Rock Placement Strategies to Enhance Operational and Closure Performance of Mine Rock Stockpiles

Phase 1 Work Program – Review, Assessment & Summary of Improved Construction Methods

prepared for

The International Network for Acid Prevention

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Environment · Water · Sustainability

&

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EXECUTIVE SUMMARY

The mining sector worldwide is experiencing significant increases in closure costs and is accumulating a growing number of stranded liabilities due to poor closure outcomes. Closure bonds, as well as financial assurance for operating sites, continue to increase as community and regulator expectations rise. The most contentious and persistent issue driving stakeholder expectations is poor post-closure water quality. Almost without exception, the problematic water quality issue is related to acid rock drainage or acid and metalliferous drainage[1] (ARD / AMD) associated with sulfide oxidation that invariably requires collection and treatment, not just during operations, but in perpetuity. Collection and treatment of ARD / AMD is often unplanned and/or underestimated, resulting in higher closure (as well as operational) costs than anticipated.

Why a Focus on Mine Rock Stockpiles?

Most mines containing reactive sulfides generate ARD / AMD from a range of site domains, including mine rock stockpiles (MRSs), heap leach pads, tailings storage facilities, open cuts, underground mine voids and assorted stockpiles. Direct and indirect measurements of acidity load from various site domains at more than 40 sites over the past 25 years have revealed that mined sulfidic rock typically contributes to the majority of the total acidity load (60 to 80%) from most mine sites, with a further 20 to 30% of acidity load associated with TSFs, and relatively minor contributions from other ARD / AMD sources (eg. underground mine void wallrock, open cuts, heap leach facilities and other stockpiles). These studies incorporate a broad range of commodities, including coal, copper, cobalt, lead-zinc, silver, gold, tin, uranium, iron-ore, graphite and diamonds.

Conventional Mine Rock Stockpiles

Conventional MRS construction typically involves releasing well sorted, relatively dry rock materials with wide particle size distributions from the back of tip trucks down angle-of-repose slopes of previously disposed material. This method is used to optimise costs associated with loading, hauling and placing rock from open pit (or underground) operations, while maintaining geotechnical stability of the MRS. This method results in coherent grainsize segregation and distinctive depositional layering, with substantial concentration of larger rock fragments in a 'rubble' zone at the base of the depositional zone (i.e., base of a lift). The propensity for segregation typically increases as the lift height increases. These features inadvertently promote passive air (oxygen) entry through advection and can accelerate the migration and discharge of internal MRS seepage that has resulted from infiltration at the surface of an MRS. The net effect is generally an optimised physical setting for sulfide oxidation while also minimising opportunity for acidity neutralisation.

Mine Rock Stockpile Hydraulic and Geochemical Performance

Oxygen supply to sulfidic mine rock is the key limiting factor for ARD / AMD generation at most sites, unless they are in hyper-arid environments. Indeed, the mining industry has understood for some time the critical role that flow and storage of gas (oxygen) within an MRS has on sulfide oxidation, and therefore acidity generation.

Mechanisms / processes influencing air entry to an MRS are relatively well known and can lead to significant fluctuations in air flow through an MRS on a diurnal and seasonal basis. Hence, to manage ARD / AMD risk, gas flow mechanisms should be considered when developing ARD / AMD management strategies for MRSs.

[1] 'ARD / AMD', or acid rock drainage / acid and metalliferous drainage, is also referred to as metal leaching and acid rock drainage, or 'ML-ARD'; both terms describe the same issue within the mining industry. This document will use 'ARD / AMD'.

To date, managing ARD / AMD from MRSs has largely been focussed on collection and treatment of any resultant MRS effluent (ie. MRS toe and basal seepage) as well as application of cover systems (to manage oxygen ingress and/or net percolation into the MRS). It can be argued that these approaches have proven unsustainable in many instances and have led to an industry reliance on treatment in perpetuity.

Improved Mine Rock Stockpile Construction Methods

More recently there is recognition that improved construction methods are being developed and applied that offer a better approach for managing ARD / AMD risk associated with MRSs. Several improved MRS construction methods are currently available. A total of 6 broad categories of improved MRS construction methods were assessed in this study. Four (4) of the methods are focussed on geotechnical engineering approaches, and two (2) are geochemically focussed methods, as listed and defined below:

Lower lift heights:	Lowering lift heights to reduce the influence of segregation within an end-dumped MRS, and thereby reduce internal MRS air flow capacity.
Engineered layers:	Installation of horizontal engineered layers in an end-dumped MRS to facilitate vertical gas management.
Base-up, layered / compacted:	Building an MRS from the base-up via paddock dumping in compacted, thin lifts simultaneously retards air flow capacity and enhances carbonate and silicate neutralisation.
Encapsulation:	Encapsulating potentially acid forming (PAF) material with material that can achieve and maintain low air permeability to manage vertical and lateral gas transport within and to the PAF rock, thereby lowering acidity generation. Encapsulation related methods can be applied proactively (greenfield sites) and retrospectively (brownfield sites).
Oxygen Consuming Materials:	Strategic placement of sulfidic non-acid forming (NAF) materials around PAF mine material (eg. encapsulation style) can limit O_2 from reaching PAF material, as it is being at least partially consumed in the oxidising NAF layer, often without generating metalliferous drainage.
Sulfide Passivation:	Sulfide passivation installations require placement of relatively thin layers of specialised alkalinity generating materials above all PAF materials, often as a component of a cover system. Alkalinity slowly flushes into the MRS via infiltrating surface water and can passivate sulfide grains with neutralisation precipitates, thereby limiting ongoing oxidation.

The improved MRS construction methods aim to limit the access of oxygen to sulfidic mine rock, by either:

i. Regulating air entry and movement in NAF and PAF material;
ii. Influencing pore gas oxygen concentrations via manipulated oxygen consumption; and
iii. Coating sulfide grains to limit reaction with oxygen.

A comprehensive and accurate physical and geochemical characterisation and classification system coupled with the formulation of an ARD / AMD risk block model and a mine rock handling strategy is integral to all of the improved MRS construction methods.

The potential benefits and limitations of each improved MRS construction method have been identified and documented in this report. Each of these improved MRS construction techniques has strengths and weaknesses that are influenced by site-specific conditions such as topography, climate and waste geochemistry and texture.

While the benefits and limitations of each improved MRS construction method will be site-specific, it is likely that application of any one of these methods, in isolation, will not be sufficient to achieve the necessary water quality improvements in most cases. The best water quality outcomes are predicted to be associated with the carefully considered and site-specific application of multiple improved MRS construction techniques.

The six categories of improved MRS construction methods are largely introduced as proactive approaches for greenfield sites (or planned new MRSs at brownfield sites). Some of the methods are also applicable to existing MRS facilities at brownfield sites, and this is discussed briefly.

Additional "acidity control" methods have been identified in this study. These are considered "evolving" technologies and have not been assessed in detail.

Communicating the Performance Benefits of Improved MRS Construction Methods

This report communicates the potential performance benefits of improved MRS construction methods by:

i. Using coupled thermal / gas / hydrological numerical modelling to evaluate differences in oxygen availability, and therefore sulfide oxidation, within conventional MRSs as compared to improved MRSs (Section 5). For this aspect, differences in performance are quantified over time, following construction, through:
    a. Changes in airflow capacity with the MRS;
    b. Changes in temperature conditions within the MRS;
    c. Changes in oxygen concentration within the MRS; and
    d. Changes in the stored acidity generated within the MRS.
ii. Documentation of case studies where one or more of the improved construction methods has been applied at current mine sites and has demonstrated water quality improvements (Section 7).
iii. Using a risk-based approach by evaluating high-level potential failure modes and effects/pathways for conventional MRSs, and inclusion of mine rock placement strategies to mitigate risk (Section 8).

Further detail on these are outlined below.

Numerical Modelling

The potential benefits of improved MRS construction methods can be quantified based on acidity loads (acidity = acid + metals). As an example of how this can be achieved, acidity generation modelling was conducted for MRSs in two different mine settings, with conventional and improved MRS construction methods modelled separately for each mine setting (in this case, a combination of shorter lifts, vertical gas managing layers, and bottom-up construction).

Numerical modelling of acidity generation from conventional and improved MRS construction methods illustrated the ability for the improved methods to limit air-flow capacity. Controlling gas flow decreased O_2 concentrations within the MRSs and decreased acidity generation by approximately 75% over 25 years, and decreased acidity generation rates by 80 to 85% in the post-closure period. Decreases in acidity generation also correlate to decreased leaching of other elements associated with sulfide minerals that may be of concern for a site. The selected combination of improved MRS construction methods may require further optimisation and/or additional methods may be required to further decrease acidity generation rates.

The numerical modelling results were used to inform on risk ranking as part of a failure modes and effects analysis.

Case Studies

A common reason many of these improved methods are not widely implemented at current mine sites is because of the perception that their relative life-of-mine costs are greater than conventional methods, as well as a lack of proof of concept at a commercial scale. This document recognises that risks for typical MRS ARD / AMD management approaches can evolve by looking at numerous sites around the world where these improved MRS construction methods are starting to be applied. Published references or public domain examples of the improved MRS construction methods are provided and discussed in this report. Other relevant unpublished examples are introduced as generic case studies to demonstrate the growing interest in, and uptake of, improved MRS construction methods. These examples provide real world evidence, by various indicators, that water quality benefits can be achieved, and that the potential exists, for increased MRS construction costs to be offset by lower closure costs and closure bonding.

The benefits to mine site water quality associated with existing full-scale applications of various improved construction methods provides strong evidence to support their broader application. The improved methods that have only been implemented at small to medium demonstration scales also show considerable promise, and additional larger-scale demonstrations are warranted.

Failure Modes and Effects Analysis

A failure modes and effects analysis (FMEA) was conducted for one of the mine settings chosen for modelling (temperate setting) and included three scenarios – conventional MRS construction (as per the model); three improved MRS construction methods combined (as per the model); and all of the six improved MRS construction methods combined. The FMEA process demonstrated that risks associated with MRS construction can be progressively lowered (ie. adaptively managed) by adoption of a combination of the improved construction methods identified in this study, and that further assessment of cost-benefits of these methods is warranted.

Next Steps

This document provides the groundwork for additional phases, or 'next steps', for building improved MRSs. Specific recommendations are provided within this report.

With an improved understanding of available construction methods and their benefits and limitations, a more detailed framework that guides construction of lower-risk MRSs with improved geotechnical, geomorphic, and geochemical stability can be developed for mine operators on a site-specific basis (eg. a Decision Tree Tool).

The Work Program to date (Phase 1) has focused on the geochemical benefits of the various improved construction methods, but now needs to expand its consideration into including a quantitative assessment of the cost differentials between conventional and improved methods in different mining environments.

Future phases of the Work Program should focus on linking reduction of acidity generation by the improved construction methods to effluent water quality and mine-life-cycle cost-benefit on a site-specific basis. If possible, existing data of MRSs from INAP member sites could be used to evaluate the cost-benefit if that MRS was constructed differently. These could inform on the best candidate sites and technologies for field trials. Ultimately, implementing these construction methods will increase the opportunity to achieve mine closure objectives. Continued work towards developing these technologies will help quantify their economic and environmental benefit.

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GLOSSARY

Acidity	Acid + Metals
Acid	Aqueous hydrogen ions (H^+)
ALARP	As low as reasonably practical
AMD	Acid and Metalliferous Drainage
ANC	Acid neutralisation capacity; also known as Neutralization Potential (NP)
ARD	Acid Rock Drainage
BCM	Brunner coal measures (geological formation)
CCR	Coarse coal reject
CO	Carbon monoxide
CO_2	Carbon dioxide
ES	Earth Systems
g O_2/m^3	Grams of oxygen per cubic metre
H_2S	Hydrogen sulfide
H_2SO_4	Sulfuric acid
HSE	Health, safety and environment
K_{air}	Air permeability
K_{fs}	Field saturated hydraulic conductivity
kg	Kilograms
kg / t	Kilograms per tonne
kg O_2 / t / s	Kilograms of oxygen per tonne of rock per second
m^3	Cubic metres
m/s	Metres per second
MPA	Maximum potential acidity (also known as acid potential)
MRS	Mine rock stockpile (waste rock)
NAF	Non Acid Forming. In general, when the ANC of mine rock is greater than its MPA, the rock is regarded as NAF. NAF is also known as Non Acid Generating (NAG) or non-PAG.
NMD	Neutral Metalliferous Drainage
NPV	Net present value
O_2	Oxygen
OKC	Okane Consultants
PAF	Potentially Acid Forming. In general, when the MPA of mine rock is greater than its ANC, the rock is regarded as PAF. PAF is also known as Potentially Acid Generating (PAG).
PCC	Precipitated calcium carbonate
ROM	Run-of-mine
Se	Selenium
SO_2	Sulfur dioxide
Suboxic	Low oxygen concentration; < 1% by volume
TSF	Tailings Storage Facility
Vol.%	Percentage by volume
VWP	Vibrating wire piezometer (for measuring pore pressures)
Wt.%	Percentage by weight

1. INTRODUCTION

1.1 Preamble

This document was prepared in response to a request from INAP, following initial discussions with Bruce Kelley (INAP) in 2017-18 and a follow up presentation in May 2018 to INAP's Operating Committee by Earth Systems (ES) and Okane Consultants (Okane), titled: *"Demonstrating Successful Operational and Closure Strategies for Waste Rock Storage Facilities – Building Better Dumps"*. Presentation and discussion on a full breadth of work scope took place in May 2018, which included several phases; this document is the key deliverable from the first phase of work.

This report is submitted jointly by ES and Okane; hereinafter referred to as the Project Team.

