INCLUDING MINE ROCK FACILITY DESIGN TO ENHANCE PROGRESSIVE RECLAMATION

Greg Meiers, P. Geo.[1]
Mark Phillip, M.Sc.[2]
Tyler Birkham, Ph.D.[3]
Mike O'Kane, P. Eng.[4]

[1] O'Kane Consultants, 229 Cedar Ave, Fredericton, NB, Canada E3A 2C7
[2] O'Kane Consultants, 108 E Park St, Anaconda, MT, USA 59711
[3] O'Kane Consultants, 905C Industrial Road 2, Cranbrook, BC, Canada
[4] O'Kane Consultants, 1000 Centre Street NE, Suite 405, Calgary, AB, Canada

ABSTRACT

While the exact language may vary, progressive mine reclamation is similarly defined across the mining industry, yet the consensus is that it represents "best available technology" for reducing environmental risks at closure and optimizing closure costs. In terms of mine rock storage facilities (MRSFs) that contain potentially acid generating material, the current industry practices and the majority of guidance documents focus on phased cover system construction and revegetation.

This paper examines whether an enhanced methodology can be applied for progressively reclaiming MRSFs during construction to change the typical physical environment in which sulfide materials are placed. The MRSFs are designed using mine rock placement strategies that focus managing gas transport as the MRSFs are being constructed. This approach limits sulfide oxidation and generation of stored acidity, increases longevity of any available alkalinity, and thus moves us closer to the essence of progressive reclamation than the typical approach.

General illustrative modeling examples and a case study are provided to illustrate MRSF design methodology.

KEYWORDS: waste rock, seepage, gas flux, sulfide oxidation rate

INTRODUCTION

While the exact language may vary, progressive reclamation is similarly defined across the mining industry. In British Columbia, Canada, the Ministry of Energy and Mines define progressive reclamation as "the process of restoring land that has been mined to a natural or economic usable state in an ongoing manner over the life of mine" (EY, 2017).

Additionally, there is a consensus that progressive reclamation is the use of Best Available Technology (BAT) for reducing environmental risks at closure and optimizing closure costs; but, what exactly is progressive reclamation for a MRSF? Current industry practices and most guidance documents focus on phased cover system construction and revegetation. The idea is that through reduction of oxygen ingress and surface water infiltration following progressive construction of the MRSF cover system, and revegetating, management of metal leaching and acid rock drainage (ML-ARD) can be "optimized". However, one needs to acknowledge that even with progressive reclamation there are sites that don't meet closure objectives from a ML-ARD perspective. In many instances, there was likely uncertainty in the generation of stored acidity, cover system performance expectations were unrealistic, and hence inadequate mitigation is provided.

It is proposed that an enhanced progressive reclamation that encompasses MRSF design can be applied to progressively reclaiming a MRSF. This enhanced progressive reclamation focusses on minimizing the generation of stored oxidation products during and following construction of the MRSF as illustrated in Figure 1. Minimizing the generation of oxidation products increases the likelihood that closure objectives will be met for collection and treatment. This provides substantially more reduction in financial security requirements, and the time frames for which financial security is required, as compared to the "typical" cover system placement and progressive reclamation approach for a MRSF.

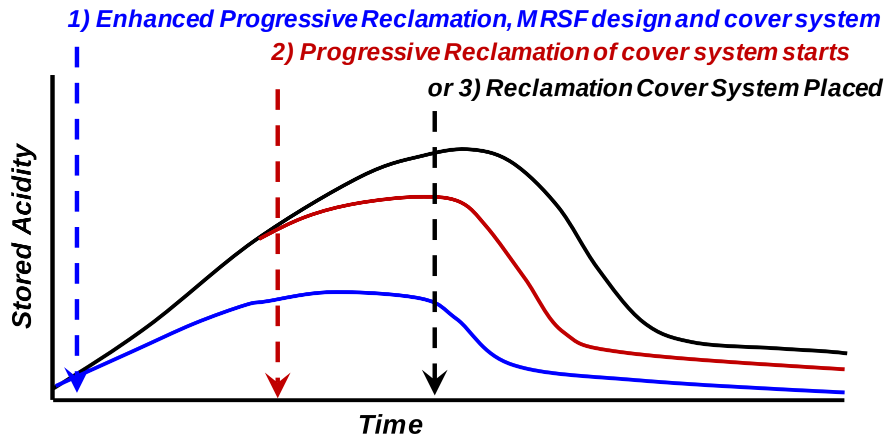

Figure 1 Illustrated stored acidity in MRSF and reclamation methods.

