluate the long term capacity for Se removal.
- What can be done to improve the prospect for success of the spoil pile?
  - Optimize design using updated model, in conjunction with water quality modelling. SRK and Stantec are beginning that work.
  - Controlled placement of spoil and coal processing reject in lifts to reduce pore space, and encourage oxygen depletion.
  - Consider compaction of the spoil in Phase 2 modeling.

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## Work in progress

- Column results are being replicated to confirm results and rates
- Share the results with other scientists to further the knowledge base in selenium mitigation.
- Study the successes others are having with various methods of selenium mitigation (e.g., saturated fills) and evaluate the potential to employ such methods in conjunction with the unsaturated fill at Crown Mountain.
- Update the model, initiate design engineering, and establish a proposed performance monitoring regime as the pile is constructed.
- Identify contingent mitigation measures

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