1.2 Closure Challenges

The mining sector worldwide is experiencing significant increases in closure costs and is accumulating a growing number of 'stranded' liabilities due to closure outcomes that require ongoing attention. Closure bonds, as well as financial assurance for operating sites, continue to increase as community and regulator expectations rise. A major issue driving stakeholder expectations is post-closure water quality. Almost without exception, water quality issues arise from acid rock drainage / acid and metalliferous drainage (ARD / AMD[1]) associated with sulfide oxidation that invariably requires collection and treatment in perpetuity. Collection and treatment of ARD / AMD is often underestimated or even unplanned, resulting in closure costs that are higher than anticipated.

Each mine site, new or existing, offers its own challenges and opportunities for improving post closure water quality outcomes. Differences in topography, climate, mine rock texture and geochemistry will significantly influence mine rock placement strategies and therefore final water quality outcomes. These same differences will also affect what remedial strategies will or will not be successful. Successful management strategies will undoubtedly be site specific, and more than likely, multiple strategies will be needed at each site.

1.3 Mine Rock Stockpile Terminology

It is common to refer to mined material that is below ore grade as waste rock and the resulting storage structures as waste rock dumps or waste rock piles. However, there is a growing movement in many regions to change the terminology of "waste rock dumps" to "mine rock stockpiles" or MRSs.

It is acknowledged that the mining industry often uses the term "stockpile" to refer to typically lower-grade material that is likely to be processed in the future. When left unused, however, these lower-grade stockpiles become a source of ARD / AMD, just like waste rock dumps (Section 1.4.1). Furthermore, "waste" implies a material has no value; all mine rock does indeed have value, just not necessarily a positive value. Using this perspective, the potential negative value of mine rock is easily communicated and the obvious benefits of limiting this negative value of mine rock can be leveraged to support improved MRS construction.

Mining operations are often conducted on land belonging to Indigenous peoples. There is a social responsibility to respect the land being used and recognise that mining is a temporary use of land. From a cultural perspective,

[1] 'ARD/AMD': used in this document in reference to metal leaching and acid rock drainage (ML-ARD) and acid and metalliferous drainage (AMD). Neutral Metalliferous Drainage (NMD), which is also referred to as neutral mine drainage, is also a subset of ARD/AMD.

many Indigenous peoples' creation stories are tied to the rock that is being mined. It is therefore insensitive to refer to a peoples' creation story as "waste".

Throughout this report, what has been referred to as waste rock piles will instead be referred to as mine rock stockpiles to address these points.

1.4 Why Focus on Mine Rock Stockpiles?

Some of the most significant environmental issues affecting mine closure throughout the world are associated with the quality of surface water (or groundwater) downstream of site domains such as:

- Mine rock stockpiles (MRSs);
- Tailings storage facilities (TSFs);
- Underground mine voids (internal mine rock and wallrock);
- Open cuts; and
- Heap leach facilities.

For mines that dewater or disturb sulfidic materials, ARD / AMD is the key water quality issue of concern. ARD / AMD includes acid and metalliferous drainage, neutral metalliferous drainage (NMD), as well as neutral, non-metalliferous but saline drainage.

The extent of ARD / AMD generation from any site, or specific domains within any site, can be quantified in terms of acidity load (tonnes H_2SO_4 equivalent) per unit time. There are two key methods to determine acidity load:

- Monitoring of drainage flow rates (L/s) and acidity concentrations (mg/L H_2SO_4); and
- Kinetic geochemical test work, combined with static geochemistry data, to determine pyrite oxidation rates that can be directly converted to acidity loads per unit time (ie. acidity generation rates).

These approaches are promoted by the Australian Government as outlined in Sections 2.6 and 4.7.2, respectively, of the recent leading practice publication "*Preventing Acid and Metalliferous Drainage*" (DIIS, 2016).

1.4.1 Acidity Contribution from Mine Rock Stockpiles

Project Team members have more than 25 years' experience each in implementing these approaches to quantify acidity loads at more than 40 mine sites throughout the world, in a manner consistent with current leading practice (DIIS, 2016). This includes operating and legacy mine sites that encompass a broad range of commodities affected by ARD / AMD issues. By quantifying ARD / AMD issues in terms of acidity loads for these mine sites, and for the individual domains within each site, this experience has provided the opportunity to identify the key polluting domains as a basis for focussing ARD / AMD management efforts.

On the basis of this experience, it is clear to the Project Team that, in most instances, MRSs typically represent the most significant source of acidity release, which can potentially adversely impact on groundwater and/or surface water resources. Quantitative studies by the Project Team indicate that mined PAF rock typically contributes to around 60-80% of a site's total acidity load at closure, with a further 20-30% of acidity load associated with TSFs, and the remaining proportion attributed to all other ARD / AMD sources combined[2]. The reasons and mechanisms for such high acidity loads from conventional MRS are described in detail in Section 3 of this report.

[2] Most ARD / AMD from underground mine voids can be attributed to sulfidic waste that is maintained / stored underground.

This conclusion emphasises the importance of focussing early stage planning and management efforts at greenfield sites (new facilities), and it also identifies that remedial strategies at brownfields sites (existing MRS facilities) may require different solutions to those proposed for proactive management at greenfield sites.

1.4.2 Acidity Contribution from Other Domains

The Project Team appreciates that tailings material is commonly more sulfidic and much finer grained (hence, higher surface area) than waste rock; however, tailings generally produce much lower acidity loads. This is because tailings generally oxidise relatively fast when they are in an unsaturated condition such that they consume O_2 far more rapidly than it can be resupplied. This occurs because O_2 transport from the tailings surface to the 'oxidation front' is dominated by diffusion-controlled processes (as opposed to advection as in a typical MRS), with diffusion rates being controlled by the finer-grained nature of the tailings and the degree of saturation of the tailings material. Tailings oxidation can be inherently self-limiting, and hence the focus on water quality management during operations and closure should therefore, in general, initially be on the bigger issue of mine rock management.

With regard to their capacity to generate acidity loads, TSFs, in general, are typically ranked second to MRSs (eg. Scott et al., 2011 and many unpublished reports), with pit or underground mine void wallrock generally ranked third (Taylor et al., 2016). While this does not mean that tailings or mine void wallrock are not an issue, particularly when considering site-specific conditions, it does indicate that a primary management focus for industry should be MRSs.

1.5 Building Improved Mine Rock Stockpiles

The focus on mine rock materials and stockpile construction presents an opportunity to develop a more robust approach for defining, applying, and quantifying progressive closure than is typically seen in the mining industry.

Mine rock stockpile construction, or more specifically mine rock placement in an MRS, is generally conducted with a focus on optimising development and extraction of a site's ore resources, while also managing geotechnical risk associated with the MRS. This document identifies and evaluates opportunities to expand this typical focus driving MRS construction (ie. optimising ore resources and achieving geotechnical stability), to incorporate the additional need to optimise geochemical stability of these facilities. A focus on risk management can demonstrate that geotechnical and geochemical optimisation of an MRS design is a consequence effect arising from addressing specific failure modes.

1.5.1 Geochemical Focus

Acidity generation from mine rock is most often directly associated with sulfide oxidation, but there are often subordinate contributions from secondary acidity generating sulfate salts (eg. sparingly soluble jarosite-type minerals). The geochemical behaviour of sulfides and secondary sulfate minerals is different; hence, their management requirements are also different. While the key acidity generating sulfide minerals are sensitive to O_2, jarosite-like secondary minerals are not. Hence the benefits of managing gas transport, and therefore oxygen availability, within an MRS are substantial for sulfide minerals. Once formed however, the stability of jarosite and acidity release from this type of mineral is not sensitive to oxygen availability, but rather, is sensitive to net percolation into the MRS, and consequent storage and release of water from the MRS.

Sulfide minerals generate the largest proportion of the acidity from almost all mine rock materials, not secondary salts such as jarosite. If the focus remains on controlling sulfide oxidation, then jarosite will not be able to form.

It is clear, then, that ARD / AMD management from sulfidic rock needs to primarily focus on preventing or slowing sulfide oxidation processes. Furthermore, it is the Project Team's experience that pore-space air within mine rock as the MRS is constructed is responsible for only a very small percentage of sulfide oxidation that occurs within an MRS (ie. ARD / AMD generation). It is the ongoing resupply of air (ie. O_2) to the pores of the mine rock within the MRS, that is responsible for acidity generation over much longer timeframes. Hence, to effectively manage ARD / AMD risk associated with mine rock, a key opportunity is to construct an MRS to reduce or prevent O_2 resupply to reactive sulfidic minerals.

While there are important geochemical controls that can influence gas transport processes, the primary control(s) on gas movement into and within an MRS are related to the physical, and hence hydraulic, characteristics of the MRS. In short, MRS construction, or more specifically the rock placement method during construction of an MRS, strongly influences gas transport into and within an MRS. As a result, a focus on the manner in which an MRS is constructed has the opportunity to significantly lower ARD / AMD generation rates.

Some improved construction methods can also strongly influence water migration through mine rock by decreasing net percolation rates, thereby enhancing both carbonate and silicate neutralisation reactions. Changing the way an MRS is constructed also provides inherent health, safety and environment (HSE) benefits that go beyond just decreasing long-term costs post closure. Improving MRS construction methods represents a true progressive closure strategy; starting with the very first earthworks, or for brownfield sites, through implementation of an adaptive management approach to reduce ARD / AMD generation in the future.

In addition to improving waste placement strategies, there are geochemical techniques that can be proactively engineered in an MRS to further control pore O_2 concentrations, limit air access to reactive surfaces of sulfide minerals and to potentially influence the mineralogy of secondary acid salts.

1.5.2 Improved Construction Methods

To date, managing MRS ARD / AMD risk from a closure perspective has largely focussed on application of cover systems (to manage O_2 ingress and/or NP into the MRS), as well as collection and treatment of any resultant effluent (ie. MRS toe and basal seepage). Mine rock stockpiles are also known in the industry as waste rock dumps because their design typically focusses on cost minimisation and geotechnical stability. It can be argued that these approaches have proven unsustainable in many instances and has led to an industry reliance on treatment in perpetuity (MEND, 2013).

This study offers an approach that builds on industry's recent learnings related to challenges and costs associated with a heavy reliance on treatment of mine effluent to manage ARD / AMD. It focuses on a holistic closure planning approach, including:

- Physical and chemical characterisation of mine rock pre-mining;
- Selective handling and strategic placement of wastes, such as creating potentially acid forming (PAF) cells with non-acid forming (NAF) perimeters, paddock dumping and/or compaction of mine waste as it is being placed, as well reducing end-dump tip heights;
- Understanding thermochemical behaviour of an MRS and its influence on gas and water transport into and within an MRS during construction;
- Controlling MRS surface infiltration (water);
- Engineering controlled oxygen consumption within an MRS (Miller, 1995);
- Influencing secondary mineral formation; and
- Increasing hydraulic retention time for pore-water (ie. slowing porewater migration) to optimise carbonate and aluminosilicate neutralisation and lower MRS toe and/or seepage rates.

2. AIM AND SCOPE OF WORKS

The aim of this Phase 1 Work Program is to review existing MRS construction methods and summarise key improved MRS construction technologies that are available to lower acidity generation and release rates. Acidity, the measure of acid plus metals, is used in this report to quantify net pollution[3]. The review includes an assessment of the physicochemical conditions that optimise the viability of the improved methods, and estimates the acidity generation reduction between implementing these methods and conventional end-dumping construction processes for a range of distinct mining scenarios.

The Phase 1 Work Program (initial review and assessment phase) included the following work items:

1. Description of conventional end-dumping methods for MRS construction and qualitative implications for acidity generation, including a series of illustrative sketches to communicate gas transport mechanisms.
2. Development of a generic 'base case' acidity generation model for a conventional end-dumped MRS using data from existing mine sites as a baseline.
3. Description of each of the alternative methods for MRS construction and qualitative implications for acidity generation, including a series of illustrative sketches to communicate gas movement.
4. Conceptual assessment of benefits and limitations of each construction method under varying physicochemical conditions, in terms of acidity generation rates, relative cost-effectiveness, ease of construction, and HSE effects.
5. Literature review on a limited number of sites that have implemented the ARD / AMD management methods for MRS construction identified in Items 3 and 4 (above).
6. Failure Modes and Effects Analysis (FMEA) of each construction method to clarify wider opportunities for commercial applications.
7. Conclusions of this study.
8. Recommendations for future work.

This study has been conducted as a desktop-based exercise that focuses on describing different MRS construction methodologies available to reduce risk associated with MRS geochemical stability, and evidence, or observations, of these methodologies influencing MRS performance at a field scale.

[3] Acidity is different from acid and has units of kg H_2SO_4/tonne of rock. Acidity loads (units of kg H_2SO_4/tonne of rock / year) are essentially pollution generation loads, incorporating both the acid and metal content of contamination.

3. CONVENTIONAL END-DUMPED MINE ROCK STOCKPILES

3.1 Introduction

MRSs are most often constructed using end-dump placement methods (Figure 3-1). This method is usually the most straightforward and cost-effective (up-front) to the operator, and it therefore makes sense from an immediate cost or NPV perspective for the operator to construct end-dumped MRSs at their site. End-dumped MRSs are constructed by dumping the mine rock from a truck at the crest, or over the crest, of an existing slope. In the former case, a dozer pushes the material over the crest. The result in both cases, the mine rock material rolls and slides down the slope face. Depending on the site location and material properties, end-dumped MRSs exceeding 300 m in height have been constructed (Claridge et al., 1986). The resulting internal structure of the MRS is a dominant influence on the eventual generation and release of ARD / AMD from a mine site. This section discusses this internal structure and the driving forces of ARD / AMD generation from an end-dumped MRS.

Figure 3-1: Conventional end-dumping MRS construction method.