This paper examines how changes in final MRSF design can produce less favourable internal conditions for the generation of acidity, and provides a case study where MRSF design alternatives were evaluated with the predicted generation of stored acidity and timing for onset of basal seepage assessed. The case study supports the concept of enhanced progressive reclamation in MRSF closure planning.

MRSF CONSTRUCTION

The methods used to construct an MRSF vary considerably and are site specific. MRSFs may be entirely end-dumped off a high point, or plug-dumped and built from the bottom up. They may be supported on sides by pre-mine topography, used to backfill previously mined structures, or be free standing structures. Lift heights and total slope lengths can vary considerably, with material segregation, and permeability, increasing accordingly.

A cover system should reduce net percolation, but likely not to a degree that prevents ML-ARD or eliminates the need for water treatment. The goal of including MRSF design in progressive reclamation is to assist with ML-ARD minimization by creating favourable internal conditions with the least effort. A favourable internal condition is one that supports the prevention or reduction of ML-ARD seepage by decreasing oxygen composition and possibly altering moisture content to create a habitat where geochemical and biological reduction reactions occur.

Co-disposal, or the joint placement of tailings and waste rock, can have several benefits such as greatly reducing the waste rock permeability and oxidation rate; however, co-disposal on the scale of an entire MRSF can be very expensive. Instead of altering how an entire MRSF is constructed, progressive reclamation can look to optimize the process of creating favourable internal conditions with focused changes in material content at specific locations.

The changes in material content may involve thinner end-dumped lift heights to minimize material segregation, compacted layers, interim layers with an amendment like tailings, geosynthetics, or compacted berms at the final slope toe. These design changes may alter the waste material water content, even up to saturation in select areas, but the main goal is to reduce oxygen composition to at least suboxic levels.

INNOVATION INCENTIVES

The primary influence on the MRSF construction method is commonly cost, and modifying MRSF design will most likely increase the capital cost; however, there are reasons to innovate and incur additional cost. A lower initial capital cost may still result in greater long-term costs if ML-ARD perpetual collection and treatment is considered. The global environmental liability for ML-ARD has been estimated to be approximately $100 billion (Wilson, 2008). When perpetual water treatment is chosen as the technology to address ML-ARD, the possibility exists that the future cost will be underestimated. A study reviewed twenty-six environmental impact statements for mines in the United States and compared the water quality predictions with the actual site water quality results during operation (Kuipers *et al*, 2006); the study found that:

1. Of 14 mines with close proximity to groundwater and elevated acid drainage and containment leaching potential, 86% developed exceedances after predicting no exceedances; and

2. Of 11 mines with close proximity to surface water and elevated acid drainage and containment leaching potential, 91% developed exceedances after predicting no exceedances.

While predictive geochemical analysis and methodology has likely improved, the risk of increased water treatment cost still exists from site characterization (hydrology), to climate change, and possibly more stringent water quality standards.

Societal expectations may also generate the need for including MRSF design in progressive reclamation. In Montana, enough citizen signatures were obtained to place a voter initiative concerning natural resources on the November 2018 ballot. Initiative 186 states that the Department of Environmental

Quality must deny a permit to a new hard rock mine "unless the reclamation plan provides clear and convincing evidence that the mine will not require perpetual water treatment…" Even if such initiatives do not pass, the required financial assurance bonds could potentially be increased to address any perceived uncertainty with water treatment costs.

MRSF STORED ACIDITY

ML-ARD risks are known to be complex and interrelated and strongly related to geochemical characteristics of the mine rock, climate and oxygen and water ingress rates (Lottermoser, 2010). The method and timing of placement, and the site environment in which they are placed have been shown to be more important in understanding ML-ARD, and yet this often disregarded (Baisley and O'Kane, 2017).

The structure of the MRSFs influence oxygen flow into and within the facility, where subsequent oxidation reactions can occur. The diffusive movement of oxygen is primarily restricted to the outer surface or near surface of the MRSF. The movement of oxygen within and into the MRSF primarily occurs by advection due to differential pressure and vertical temperature gradients (Pearce and Barteaux, 2017 and Lu, 2001). Oxygen ingress can also occur as dissolved oxygen in infiltration water.

Enhanced progressive reclamation focusses on the mine rock placement strategy to address ML-ARD risk through minimizing oxidation of sulfide minerals during and following mine placement. By placing mine rock in a manner to minimize stored oxidation products (or more appropriately, stored acidity), long-term reliance on a cover system and/or mine water effluent collection and treatment as the "sole" means of managing seepage from a WRD is reduced or eliminated entirely. Minimizing oxidation of sulfide minerals involves strategic placement of mine rock such that advective gas transport within the WRD (i.e. oxygen transport) is limited because airflow capacity (air permeability) is controlled. MRSF air flow capacity is reduced by one, or some combination of the following methods: short end-tipping heights, paddock dumping, fine texture traffic layers (interim cover), and toe bunds.

GENERAL PROGRESSIVE RECLAMATION EFFECTS

To demonstrate how changes to a final MRSF design can affect pore gas oxygen composition, a series of models were evaluated using GEOSLOPE software (2018). A generic MRSF created by end-dumping was selected, approximately 150 m above the natural ground at the crest. Because of expected material segregation, a zone of coarse content is present along the entire base of the MRSF. A thermal gradient was established in the MRSF between the natural ground temperature and the atmosphere during winter.

In addition to a base case of exposed waste rock, four options were evaluated (Figure 2):

1. A compacted toe berm at the base of the final slope to reduce advective flow into the toe though the coarse material at the base;

2. An interim low-permeability layer, 1 m thick, constructed of glacial till across most of the MRSF top surface;

3. The combination of the compacted toe berm and the interim low-permeability layer; and

4. An elevated compacted toe berm that covers the bottom half of the slope face.

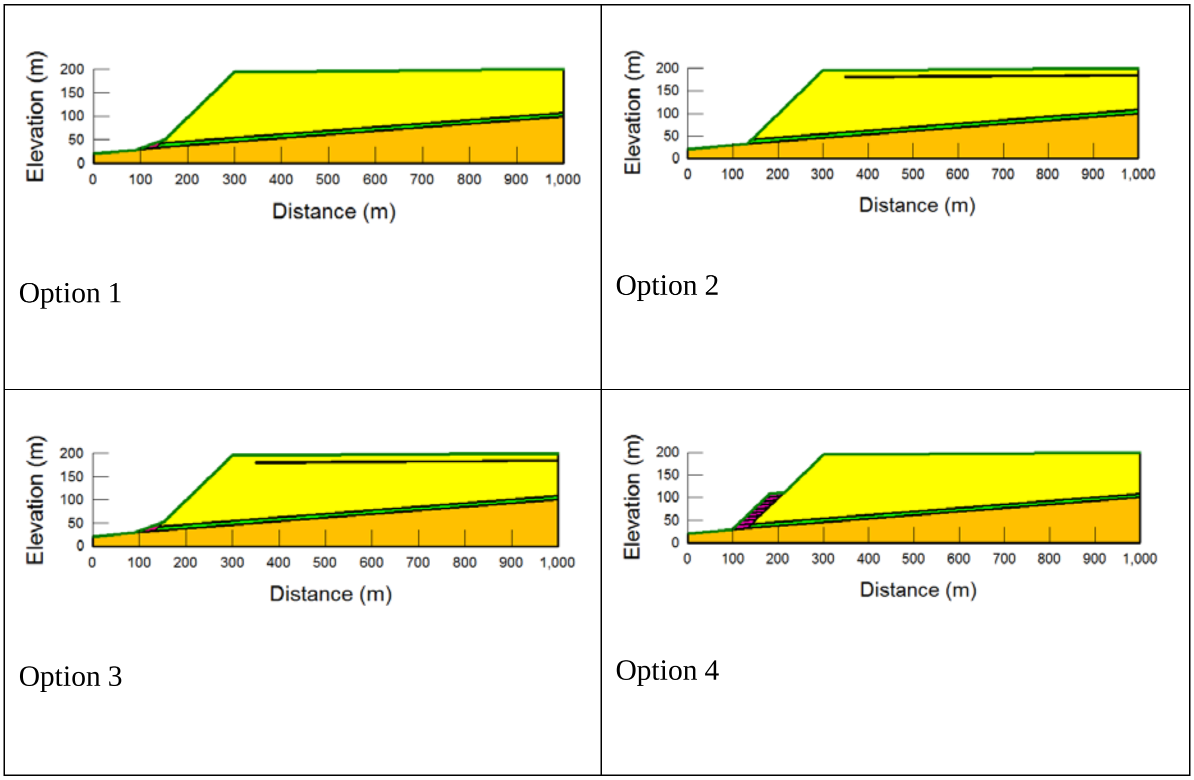

Figure 2 Progressive reclamation MRSF design options.

The effect of each design option is judged by the increase in the zone with oxygen content less than 6%. The extent of the 6% oxygen isoline is shown in Figure 3, and the increase in the cross-sectional area of the 6% isoline is found in Table 1.