3.2 Mine Rock Characteristics

The action of end-dumping materials down a slope face results in grainsize segregation of the material and creates zones of variable texture vertically and laterally in the MRS (Figure 3-2). Natural segregation occurs during end dumping and results in a particularly coarse-textured 'rubble zone' at the base of an MRS (Claridge et al., 1986; Tran et al., 2003; Wels et al., 2003). In addition, segregation within the mine rock above this rubble zone tends to manifest in a combination of two ways; first, alternating coarser- and finer-textured bedding planes at angle of repose, and second, with a vertical profile of waste rock that is generally coarser-textured at the base of the MRS above the rubble zone, and becoming more finer-textured towards the top of the end-tipped lift. This textural heterogeneity strongly influences the hydrogeology of the MRS due to the variable permeabilities of the placed rock (Herasymiuk 1996).

These facets of mine rock segregation occurring as a result of end dumping, coupled with the rubble zones at the base of an MRS, as well as an initial relatively low internal MRS water content, allows for relatively high airflow capacity within the MRS for advective gas transport. In other words, given an appropriate air pressure gradient, there is typically sufficient internal MRS airflow capacity to re-supply O_2 consumed by sulfide oxidation.

The texture of mine rock will vary from site to site, and therefore the magnitude and potential for gas transport is site-specific. However, the net effect of end-dumping is generally an optimised physical setting for sulfide oxidation while also minimising opportunity for acidity neutralisation, by either carbonate or silicate minerals, due to limited water retention time.

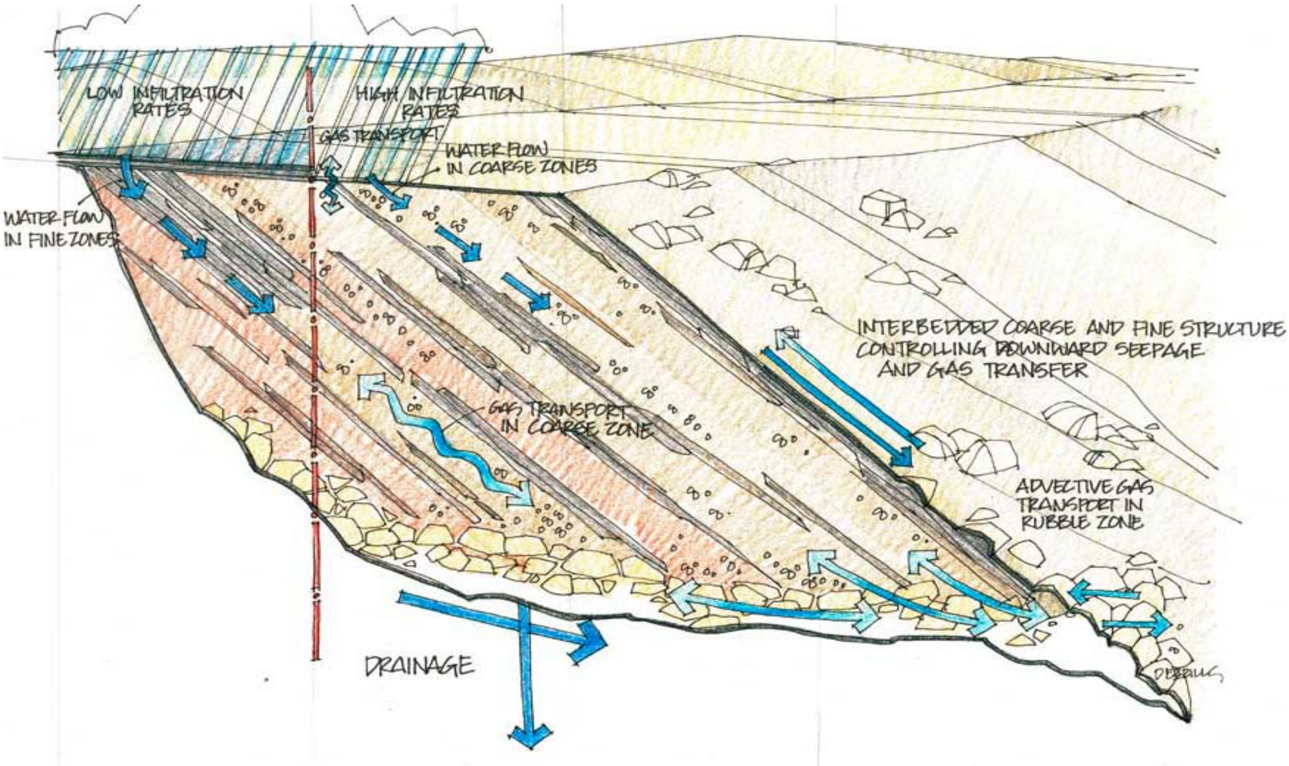

Figure 3-2: Conceptual gas and water transport mechanisms in an end-dumped MRS.

An example of an end-dumped MRS that demonstrates the propensity for advective air movement is the West Line Creek MRS in the Elk Valley, Canada. The West Line Creek MRS is hundreds of meters tall and O_2 is available in many sections throughout the depth of the MRS (Figure 3-3). Zones with decreased O_2 concentrations also exist in this MRS, demonstrating that there are mechanisms controlling O_2 concentrations. While there were no considerations made for controlling O_2 when this MRS was built, these low-O_2 zones demonstrate the potential opportunity to design improved MRSs by engineering the characteristics that have unintentionally controlled O_2 in existing MRSs.

The hydrological state of the end-dumped MRS also influences gas transport potential as it controls water and gas permeability (Wels et al., 2003). Zones of finer-textured mine rock have increased water retention capacity (Herasymuik 1996). While higher degrees of saturation inhibit gas transport through finer-textured material, nearby coarser-textured materials will be less saturated and will promote gas transport. Once oxidation begins inside an end-dumped MRS, the storage and flushing of oxidation products out of the MRS will also be dependent on MRS hydrology.

There are two conceptual models for water movement in an MRS. In the first conceptual model, higher rates of water infiltration through the MRS causes water to move primarily through 'preferential' flow paths only (ie. coarser-textured material) and flush oxidation products out of the pile. The second conceptual model suggests higher rates of water infiltration is limited to near surface within an MRS (say 5 to 10 m, and past this depth flushing efficiency is much higher). In the former conceptual model, oxidation products will tend to accumulate in layers of finer-textured materials as water flow rates are much lower in these zones (Tran et al., 2003). For the latter conceptual model, the preferential flows result from high surface infiltration rates of a bare mine rock surface (eg. during an intense rainfall) and this preferential flow is limited to near surface. At some point, there is insufficient textural contrast for preferential flow and vertical flow dominates within the MRS as the intensity of the rainfall event is 'dampened' with depth.

It is likely both conceptual models occur within an MRS, with their relative significance dependent on site-specific MRS physical and climatic characteristics.

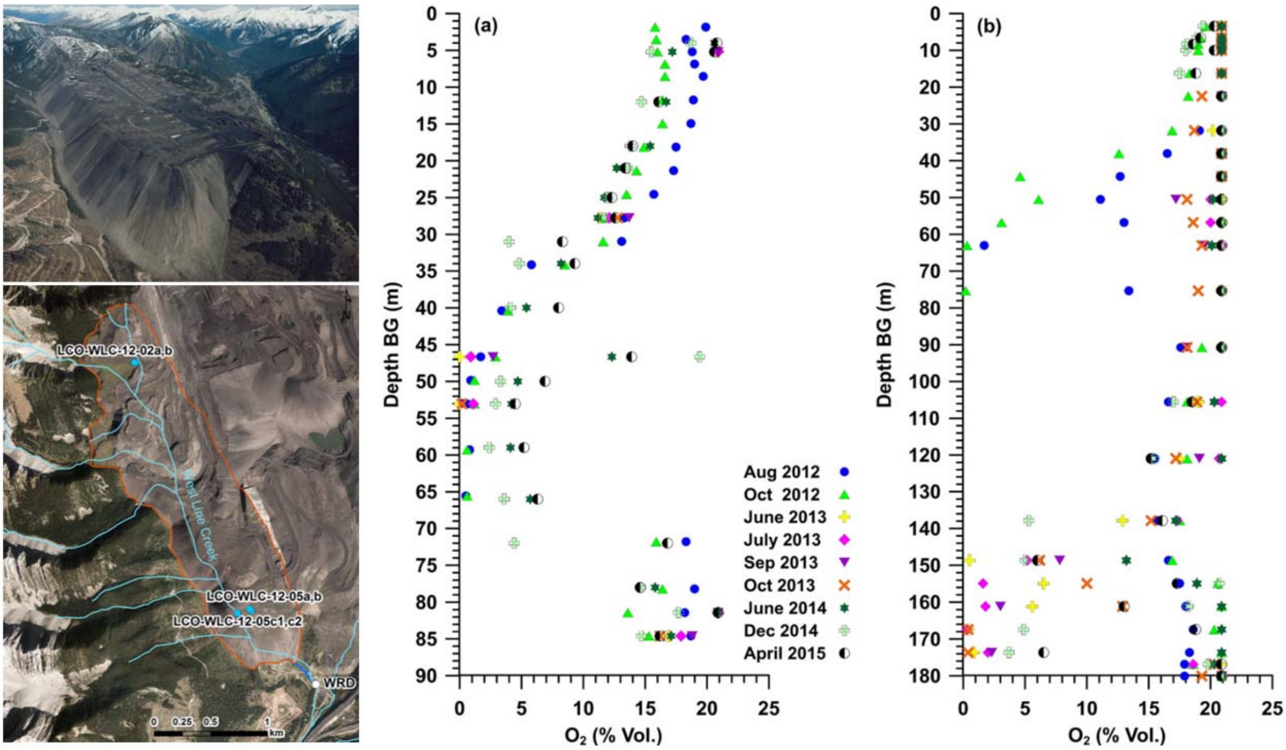

Figure 3-3: Photographs of the West Line Creek MRS and pore-gas O_2 concentration profiles at the points labelled (a) LCO-WLC-12-02a and (b) LCO-WLC-12-05C2 (after Mahmood et al., 2017).

3.3 Key Controls on Gas Transport within an MRS

3.3.1 Introduction

The key driver for oxidation processes in an MRS is the ability for air to enter and move through the pile. Oxidation rates are controlled primarily by availability of O_2, hence, controlling re-supply of O_2 is critical in managing ARD / AMD. Gas transport into an MRS can occur through either diffusive or advective mechanisms. Both mechanisms will be active in any MRS; however, the physical and hydrological characteristics of the stockpile will control which mechanism is dominant. Within an MRS, advection typically has much higher gas transport potential than diffusion as the former can result in O_2 ingress deep into an MRS.

The influence of diffusion as an O_2 transport mechanism, however, should not be discounted. Diffusion of a gas is driven by concentration gradients. In the context of an MRS, oxygen concentration gradients are formed by consumption or generation of a gas through processes such as oxidation or microbial activity. An MRS with a large surface area exposed to the atmosphere and containing sulfidic material can result in substantial sulfide oxidation and acidity generation due to O_2 diffusion. This depends on the degree of saturation of the near surface mine rock material, which is a function of mine rock material texture and density, as well as site-specific climate. The relative importance of diffusion through MRS surfaces also increases when advective transport is curtailed. In short, it is important to consider exposed surface area for diffusive transport of O_2 into an MRS, in addition to advective gas transport deeper into the MRS.

Air permeability, or k_{air}, akin to the hydraulic conductivity for water flowing in groundwater, strongly influences air-flow capacity within an MRS. Bulk k_{air} within an MRS is a function of material texture (porosity), continuity of the dominant texture, and water content of the material. The k_{air} of an end-dumped MRS is typically high and favours increased air flow (although the k_{air} can change with time as the MRS 'wets up'[4]).

Advection is the movement of a gas as a result of the bulk motion of a fluid. As such, a driving force to move the fluid must first be applied. In the context of MRSs, these driving forces typically occur as pressure gradients resulting from changes in barometric pressure and convective flows resulting from thermal gradients influencing partial pore-air pressure and thus gas density. Temperature-driven convection has been noted as the dominant mechanism in most MRSs (Morin et al., 1991).

Geometry and total exposed surface area also influence gas movement into an MRS. Irregular surfaces, such as those formed from benches, can provide preferential gas entry and exit pathways (Wels et al., 2003). Large-scale configuration of the MRS will determine the final exposed surface area of the mine rock. The rate of construction also influences how long surfaces are exposed to the atmosphere before they are covered up with more mine rock or reclaimed with vegetation. An exposed slope or bench will be susceptible to diffusive O_2 fluxes that it normally would not be in the final form of the MRS. This exposure could lead to accumulation of oxidation products that could be flushed out after the section has been covered.

3.3.2 Internal MRS Gas Transport

Figure 3-4 shows an example of detailed data for around one-month of continuous internal MRS O_2, temperature, and barometric (total) pressure monitoring at a single depth / location, as well as external temperature and barometric (total) pressure. Continuous measurement and frequent logging of gas concentrations, temperature and pressure variations within an MRS, relative to ambient environmental conditions, can improve understanding of site-specific controls on gas transport over short and long-time scales.

Several observations can be made from the data shown in Figure 3-4.

- No discernible barometric (total) air pressure difference between inside and outside the MRS was measured.
- There was little variation in stockpile temperature (~23°C) over the one month period.
- Diurnal atmospheric temperature variation was from ~5°C to ~20°C.
- Oxygen concentrations within the MRS vary from atmospheric levels (~21 vol.% O_2) to well below 10 vol.% (eg. first 8 days of data). For these first 8 days of the monitoring record, internal MRS temperature is almost always greater than ambient temperature.
    - Internal O_2 concentration peaks at atmospheric concentrations during the coolest part of the day (at night), when the temperature gradient is greatest between inside and outside the MRS. Hence, for this condition the warmer and more buoyant gas inside the MRS rises within the MRS, and likely draws gas representative of ambient conditions to the monitoring point. Very likely, this is lateral gas transport from the side slope of the MRS (perhaps as a result of the presence of a coarser-textured rubble zone along the base of the lift). For this condition, O_2 supply is great than O_2 demand within the MRS (due to sulfide oxidation).