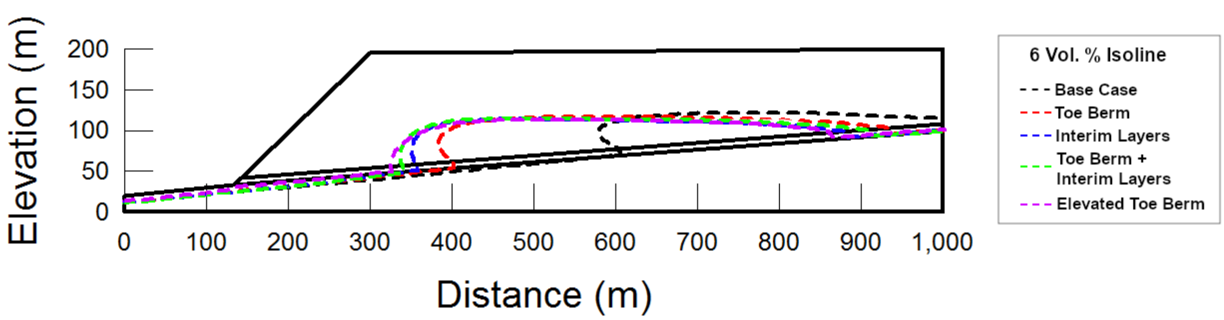

Figure 3 The 6% oxygen isoline results for the base case and four design options.

Table 1 Progressive reclamation MRSF design option results.

Option	Description	Increase in 6% or less Oxygen
Base case	Unmodified MRSF design	NA
1	Compacted Toe Berm	56%
2	Interim Low-Permeability Layer	61%
3	Compacted Toe Berm and Interim Low-Permeability Layer	67%
4	Elevated Compacted Toe Berm	56%

The modelling conducted is simplistic but shows the relative benefit of modifications that can alter pore gas composition. All of the options increased the cross-sectional area of the 6% oxygen isoline, moving it toward the MRSF outer slope along the base. When the likely effort is compared to the result in this example, constructing a compacted toe berm to reduce advective air flow into the slope base may be the most cost-effective option.

CASE STUDY – MRSF DESIGN EVALUATION

The focus of the engineering work in this case study was to evaluate the effect of (PAG) mine rock placement in relation to reduction of oxygen ingress, and timing of basal seepage that can lead to ML-ARD from the MRSF. The conceptual model is that the mass of oxygen available is related to the amount of stored oxidation products generated within the MRSF, the latter of which has potential to result in ML-ARD. Two scenarios were modelled and are:

- Scenario 1 – Placing PAG mine rock in nominally 2 m thick layers (i.e. block dumping); and
- Scenario 2 – End dump 7 m PAG rock, with placement of an interim cover immediately above.

The DumpSim evaluation tool was used to integrate conditions imposed by MRSF configurations and *in situ* properties to determine available oxygen to react with the material through diffusive and advective transport mechanisms. The available oxygen is used to calculate the potential mass of H_2SO_4 produced per tonne of PAG mine rock placed resulting from sulfide oxidation due to oxygen ingress into the facility. The conditions of the MRSF are determined by site-specific controls, material geotechnical and geochemical properties, and the facility physical features determined by construction methods. In this way, the requirement for 'scaling' of laboratory results, as is typically undertaken with water quality predictions, is superseded because the physical facets influencing *in situ* sulfide oxidation, and dissolution of stored products leading to ML-ARD for commercial scale placement of mine rock have been included in the evaluation.

One-dimension (1-D) scenarios were simulated for a situation similar to that indicated on Figure 4, where two lifts of PAG are in contact with each other. Two-dimension (2-D) scenarios were completed of the proposed MRSF configuration to enhance interpretation of the 1-D assessments by providing an evaluation of air movement within the facility. The current focus of the simulations was on the construction period; hence, the MRSF was not evaluated with a final cover system placed on the surface.

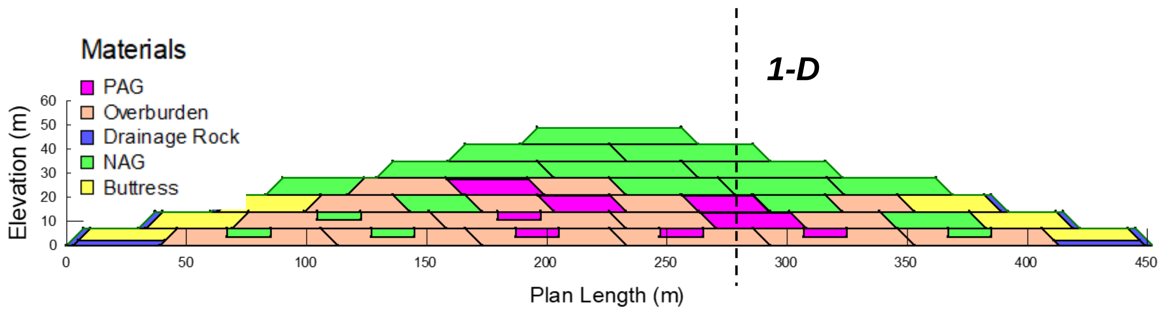

Figure 4 Configuration of proposed MRSF.

The mine rock predictive analysis as assessed is independent of any neutralization processes, which will occur given the nature of the material, because the focus is intentionally on the oxidation reaction of sulfides only. Hence, the “load” generated must not be taken to be that which would emanate from the facility over time as basal and/or toe seepage. Sulfide oxidation, for the purposes of this analysis, is being used as a surrogate for evaluating the extent of geochemical stability. A high level summary of model input parameters are provided in Table 2 and are described in brief below.

Climate

The climate at the site is classified as Cold, Without Dry Season, and Warm Summer (Dfb) in the Köppen Geiger classification system. Average annual precipitation is approximately 720 mm. A climate database was developed as climate is a key site-specific factor controlling processes and mechanisms. The 100-year historical climate database was developed based on climate stations at the site and within 55 km of the site.

MRSF Construction Schedule

The water content of the rock and the cover system material was assumed to be at residual water content at placement. Material placement was simulated following the same general schedule:

- First 7 m lift of Overburden placed at start of simulation;
- Second 7 m lift of Overburden placed at start of Year 2;
- First PAG lift placed at start of Year 3:
    - Scenario 1– Additional 2 m PAG lifts placed at the start and middle of Year 4;
    - Scenario 2 – Interim cover system placed over PAG lift in the middle of Year 3;
- PAG lift placed at the start of Year 5:

- Scenario 2 – Interim cover system placed over PAG lift in the middle of Year 5;
- Scenario 1– Additional 2 m PAG lifts placed at the start of Year 6 and 7;

- 7 m lift of NAG placed at the start of Year 8 and 10.

Table 2 Summary of key analysis inputs.

Key Inputs	Description
Climate	Synthetic average climate year developed using 100-year historical database
1-D Physical MRSF Scenarios	
Scenario 1: 2 m PAG Scenario	Two, 7 m lifts of Overburden, overlain by nominal 2 m lifts of PAG, followed by two, 7 m lifts of non-acid generating (NAG) mine rock.
Scenario 2: 0.5 Overburden Interim Cover	Two, 7 m lifts of Overburden, overlain by two, 6.5 m lifts of PAG each topped with a 0.5 m Overburden Interim Cover, followed by two, 7 m lifts of NAG mine rock.
2-D Physical MRSF Scenarios	
Scenario 1: 2 m PAG Scenario	Same boundary conditions as Scenario 1, but with internal increase in temperature of the PAG material simulated to represent exothermic reactions within the PAG
Scenario 2: 0.5 Overburden Interim Cover	Same boundary conditions as Scenario 2, but with internal increase in temperature of the PAG material simulated to represent exothermic reactions within the PAG.
Material Properties	
Geotechnical Mine Rock Material	Estimated associated hydraulic material properties for texture.
Geochemical Properties	POR Blended oxidation rate $1.4x10^{-09}$ *kg* O_2*/tonne of PAG/sec*

Material Properties

Geotechnical

The texture of the mine rock was used to estimate a range of material properties for the modelling program. The 2 m PAG lifts were assumed to have a higher density compared to a 7 m end dumped material due to increased compaction from construction traffic and less material segregation. It was assumed that end dumped PAG would have a porosity of 0.225 m^3/m^3, but that block dumping in 2 m lifts would lower the porosity to 0.15 m^3/m^3. These estimates were based on similar materials in the SVSoils (2017) databases.

Geochemical

Material at the site is recognized to contain both potentially acid forming sulfides, such as pyrite, and neutralizing minerals containing carbonates. Previous assessments of ML/ARD risk have predominantly focused on the neutralization potential ratio (NPR) to classify both material and assess risk.

For the purposes of this assessment the kinetic pyrite oxidation rate (POR) is the principal geochemical material property; therefore, no distinction is made between material types based on NPR ratio, sulfide content, or neutralizing potential.