[4] Wetted up (and time to wet up): defined in this context as the condition where a 'drop of water at the surface of an MRS results in a pressure response at the base of the MRS to 'push a drop of water' out the base. This does not represent pore-water velocity (the time for the 'drop of water' to move through the full height of the MRS). In addition, different areas of an MRS 'wet up' faster / slower due to material thickness, all other variables controlling wetting being the same; also, the material will drain due to gravity before the system is 'fully wetted up'. Hence, seepage from the base of an MRS will occur before the entire MRS is 'fully wetted up'. Finally, a 'wetted up condition' does not necessarily imply 'saturated conditions'; it simply describes the 'steady-state' volumetric water content of the material for the given surface infiltration (or net percolation) rate, depth of material, texture of material, etc.

   - Internal O_2 concentrations are at their lowest (as low as ~8 vol.% O_2) during the warmest part of the day (during the day), when the temperature gradient is lowest between inside and outside the MRS. In this case, transport of ambient air conditions to the monitoring point is limited (very likely due to the reduction in partial pore-air pressure gradient because of the reduced temperature difference), internal MRS demand for O_2 at this monitoring location exceeds O_2 supply, and internal O_2 concentration decreases. This is a reasonable interpretation of the dataset because the material and internal moisture conditions will not have changed at this monitoring location over such a short time frame.

- Oxygen concentrations within the MRS are consistently below 10 vol.% during the next 7 to 8 days of data, rising from initially ~8 vol.% O_2 to ~10 vol.%. For this period of the monitoring record, diurnal temperature ranges to above 25°C to more than 30°C during the day (ie. above internal MRS temperature), and then to below internal MRS temperature at night.

   - During this period, when internal MRS temperature is lower during the day than external MRS temperature, internal MRS gas will be denser, and thus 'falling' within the MRS. It is likely that at the monitoring point, it is located deeper within the MRS and ambient gas conditions are not transported within the MRS to the monitoring point for the time frame of the diurnal cycle. In this case, internal MRS demand for O_2 at this monitoring location exceeds O_2 supply, and thus internal O_2 concentration remains low.

   - During the night, as with the first 8 days of the monitoring record, external temperature drops, and internal temperature is higher, and thus the direction of gas movement internal within the MRS will have changed. However, likely because there is not the same gradient as observed in the first 8 days, only a slow rise within internal O_2 concentration is observed. This slow rise is also a function of the slowly decreasing temperature gradient for internal gas to be falling because daily temperature maximums are slowly reducing over the 7 to 8-day time frame. This is a reasonable interpretation of the dataset because the material and internal moisture conditions will not have changed at this monitoring location over such a short time frame.

- The above patterns repeat for the remaining dataset shown in Figure 3-4, to a greater and lesser extent, depending on differences in internal and external MRS temperature.

The data shown in Figure 3-4 illustrates the strong dependence on internal O_2 concentration related to internal and external temperatures, which can occur on a diurnal and seasonal basis. The net effect is, given sufficient demand for O_2 within an MRS, and sufficient airflow capacity within the MRS, continuous re-supply of O_2 can lead to substantial and ongoing acidity generation.

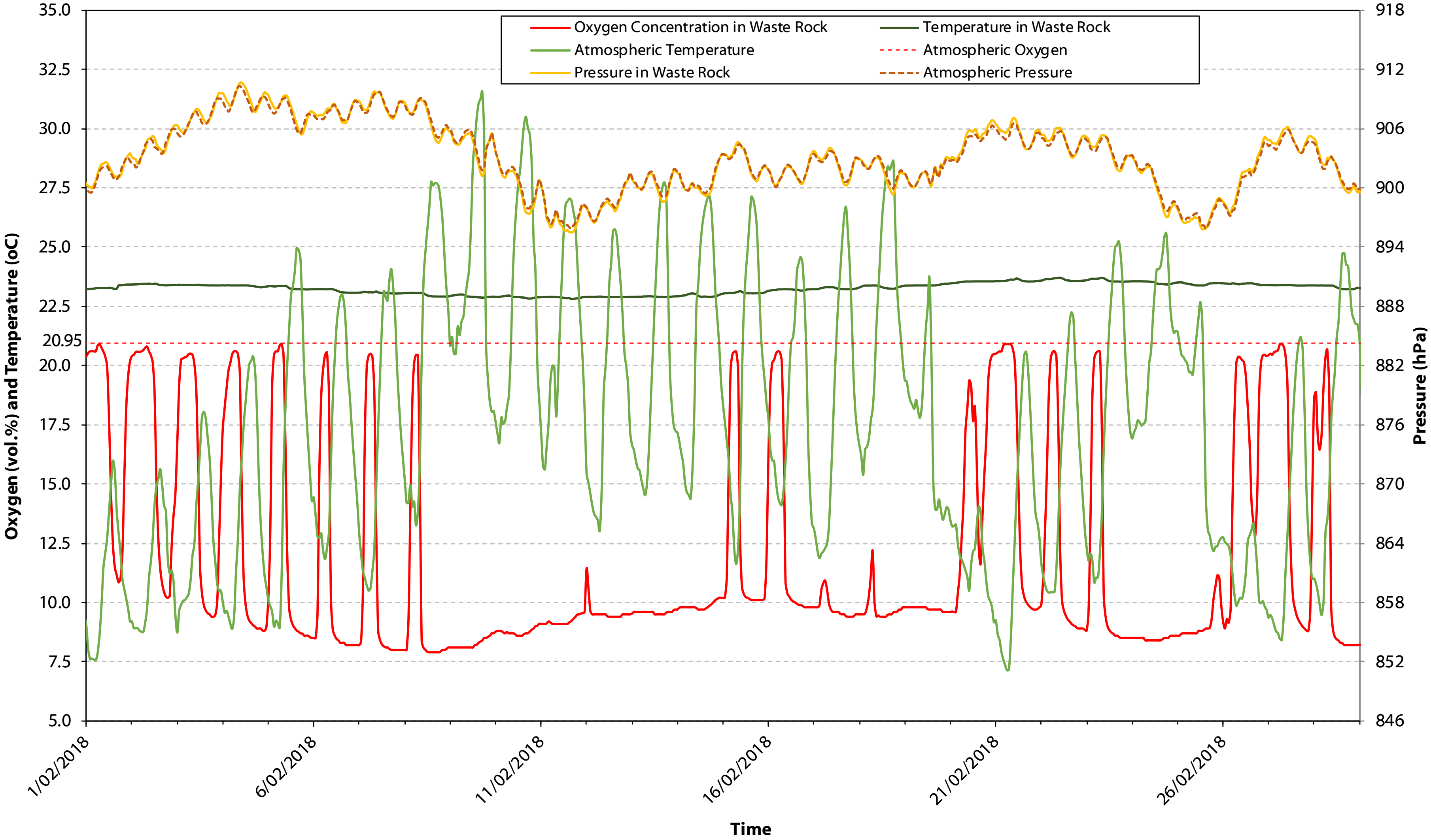

Figure 3-4: Example of continuous internal MRS O_2, temperature, and barometric (total) pressure monitoring for a single depth / location at a (confidential) mine site located in Australia.

4. IMPROVED METHODS FOR MINE ROCK STOCKPILE CONSTRUCTION

4.1 Context

This section identifies improved MRS construction technologies that build on industry's recent learnings related to challenges and costs associated with a heavy reliance on treatment of mine effluent to manage ARD / AMD.

A combination of research and development and field-scale application has demonstrated the potential value of alternative mine rock placement and management strategies. While many of these strategies are not new to the industry, they are generally not favoured in comparison with conventional mine rock management methods. While some form of 'end-dumping' from a truck will generally be required to construct an MRS, it is the height, subsequent handling, and overall placement strategy that influences ARD / AMD generation.

It is acknowledged that these improved methods can result in higher operating cost; however, conceptual models, numerical models, laboratory data, and field data at sites that have implemented these strategies have shown decreases in ARD / AMD generation rates (whether or not this was their primary intent). Any reduction in ARD / AMD generation rates will lower the severity of ARD / AMD-related risks, thereby reducing (or eliminating) the reliance on collect and treat systems in the future and making the operation a more valuable investment in the present.

This section outlines alternative mine rock placement strategies and describes the mechanisms by which they reduce ARD / AMD generation rates. It is important to consider the site-specificity of these strategies (ie. the site-specific controls on these mechanisms) while evaluating their potential application at a site. For example, the value and overall performance of a given strategy may depend on local climate, the relative proximity and position of the orebody to the proposed stockpile site, availability of construction materials, and the geochemistry of the mine rock itself. Understanding site-specific performance that can be obtained from these strategies will be critical in extracting the most value from changing the way MRSs are constructed.

4.1.1 Key Mine Rock Stockpile Construction Methods

There are at least six fundamentally important, distinctive, established and/or emerging management strategies for MRSs to mitigate the effects of ARD / AMD, which are increasingly being applied at mine sites worldwide. They represent leading practice / best practicable strategies for preventing and minimising ARD / AMD from MRSs. These methods focus on source control by limiting O_2 supply to reactive wastes and sulfide passivation, while inherently providing health, safety and environment (HSE) benefits.

These strategies are listed below, broadly grouped into three general areas:

- Control of Gas Transport due to Advection into and within an MRS, using;
    i. Lower Lift Heights;
    ii. Engineered Layers to Manage Vertical Gas Transport;
    iii. Encapsulation; and
    iv. Paddock Dumping and Base-up Construction of MRSs;
- Oxygen Consuming Materials; and
- Sulfide Passivation.

4.1.2 Current Application of Emerging Construction Methods

There are a few sites where these improved methods are being applied, although often they are used individually rather than in combination. In addition, while not the specific intent, there are sites where field performance monitoring of an MRS has provided evidence that the influence of, for example, lift height and material texture, has influenced internal MRS gas transport. In general, however, the Project Team consider it more likely that implementation of several of these strategies in any one MRS has a far greater chance of reducing risk associated with MRS geochemical stability, than relying on a single method; noting that the most appropriate approach is based on site-specific conditions and landforms.

Site-specific conditions will strongly influence the most cost-effective implementation strategies. As the costs, liabilities, and bonds for rehabilitation and closure increase, the real benefits of managing ARD / AMD risk prior to, or during mining will become increasingly evident. In addition, interpretation of cost-benefit evaluations can often be hampered by using the common cost comparison tool; namely net present value (NPV). It is challenging to compare strategies using an NPV approach because: i) annual costs associated with ARD / AMD treatment are substantially discounted, and ii) ARD / AMD treatment costs are assumed to be static over the long-term. Rather, annual ARD / AMD treatments costs are not static due to numerous factors (Meints and Aziz, 2018; Thomas and O'Grady, 2018). Factors relate to cover system performance, seepage collection efficiency, conveyance of collected effluent, storage of collected effluent prior to treatment, increasing reagent costs, and changing regulatory requirements. Complicating this issue is that risk assessment for closure planning is conducted over a mine-life-cycle time scale[5], whereas risk assessment for mine planning is typically conducted over a life-of-mine time scale[6]. Risk assessment at the life-of-mine time scale emphasizes the most cost effective way to extract ore; risk assessment over a mine-life-cycle time scale includes all mining activities, including progressive reclamation.

The key message is that the Project Team recognise the challenges with demonstrating cost-benefit when introducing different MRS construction opportunities using typical cost comparison tools. In addition, there is a recognition that properly conducting a cost-benefit analysis can likely only be completed using site-specific conditions and site-specific risks for ARD / AMD management. However, the work program outlined here is designed to introduce INAP Member companies to the benefits and limitations of leading practice and emerging MRS construction methods for lowering ARD / AMD generation and release from mine sites, while also realizing HSE benefits of these methods to implement robust, progressive closure, and achieve desired closure objectives. A cost-benefit analysis is not included in the current phase of the project.

4.2 Control of Gas Transport within an MRS due to Advection

Gas transport within a conventional MRS can be dominated by advection; the result is high air flow and O_2 supply rates deep into the MRS, with a consequent increase in sulfide oxidation and acidity production, and therefore an increase in risk associated with ARD / AMD. There are several opportunities to control advective gas transport within an MRS. These opportunities focus on limiting vertical and lateral gas transport capacity. The concept with this approach is to move from a state where there are large zones of high O_2 concentration within an MRS, characterised as having:

- High potential for sulfide oxidation and acidity production;
- High potential for acidity mobilisation (ie. acidity load) to the toe / base of the MRS; and

[5] The mine-life-cycle time scale for the purposes of this report is the time frame beginning with exploration, through to construction, production, closure works, and post-closure.

[6] The life-of-mine time scale for the purposes of this report is the time frame where ore reserves will be extracted.

- An increased potential for depleting and exhausting available neutralisation potential.

To a state where the internal conditions of the MRS have been altered and can be characterised as having:

- Potential to create large-scale suboxic zones which, after consuming the initial pore-space O_2, limit O_2 re-supply;
- Decreased sulfide oxidation and acidity production potential; and
- Enhanced ability for slower-reacting (silicate) minerals to provide neutralisation capacity.

This section is an introduction to emerging technologies and methodologies that are available to control advective gas transport within MRSs and thereby control ARD / AMD generation.