A range of PORs were interpreted to provide a range of POR used in the analysis ($1x10^{-9}$ to $1x10^{-8}$ kg O_2 per tonne of PAF per second). The POR relationship with %S was combined with the histogram of %S measured by LECO to develop the blended rate. The blended POR was $1.4x10^{-9}$ kg O_2 per tonne of PAF per second. Approximately 80% of all mine rock samples were 1% Total Sulfur or less, which combined with an assumed POR of $1x10^{-9}$ for %S up to 1% produced the value for the blended rate closer to the lower end of the range. For this comparative analysis the blended POR was used.

2D Model Scenario Inputs

2-D simulations were completed on the proposed MRSF configurations to compare air movement within the two configurations. The model domains for the proposed MRSF configurations is shown in Figure 1. The models were simulated with the following inputs:

- A water flux boundary was applied to the surface equivalent to a net infiltration rate of 48% of annual precipitation. This flux rate based on the 1-D water balance results.
- Total air pressure was set at 100 kPa based on air pressure measurements on site.
- Temperature at surface was set at the average annual air temperature.
- Temperatures within the PAG regions were set to 4.5°C, based on the highest temperatures estimated by the 1-D assessments.
- A unit hydraulic gradient lower boundary.

<u>Results</u>

Water balance

The results of the water balance were used to determine the manner in which each scenario influences water storage within the facility, as well as seepage from the base of the facility. The annual net infiltration and seepage rates are the same once the facility has "wetted up" and there is no storage capacity remaining. The modelled results indicate that the wetting up period is similar for each scenario and it takes approximately two years for the facilities to completely wet up after placement of the final lift. Water balance results for Scenario 1 are shown Figure 5.

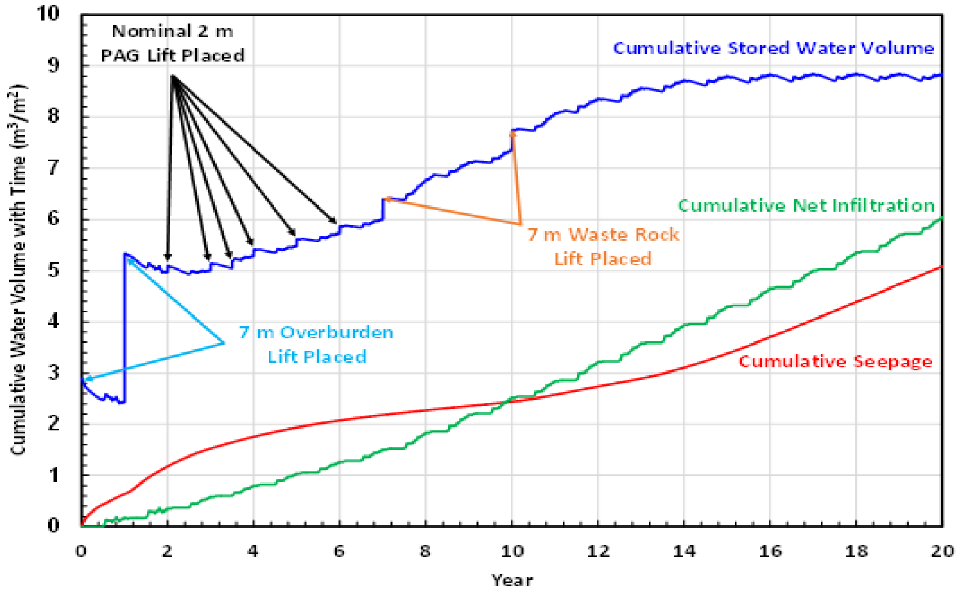

Figure 5 Cumulative water balance with time for Scenario 1.

Degree of Saturation

The average degree of saturation for each mine placement scenario was calculated as part of the numerical modelling completed for the water balance analysis. The overburden lifts for both scenarios wet up to a degree of saturation of approximately 83%. The 2 m PAG lifts equilibrate to a degree of saturation above 90%. The interim cover systems have a degree of saturation over 95% in the long-term; the underlying PAG has a degree of saturation of approximately 65%. The two NAG lifts at surface for both scenarios wet up to a degree of saturation of approximately 60%.

Diffusive and Advective Oxygen Ingress and Loading

The degree of saturation of the mine rock facility was used as a key input to calculate the "load" or mass of H_2SO_4 resulting from sulfide oxidation as a result of oxygen ingress into the pile through diffusive and advective processes. For simplicity and because this is a semi-quantitative assessment method, the term "acid load" is carried through this assessment and is deemed appropriate, and relates to the maximum calculated mass of H_2SO_4 that is generated under the model scenario.