4.2.1 Lower Lift Heights

Lift heights are controlled by the height of a tip head, which is defined as the vertical distance between the back of the truck and the surface the material is being placed on. Tip head heights in conventional end-dumped MRSs are often very large (50 to 200 m). In particular, valley-fill MRSs will have very large tip head heights if the material is being dumped from a ridgeline. It is the tip head heights themselves that create the segregated internal structures of end-dumped MRSs responsible for high air-flow capacity and preferential flow paths of air and water (Section 3.1). Reducing the tip head height tends to decrease grainsize segregation, thereby decreasing lateral and vertical air-flow capacity. A more uniform wetting-up process can occur as well. Smaller tip head heights are inherently a part of some of the subsequent construction methods to be discussed later. This section focusses on the mechanisms and benefits of simply decreasing tip head heights alone.

In general, grainsize segregation is minimal in tip head heights smaller than 4 to 6 m (Wilson, 2011). Segregation then occurs at tip head heights above 6 m, although the total height may not change the degree of segregation above this height (Morin et al., 1991). In this case, decreasing to not less than 6 m will increase the number of rubble zones, although it is likely these rubble zones would be smaller than large, end-dumped lifts.

Decreasing tip head heights also has implications on MRS construction sequence, which can assist with the prevention of ARD / AMD. First, smaller tip head heights result in lifts being completed faster. This means that lift surfaces are exposed to the atmosphere for less time than a larger lift, thus decreasing the depth of O_2 penetration by diffusion. Additionally, more surface area is trafficked by haul trucks and dozers on thinner lifts, creating more frequent horizontal layers of denser material with potential to have lower air permeability provided the appropriate degree of saturation is present.

4.2.2 Engineered Layer(s) to Manage Vertical Gas Transport

Vertical and lateral gas transport capacity within a conventional MRS can result in deep penetration of ambient conditions simply because of oxygen demand within the MRS and geometry of the MRS (ie. the difference in height), as shown in Figure 4-1. Introducing horizontal engineered layers to create textural discontinuities can result in an overall reduction in vertical air flow capacity within the MRS, as shown conceptually in Figure 4-2. In this case, penetration of ambient conditions is limited to that near the sloping area of the MRS because the engineered layer limits vertical gas flow; in short, the geometry of the entire MRS can influence gas transport.

In this context, the engineered layer is intended to reduce air flow capacity because it functions as a 'barrier' to air flow. This is accomplished through a reduction in k_{air} of this layer. Achieving the required reduction in k_{air} is a function of the engineered layer's texture, density, thickness, water retention characteristics, and flow conditions within the MRS. For example, a thin layer of silty clay (say ~0.5 m), placed with relatively low density, and in a wetter environment could provide sufficient saturation conditions to reduce k_{air}. A 2 m thick well-graded run-of-mine material placed at a relatively high density (as compared to the silty clay for example), also has the potential to provide the required decrease in k_{air}, depending on whether the degree of saturation can be maintained.

Figure 4-3 shows calculated k_{air} as a function of degree of saturation for materials of varying texture, and density. The extent to which k_{air} must be reduced for the engineered layer will be site-specific. The presence of the engineered layer, or a series of them on top of MRS lifts, can also slow down MRS wetting up and draindown, thereby decreasing seepage rates or offsetting the time until seepage occurs.

Caution is required to minimize risk of the engineered layer being a 'barrier' to water flow, as this may influence internal MRS pore-water pressure conditions and potentially MRS geotechnical stability. Whether the engineered layer becomes a 'barrier' to water flow, which then leads to an influence on geotechnical stability, is entirely site-specific. In general though, when modelling and monitoring, one would be looking for minimal generation of excess pore water pressure above or within the engineered layer.

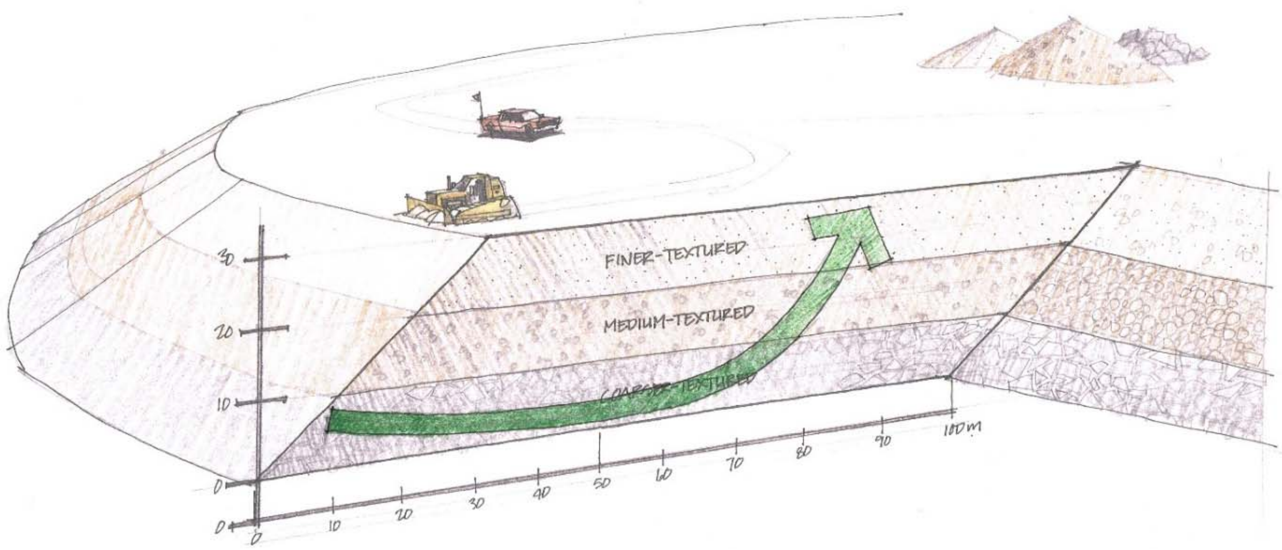

Figure 4-1: Conceptual gas transport regime in an MRS with no engineered layering.

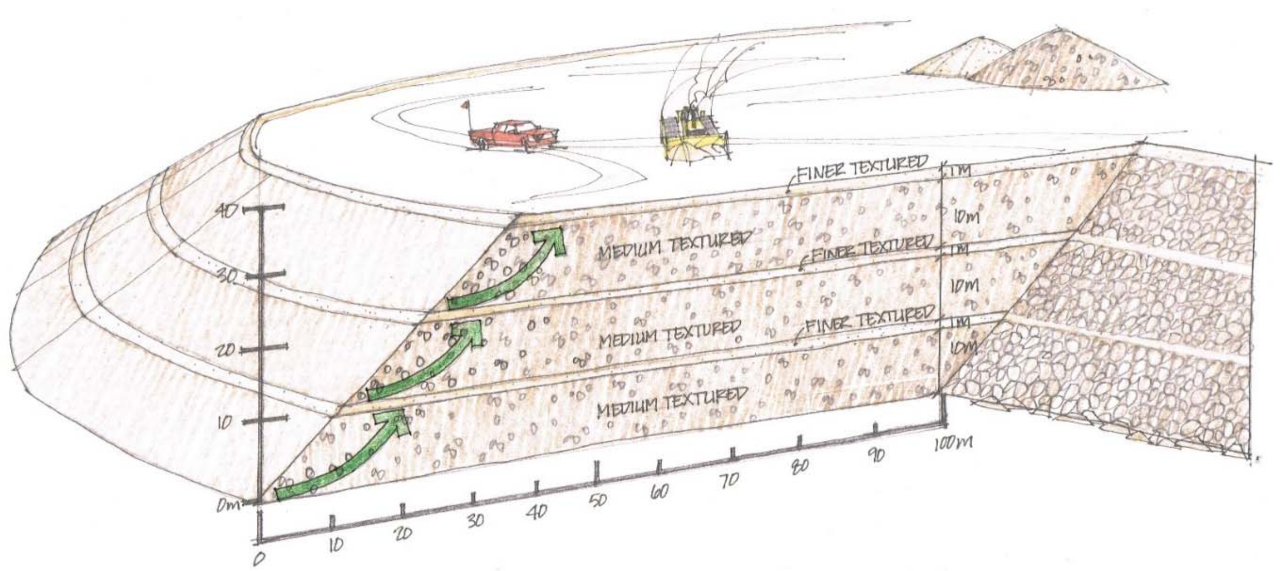

Figure 4-2: Conceptual gas transport regime in an MRS with trafficked air-entry disruption layers.

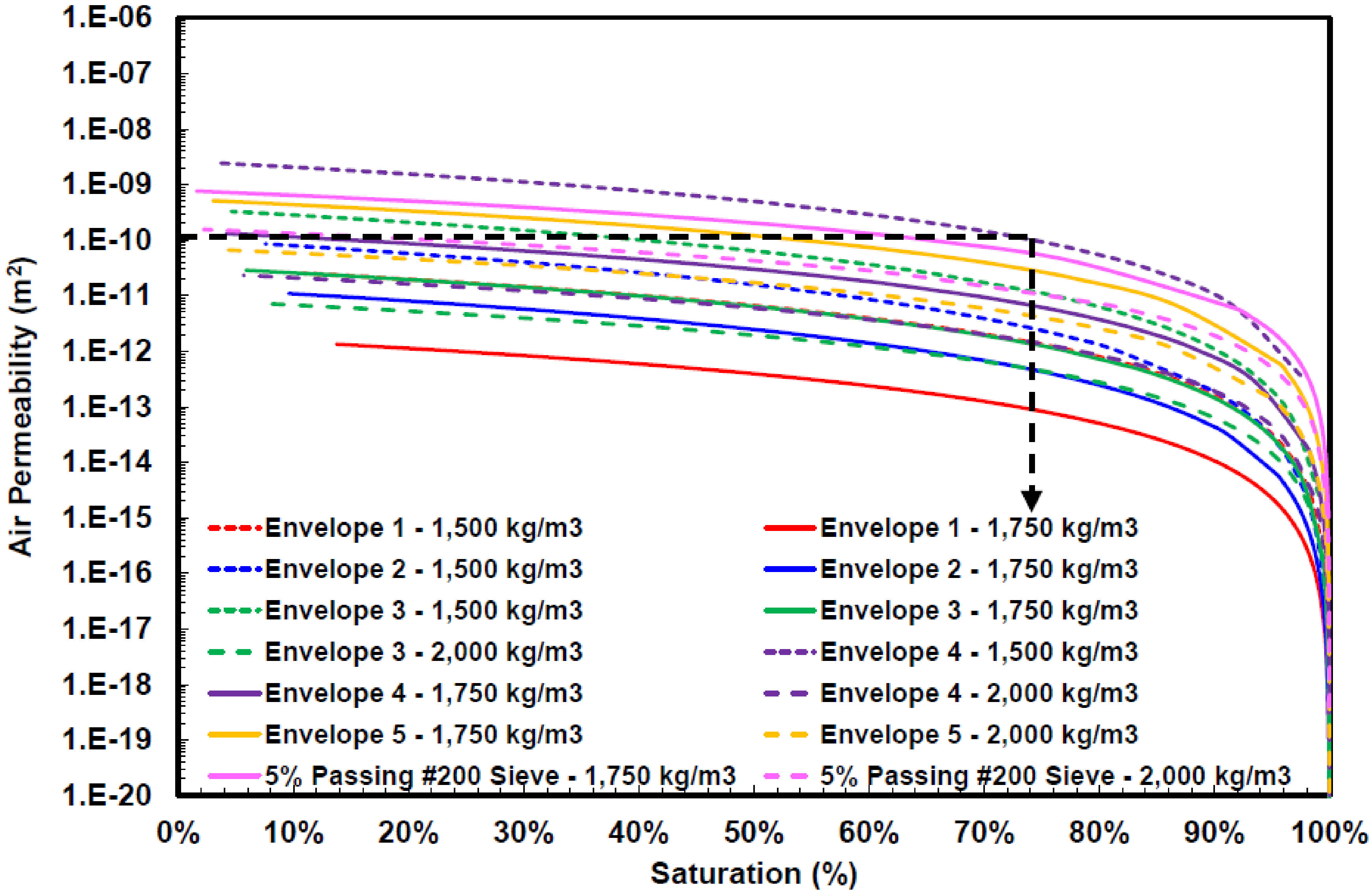

Figure 4-3: Calculated air permeability as a function of degree of saturation, texture, and density (from Pearce et al, 2017).

4.2.3 Encapsulation

Encapsulation is defined in the context of this study as encapsulating PAF mine rock material with layers that limit air flow capacity into the MRS, within the MRS as it is being placed, and before a final cover system is placed. In other words, encapsulation does not mean 'encapsulating the entire MRS with a final cover system' and is not a blending strategy to mix PAF and NAF. Furthermore, encapsulation does not necessarily refer to placement of neutralising material around PAF cells (although use of neutralising material may form part of a broader encapsulation strategy to lower air entry into an MRS).

The same principles required for design of the engineered layer described above, apply to placing an engineered layer for lateral gas management to achieve encapsulation of PAF material within the MRS during construction.

Encapsulation requires a well-organized mine plan, strong understanding of geochemical and physical characteristics of on-site materials, and their schedule / availability during MRS construction. The engineered layer of material for encapsulation does not necessarily require NAF material, as long as it is not exposed to atmospheric oxygen. Rather, its physical and thus hydraulic characteristics are more important, with these being as described above for the engineered layer approach to manage vertical gas transport. To optimise cost and minimise double-handling, the encapsulating material is ideally sourced directly from mining operations. Another key aspect of encapsulation is the method of material placement; if a PAF cell and the material encapsulating it is end-dumped, this approach may not be effective.

An example of an encapsulation method with multiple encapsulation cells being constructed over the life-of-mine is illustrated conceptually in Figure 4-4. The lateral and vertical dimensions of the cell are a function of material availability, but ideally the time frame needs to minimise sulfide oxidation during MRS construction before the entire cell is encapsulated, and the next cell started. Larger PAF cells would decrease the overall amount of encapsulating material required but would leave the PAF cell exposed longer and is dependent on the mine schedule. In practice, more than one cell is constructed at once with varying stages of progress to maximise flexibility with placement run-of-mine rock. As with inclusion of horizontal engineered layers to limit vertical gas flow capacity, introduction of engineered layers to include lateral gas management also requires careful consideration of constructability and geotechnical stability.

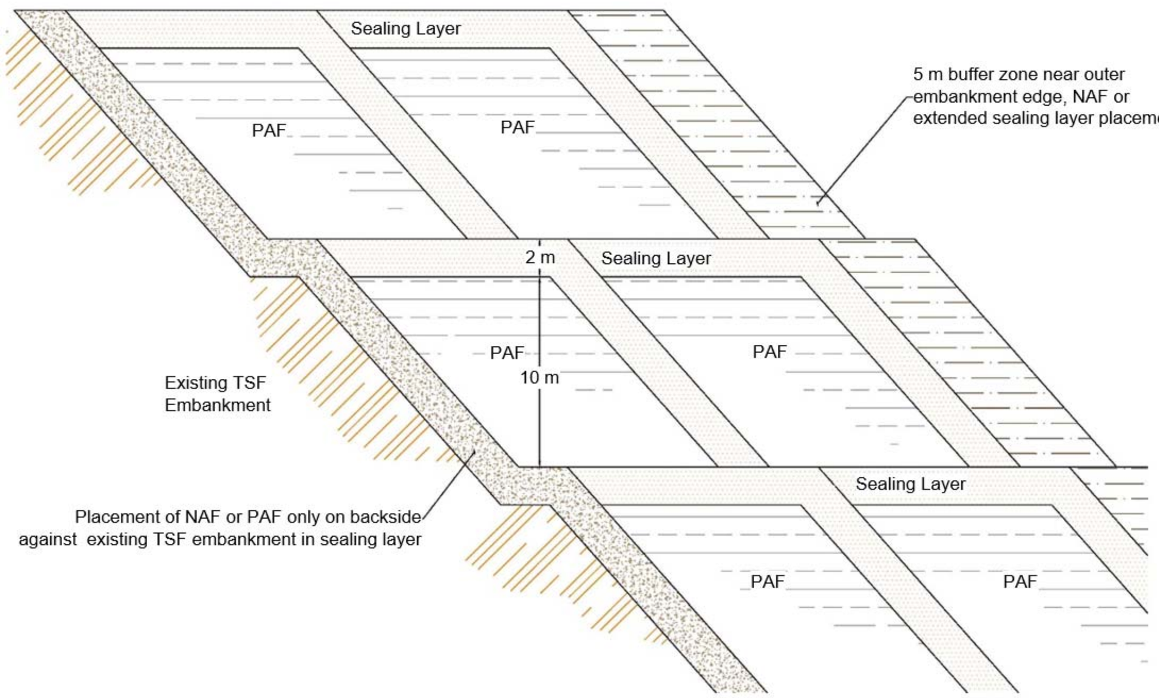

Figure 4-4: Example of MRS construction approach incorporating multiple PAF mine rock zones encapsulated by low permeability NAF sealing layers.

4.2.4 Paddock Dumping and Base-up Construction

Paddock dumping is defined in the context of this study as mine rock haul trucks dumping material onto a flat MRS surface to create singular conical pyramid rock deposits. Minimal segregation results, particular if the 'tops' of the paddock dumps are 'knocked down' by a dozer prior to placement of the next layer of paddock dumping. In terms of placing run-of-mine rock into an MRS, paddock dumping provides the highest potential for minimal segregation and a more homogeneous internal structure. They are commonly 1.5 to 4 m high, depending on the truck capacity. Subsequent paddock dumps, either adjacent to or overlapping the initial dump create a hummocky landform that cannot accommodate traffic until it is flattened and compacted. This process generally only occurs once an entire layer has been deposited.

This method needs to include the conventional approaches of identifying, segregating and selectively placing NAF and PAF materials. In this way, thin-lift, compacted NAF zones (or even O_2 consuming NAF zones) can surround (encapsulate) thin-lift, compacted PAF zones.

Figure 4-5 demonstrates the encapsulation process at a site where end-dumped PAF mine rock is being encapsulated via placement of NAF material in paddock dumps around the margin of the MRS. The NAF zone is being constructed from the base up, with each layer of paddock dumps compacted to form thin lifts.

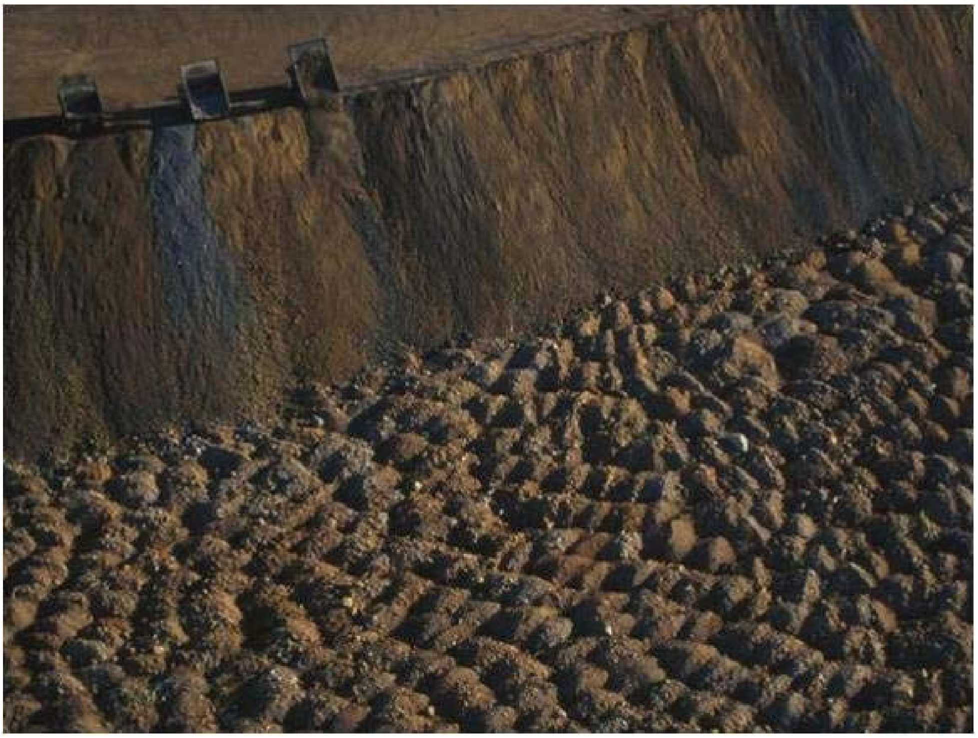

Figure 4-5: Combination of encapsulation and paddock dumping with base-up (thin lift) MRS construction methods. In this case, end-dumped PAF mine rock is being encapsulated by paddock-dumped NAF material. The paddock-dumped lifts are visible around the batters of the end-dumped PAF material in this image and will ultimately extend above the full height of the end-dumped material.

4.3 Oxygen Consuming Materials

Mine rock commonly contains a mixture of sulfidic and carbonate minerals. Depending on the proportion of each of these reactive minerals, the waste is either classified as PAF or NAF. In general, when the maximum potential acidity (MPA) of mine rock is greater than its acid neutralisation capacity (ANC), the rock is regarded as PAF. When ANC is greater than MPA, the rock is considered to be NAF.

PAF materials are invariably O_2 consuming and acidity generating. NAF materials containing sulfide, must, by definition, contain an excess of neutralising capacity. However, they can then also be regarded as O_2 consuming and acidity generating, but not acid generating. This is one scenario by which NMD can be produced. Hence, NAF rock containing sulfidic material is a potential O_2 consuming resource and could be used to lower or prevent ARD / AMD if it is strategically placed to manage O_2 entry into PAF materials.

Few mine sites worldwide that proactively classify mine rock into NAF and PAF consider extending their classification system to identifying O_2 consuming NAF material (ie. elevated sulfur NAF), despite the fact that no additional information would be required to create this new category. Subcategories of existing NAF material such as low, medium and high O_2 consumption capacity could potentially be identified (based on site-specific criteria) and mapped in an ARD / AMD risk layer in the mine block model at essentially no expense. Using existing static geochemical data to improve the sophistication of waste placement can be expected to significantly lower acidity generation rates. This would be achieved by extending the period over which acidity is generated and thereby lowering the acidity load per unit time from sulfidic MRSs, or even by slowing the ARD / AMD release rate to loads that can be sustainably accommodated by the receiving environment, or until other ARD / AMD management methods become successful.

The use of oxygen consuming materials as an ARD / AMD management strategy for MRS construction inevitably requires an understanding of the potential for NMD and confirmation that the risk of NMD is minimal or can be otherwise managed.

4.4 Sulfide Passivation

Carbonate minerals that occur naturally in mine rock are known to be effective in neutralising acid generated via sulfide oxidation. It is also well known that often these carbonate minerals are so effective at neutralising acid that they become coated and inactivated by neutralisation precipitates. This process is referred to as carbonate passivation (or armouring), meaning that despite an abundance of carbonate, acid conditions within an MRS can persist if the carbonate is no longer accessible to acidic fluids. Application of an ANC/MPA ratio of 3 and above, as a general industry standard to define NAF rock, is in part a consequence of the likelihood of carbonate passivation and the potential for over-estimation of ANC if carbonates such as ankerite or siderite are present. The observation that carbonate could be abundant in an MRS but largely unreactive led to an assessment of mechanisms to passivate reactive sulfides.

The concept of sulfide passivation is based on the ability to treat the surface of individual sulfide grains on rock aggregates exposed to atmospheric O_2 in MRSs in order to slow or halt formation of acid salts.

Acid salts are known to form on pyrite grains (eg. melanterite / rozenite salts) directly as a result of sulfide oxidation. The sulfuric acid formed can attack any mineral in contact with the pyrite grain. Most non-sulfide minerals are aluminosilicate based (eg. potassium feldspar); hence, generation of soluble, acidic, secondary aluminium minerals is essentially unavoidable in most MRSs. A typical acid generating secondary aluminium phase is alunogen, which in the presence of water partially decomposes to form soluble aluminium and sulfate ions. If soluble aluminium is permitted to react with some alkalinity, potentially released from local carbonate minerals, aluminium hydroxide (and gypsum) can form close to or on the surface of the pyrite.

A key property of aluminium hydroxide is that is forms a white, amorphous, gelatinous, adhesive compound that sticks to surfaces in the same way that silicone cement behaves. Both laboratory and field studies have shown that it can form an effective local barrier to both water and O_2. Hence, if the aluminium hydroxide forms on or close to the pyrite grain around which the secondary aluminium mineral (eg. alunogen) forms, then it can generate an effective local O_2 barrier around the pyrite. This chemical process is referred to as sulfide (pyrite) passivation. Minerals / phases other than aluminium hydroxide, such as iron hydroxides (Huminicki and Rimstidt, 2009), may assist with passivation; however, the properties of aluminium hydroxide make it particularly effective for sulfide passivation.

Sulfide passivation has been shown to occur in laboratory testwork, with decreases in sulfide oxidation rates of 98% recorded over 280 days using aluminium hydroxide as the passivation material (Zhou et al., 2017).

A fundamental benefit of the sulfide passivation process is that the mass of alkalinity released to achieve this effect does not need to match the amount of acidity that an MRS can generate, but simply needs to match a small proportion of the acidity initially created by surficial pyrite grains.

Sulfide passivation differs substantially from the traditional concept of 'limestone blending'. To be successful, the intimate blending of mineral carbonates (limestone) with sulfidic mine rock requires addition of a significant excess of neutralising reagent in order to account for the maximum potential acidity (MPA) of the mine rock, as well as the limestone armouring and grain size effects (eg. Miller et al., 2003). However, alkalinity producing materials in cover systems require much less alkaline material to achieve a water quality improvement because the intention is not to treat the MPA of the mine rock, but to prevent ongoing oxidation of sulfidic grains, and to coat preferential pathways with inert, gelatinous precipitates, that help to isolate water from the sulfides.

The key parameter to understand is the rate at which alkalinity can be transferred into an MRS. The amount of alkalinity introduced from an 'alkalinity generating' material will be a function of the solubility and dissolution rate of the material, along with the amount and rate of infiltration. Without very high rainfall and thick carbonate-rich cover systems over an MRS, natural mineral carbonates are limited in their ability to deliver measurable improvements in acidity discharges from MRS, and thus are often found to perform poorly in most settings. This is because natural mineral carbonates have low solubilities and very sluggish dissolution rates. These effects are exacerbated by the normally rapid migration of water infiltrating into typical end-dumped material, which prevents significant fluid-mineral interaction (dissolution) times.

While the general principles of the passivation process have been understood for some time, key questions are how to consistently deliver alkalinity to acid generating surfaces, and how to ensure that the rate of alkalinity production broadly matches the rate of acidity generation during the passivation phase. In addition, how can alkalinity generating materials be added to an acid generating MRS without passivating them with treatment precipitates?