The total loading for Scenario 1 attributed to diffusive and advective oxygen is ~5,500 tonne and ~7,000 tonne H_2SO_4, respectively (See Figure 6) for a total of approximately 12, 500 tonne. Oxygen diffusion dominates in the early stage of the mine rock placement for Scenario 1 (2 m Paddock Dumped), then advective oxygen transport surpasses oxygen diffusion because of increased volume and height of the facility with time. For Scenario 2, the total loading is ~4,500 tonne H_2SO_4 resulting from diffusive oxygen ingress and ~1,500 tonne H_2SO_4 resulting from advective oxygen ingress for a total of 6,000 tonne.

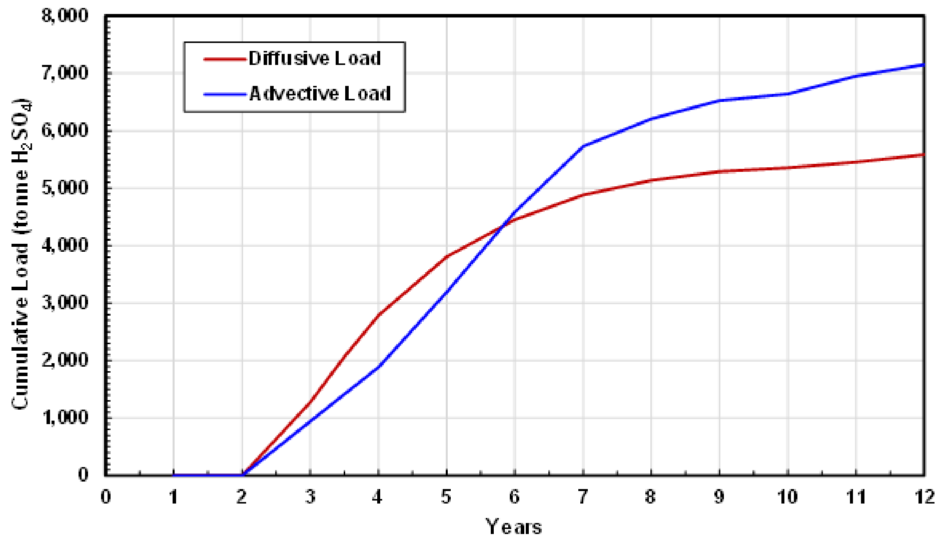

Figure 6 Cumulative loading due to diffusive and advective gas transport for Scenario 1.

The cumulative loading rates from the assessment are shown in Figure 7 for each scenario. All scenarios have relatively low loading rates over the construction period; this relates to the low POR function applied of $1.4x10^{-9}$ kg O_2/t/s. Scenario 2 (Interim Cover) has a lower loading rate over the assessment period than Scenario 1 (2 m Paddock Dumped). Advective flux is the dominant oxygen ingress mode near the end of the assessment period for Scenario 1, although this can be reduced once a cover system is placed over the mine rock facility (i.e. diffusive flux becomes the dominant oxygen ingress mode once a cover system is placed).

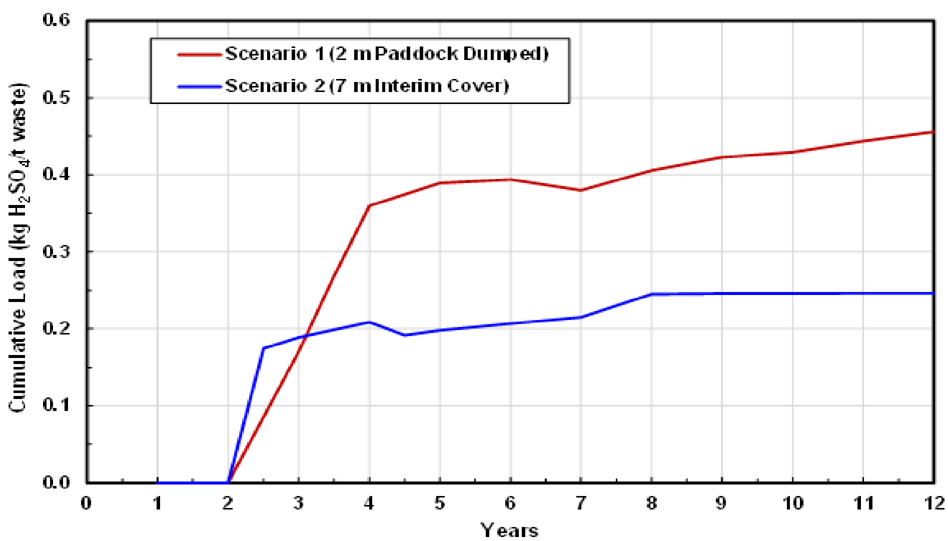

Figure 7 Comparison of cumulative acidity load per tonne of waste for Scenarios 1 and 2.

2-D Results

Figures 8 and 9 show the air flux rate and vectors, as well as general air flow paths for the proposed MRSFs. Air flux is minimized in the proposed MRSFs showing that most of the air flux is occurring along the side slopes of the upper NAG lifts and does not penetrate deeper in the facility where PAG is placed in the proposed plan. Comparing the two proposed PAG placement options, air flux is further minimized with inclusion of interim cover systems.

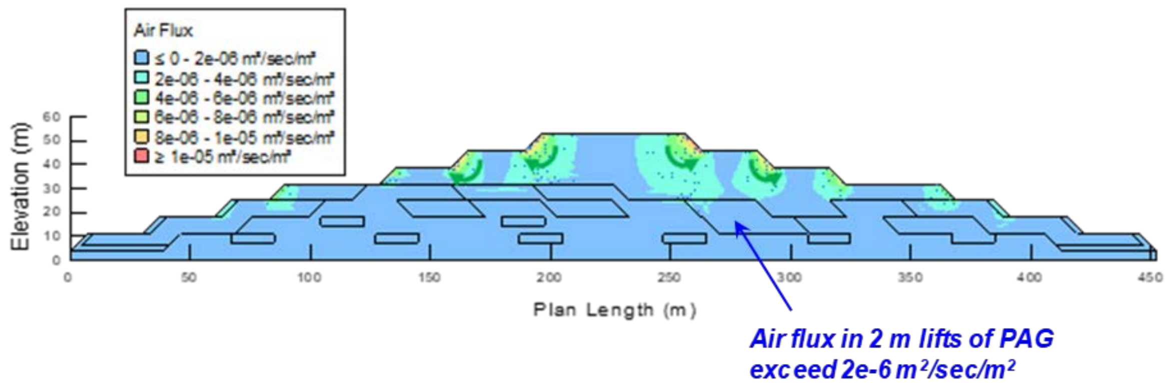

Figure 8 Air flux rate, vectors and general flow paths for Scenario 1.

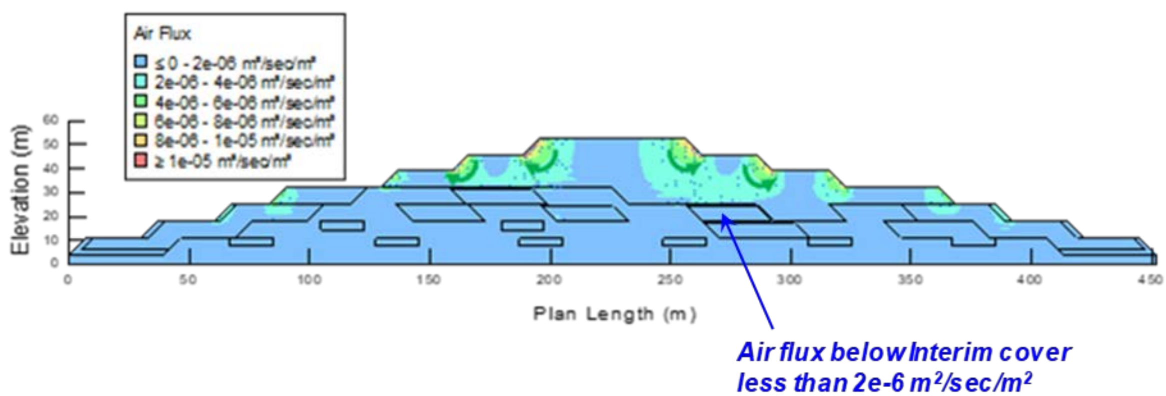

Figure 9 Air flux rate, vectors and general flow paths for Scenario 2.

CONCLUSION

The use of progressive reclamation as best available technology for closure of MRSFs, while beneficial, may fall short of meeting key overarching objectives that define progressive reclamation. Taking a step back, MEND (2013) reported that within the mining industry a high percentage of sites expect treatment in perpetuity. This may suggest that advancement in BAT is required for closure of MRSFs. This should include a methodology that encompasses “enhanced progressive reclamation”, in that reclamation occurs throughout life-of-mine. This strategy allows mine planners to better understand the ML-ARD risk at closure and start framing performance expectations for the final cover system. Enhanced progressive reclamation reduces the ML-ARD risk using multiple forms of mitigation with a greater opportunity to succeed is realized.

Incorporating MRSF construction design into progressive reclamation can facilitate the evaluation of risk management, reduce reliance on cover system performance and longevity, and possibly reduce financial security requirements.

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