The approach adopted is to keep the alkalinity producing material above all PAF material, to completely avoid passivation. In many situations, this means that the alkalinity producing materials are introduced to the base of cover systems overlying MRSs. The two ways that have been established to enhance the rate of alkalinity release to better match acidity generation are as follows:

- Use a significant excess of low-cost, low alkalinity producing materials such as limestone, in high rainfall settings (eg. > 3 m/year). Under these circumstances, the low solubility and slow dissolution kinetics of limestone can potentially be overcome by the very high volumes of water infiltrating into a stockpile, dissolving the low concentrations of alkalinity.
- Use a small quantity of high cost, high alkalinity producing material, such as specialised caustic magnesia or certain types of precipitated calcium carbonate (PCC), in most climatic settings. The relatively high solubility and rapid dissolution kinetics of these materials can help overcome the limitations of low net percolation into an MRS (ie. moderate to low rainfall areas).

The ability of alkalinity generating cover materials to sustainably lower acidity discharges from MRS can be significant under relatively unique conditions (very high rainfall and carbonate-rich mine rock and cover). However, alkaline amendments with the potential to achieve similar improvements in the quality of seepage at mine sites in essentially any geological or climatic setting are only now being tested (Taylor et al., 2009).

Evidence from the Papua Province of Indonesia (Miller et al., 2003), Tasmania in Australia (Ray and Kent, 2004; Hughes et al., 2009; Hutchison et al., 2009; Li et al., 2011; Li et al., 2012) and Brukunga in South Australia (Taylor et al., 2009; Stimpfl et al., 2009; Taylor et al., 2006) supports the approach that alkalinity producing cover systems have the potential to progressively, sustainably and passively minimise acidity discharges from an MRS over time.

Section 7.6 provides some examples where the benefits of sulfide passivation have been quantified at test pile scale.

5. ACIDITY GENERATION MODELS FOR MINE ROCK STOCKPILES

The physical and chemical processes that control ARD / AMD generation in an MRS are complexly coupled and site-specific. Many of these processes were described qualitatively in the previous sections. While it is important to have a strong conceptual understanding of these processes, their influence and benefits can be challenging to visualize, especially when coupling many of these processes together at a site-specific level. Numerical modelling of these processes provides a tool to communicate their influences on ARD / AMD generation, both visually and semi-quantitatively.

Much of the challenge in communication the benefits for applying improved MRS construction methods lies in quantifying the benefits to develop a proper business case. While it is unlikely that a truly quantitative and reliable method will ever be developed, increasingly powerful numerical models make it possible to compare the relative outcomes of different MRS construction methods on a site-specific basis.

This component of the study communicates acidity generation risks of conventional and improved MRSs using numerical modelling software.

The acidity generation model was constructed and simulated using the GeoStudio 2019 suite of numerical modelling software. The modelling methodology and details are provided in Appendix A. Four generalized scenarios were developed as settings for the acidity generation models based on different climates, topographies, placement techniques and material properties. Table 5-1 shows the options available and the four scenarios are summarized in Table 5-2.

The modelled acidity generation values are not expected to be the true values that would result from a particular MRS configuration. Rather, the relative differences between an MRS at the same site but placed with different construction methods can easily be compared to demonstrate the direction and relative magnitude one might expect from implementing one scenario over another.

Table 5-1: Site-specific properties and variables considered for the MRS models.

Property		Range / Classification		
1.	Climate (Temperature, Precipitation)	Arid	Temperate	Tropical
2.	Mine Setting and Rock Placement	Ridgeline Mine (hill-top); Valley Fill MRS	Contour Mine (hill-side) Valley Fill MRS	Open Pit Mine; Flat Terrain MRS
3.	Texture of Mine Rock	Finer	Moderate	Coarser
4.	Reactivity of Mine Rock	Higher		Lower
5.	Rock Placement General Approach	Top Down		Bottom Up
6.	Vertical Gas Management on Lift Plateau	Yes		No
7.	Lateral Gas Management on Lift Face	Yes		No
8.	Lift Height	Smaller (e.g. < 10 m)	Medium (e.g. 10 - 30 m)	Higher (e.g. > 30 m)

Table 5-2: Summary of site-specific parameters chosen for each modelling scenario. Highlighted cells differentiate variables that were changed between scenarios.

Property		Model 1		Model 2	
		A. Conventional	B. Improved	A. Conventional	B. Improved
1.	Climate (Temperature, Precipitation)	Arid	Arid	Temperate	Temperate
2.	Mine Setting and Rock Placement	Open Pit Mine; Flat Terrain MRS	Open Pit Mine; Flat Terrain MRS	Ridgeline Mine; Valley Fill MRS	Ridgeline Mine; Valley Fill MRS
3.	Texture of Mine Rock	Moderate[1]	Moderate	Moderate	Moderate
4.	Reactivity of Mine Rock	Higher[2]	Higher	Higher	Higher
5.	Rock Placement General Approach	Top Down	Bottom Up	Top Down	Bottom Up
6.	Vertical Gas Management on Lift Plateau	No	Yes	No	Yes
7.	Lateral Gas Management on Lift Face	No	No	No	No
8.	Lift Height	Higher (e.g. > 30 m)	Smaller (e.g. < 10 m)	Higher (e.g. > 30 m)	Smaller (e.g. < 10 m)

[1] Moderate texture defined for the model as 65% cobble/gravel, 25% sand, and 10% clay/silt.
[2] Higher reactivity was parameterized to a first order oxygen consumption reaction rate equivalent to an intrinsic oxidation rate of 1×10^{-8} kg O_2 / t / s.

5.1 Acidity Generation Model – Scenario 1A

Scenario 1A was based on a cross-section of an end-dumped MRS located in an -arid climate. The initial cross-section (Figure 5-1) was relatively complex. To facilitate an easier comparison, the cross section for Scenario 1A was simplified but used the same total mine rock volume (Figure 5-2), which shows MRS construction over ten years. The climate modelled was hot (20 to 35°C) and arid, represented as a Bsh in the Koppen-Geiger classification system.

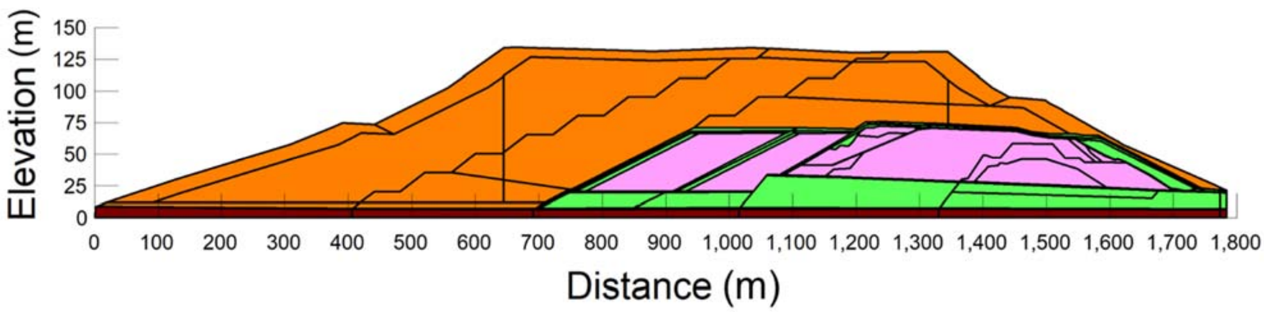

Figure 5-1: Cross-section of the existing MRS that was used the basis for Scenario 1A. Different coloured sections represent different material types (arbitrary for the purposes of this report).

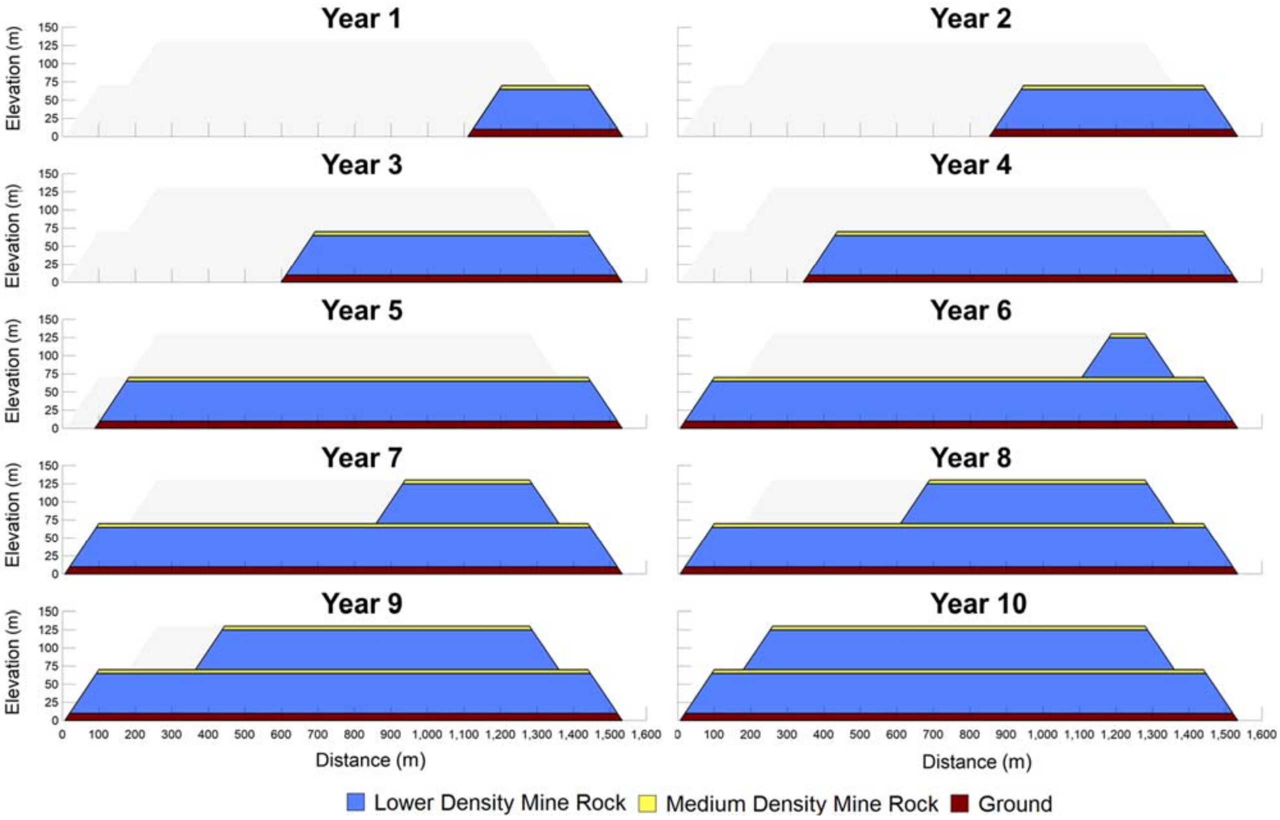

Figure 5-2: Cross-section and construction sequencing of Scenario 1A (the Y-axis is exaggerated 2x for clarity).

Two sets of 60 m lifts at angle of repose were constructed. Material segregation by end-dumping was simulated by assuming a lower bulk density (1700 kg/t) of the mine rock in the majority of the lift (55 m) and moderate bulk density (1900 kg/t) of the mine rock in the top 5 m. A lower bulk density increases the void volume and allows for greater air permeability, as would be expected in an end-dumped MRS.

As the material was placed, pore gas O_2 was gradually consumed by the reactive material (Figure 5-3). Infiltration from precipitation started to wet up the material, although because of the arid climate, wetting up was slow and moisture content of the MRS played a smaller role on influencing air permeability.

Due to the higher reactivity of the material, suboxic zones (defined as < 1% O_2 or approximately < 20 g O_2/m^3) developed as early as Year 2 at approximately 100 m into the MRS. Diffusion through the top and sides of the lift and advection of air driven by temperature differentials continually supplied O_2 to the outer shell of the MRS. Development of suboxia in deeper parts of the MRS was largely due to the consumption of O_2 in these zones, then limited re-supply because of O_2 consumption in the outer layers of the lift before O_2 could reach the horizontal centre (approximately 750 m into the lift).

Prior to construction of the second lift on top of the first lift, O_2 diffusion penetrated the MRS on all sides exposed to the atmosphere. In Year 6, when construction of the second lift began, O_2 diffusion through the top of the first lift was stopped once the area was covered up.

At Year 10 and beyond a suboxic region covering 55% of the MRS was established and remained mostly constant. Oxygen was able to penetrate vertically approximately 20 m and laterally approximately 50 to 100 m until it was consumed. The effect of oxidation in the outer shell was evident through the gradually increasing internal temperature due to exothermic reactions. The elevated temperature in the outer shell, which was still gradually increasing beyond Year 25, indicated that the internal suboxic region was a result of O_2 being consumed in the outer shell before it could reach the MRS interior. Although not included in the scope of this study, Project Team experience is that extending the model beyond Year 25 would clearly illustrate that the temperature continually increases, thereby allowing greater advective flows and decreasing the extent of suboxia (ie. heating could increase O_2 concentrations over time).

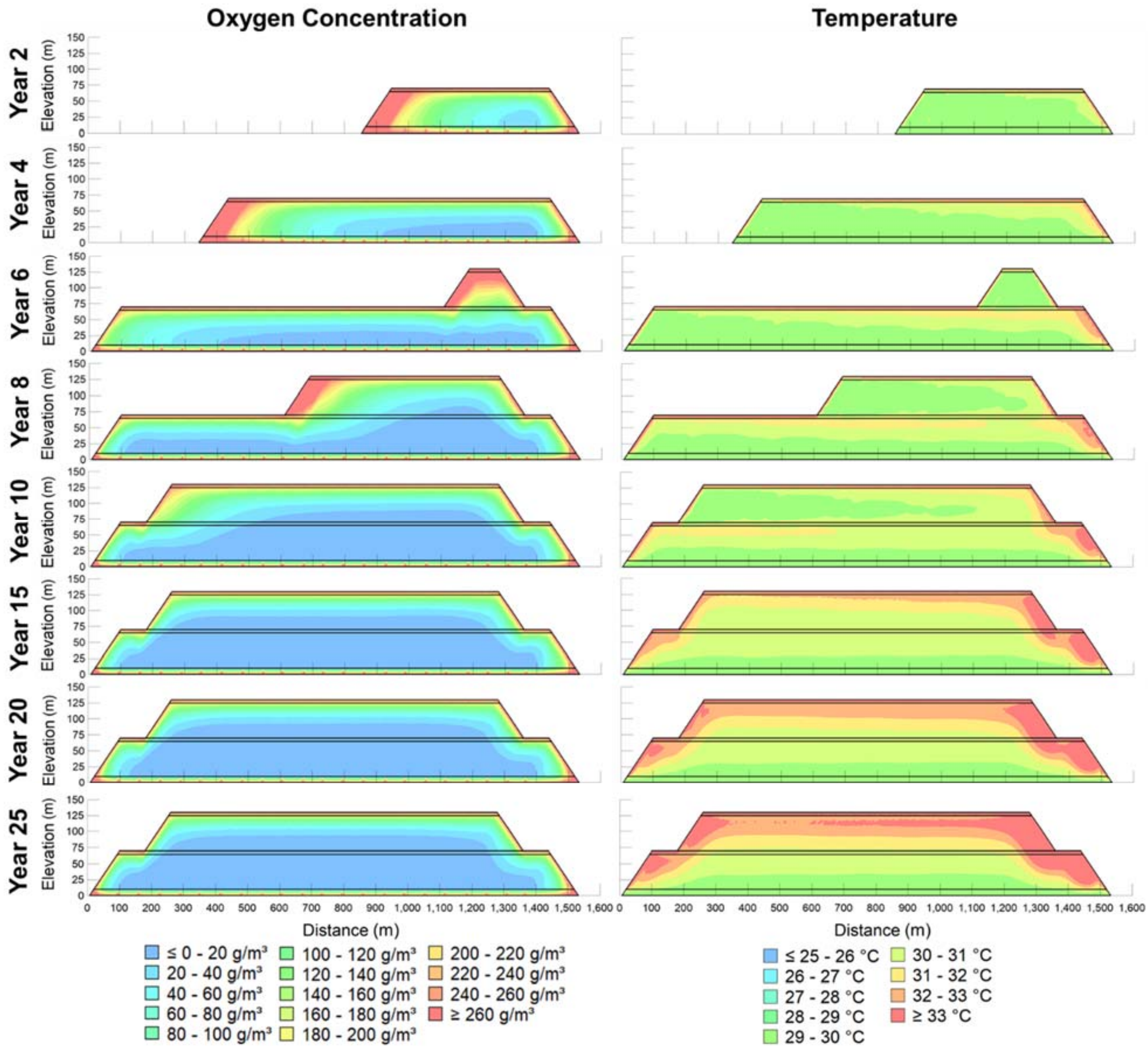

Figure 5-3: Progression of O_2 concentration and temperature profiles in Scenario 1A over 25 years.

Temperature-driven air fluxes are evident at all stages of the 25-year model duration. As the MRS is constructed, the direction of the temperature gradient switches with seasonal changes in temperature, thereby changing the direction of air flux (not shown here). After the MRS is constructed and heat begins to accumulate due to oxidation reactions, air fluxes became more complex as they are influenced by seasonality and exothermic reactions (Figure 5-4). Nonetheless, internal MRS air-flow capacity is substantial in Scenario 1A, and allows for continual re-supply of O_2 to the MRS.

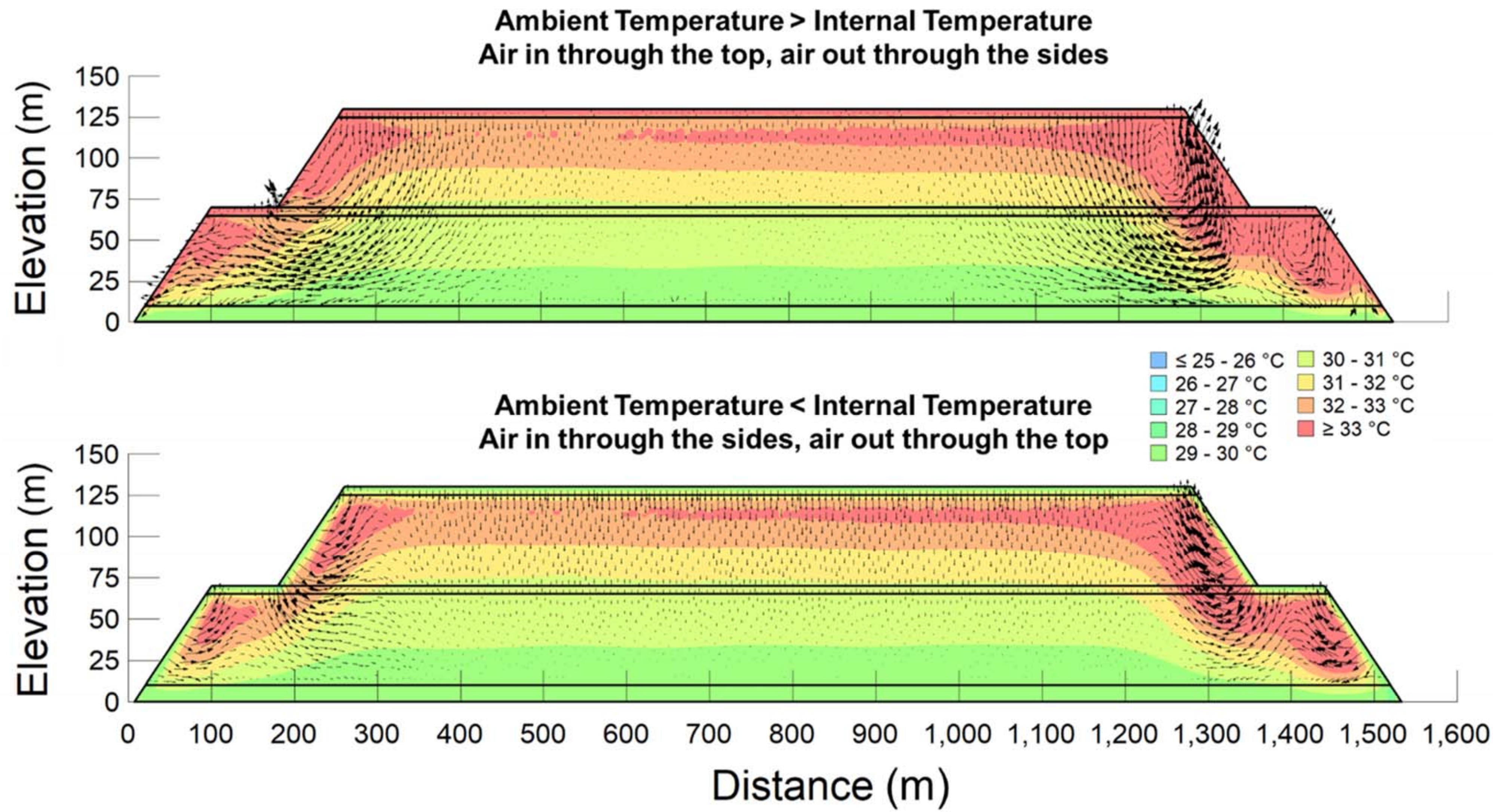

Figure 5-4: Air flux vectors in Scenario 1A at Year 25 when ambient temperature is greater or less than the internal temperature.

5.2 Acidity Generation Model – Scenario 1B

Scenario 1B used the same footprint as Scenario 1A but was constructed with 10 m lifts containing 1 m thick engineered layers to control vertical gas transport (Figure 5-5). Because the lifts were shorter than the end-dumping scenario (1A), less segregation should occur. Therefore, material properties for the lifts were based on a moderate-textured material with moderate bulk density (1900 kg/t). The 1 m engineered layer at the top of each lift was assumed to be compacted to a higher bulk density (2100 kg/t) after the lift was completed.

Like Scenario 1A, the initial pore gas O_2 was consumed over multiple years to establish a zone of suboxia (Figure 5-5). However, this zone of suboxia covered a more extensive region of the MRS during the construction and post-construction phases as compared to Scenario 1A. At Year 25, the suboxic zone covered approximately 80% of the MRS (compared to 55% in Scenario 1A) and was still slowly expanding at that point in time.

Unlike Scenario 1A, the internal temperature of Scenario 1B remained mostly constant for the 25-year period (Figure 5-5). Only the outer 20 m were affected by the seasonal variations in temperature. A small zone of active oxidation was present in the top right corner of the MRS after 25 year (indicated by higher temperature) but was much smaller than the active oxidation zones present in Scenario 1A. The relatively stable internal temperature is indicative of decreased oxidation rates as a result of greatly reduced air-flow capacity into the MRS.

The decreased air flow capacity in Scenario 1B is illustrated by the air flux vectors in the model (Figure 5-6). The shorter lifts and engineered vertical gas management layers effectively limit gas transport into the MRS, resulting in diffusion being the dominant mechanism for O_2 supply to the MRS. Temperature changes still resulted in advective transport in the top lift of the MRS, but these fluxes were small relative to Scenario 1A (Figure 5-4).

Given that equal volumes of mine rock and a similar footprint was used to construct the models in Scenario 1A and 1B, comparison of the acidity generated (calculated from the amount of oxygen consumed; see Appendix A) due to oxidation reactions can illustrate the relative benefits provided by the improved construction methods (Figure 5-7). Acidity generation over 25 years was decreased by approximately 75% by incorporating shorter lifts, vertical gas management, and base-up construction. Furthermore, the rate of acidity generation after Year 10 decreased by nearly 85% from Scenario 1A to Scenario 1B. This reduction is attributed to the improved control gas transport into the MRS and demonstrates, from first principles, the viability of these improved methods.

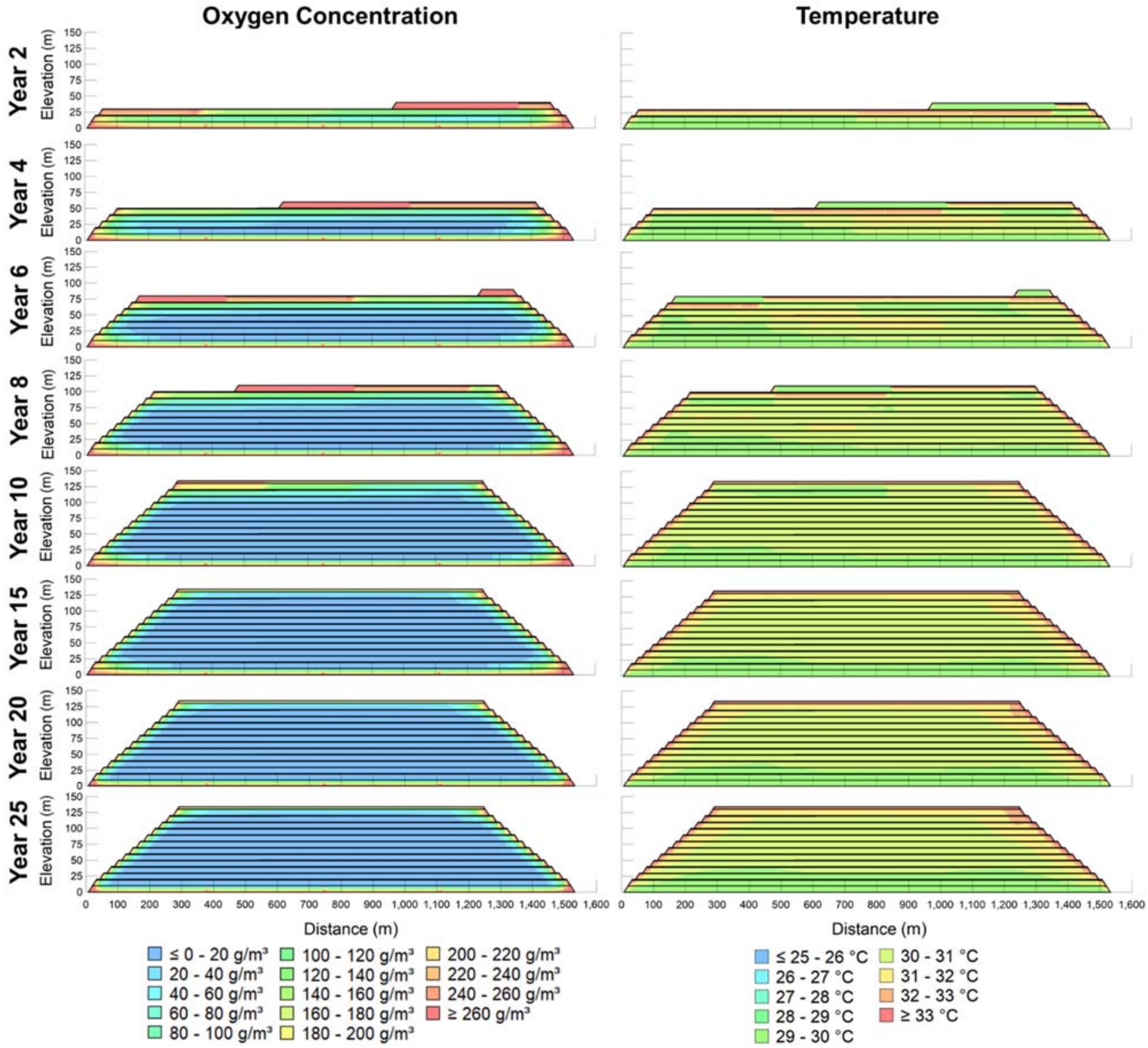

Figure 5-5: Progression of O_2 concentration and temperature profiles in Scenario 1B over 25 years.

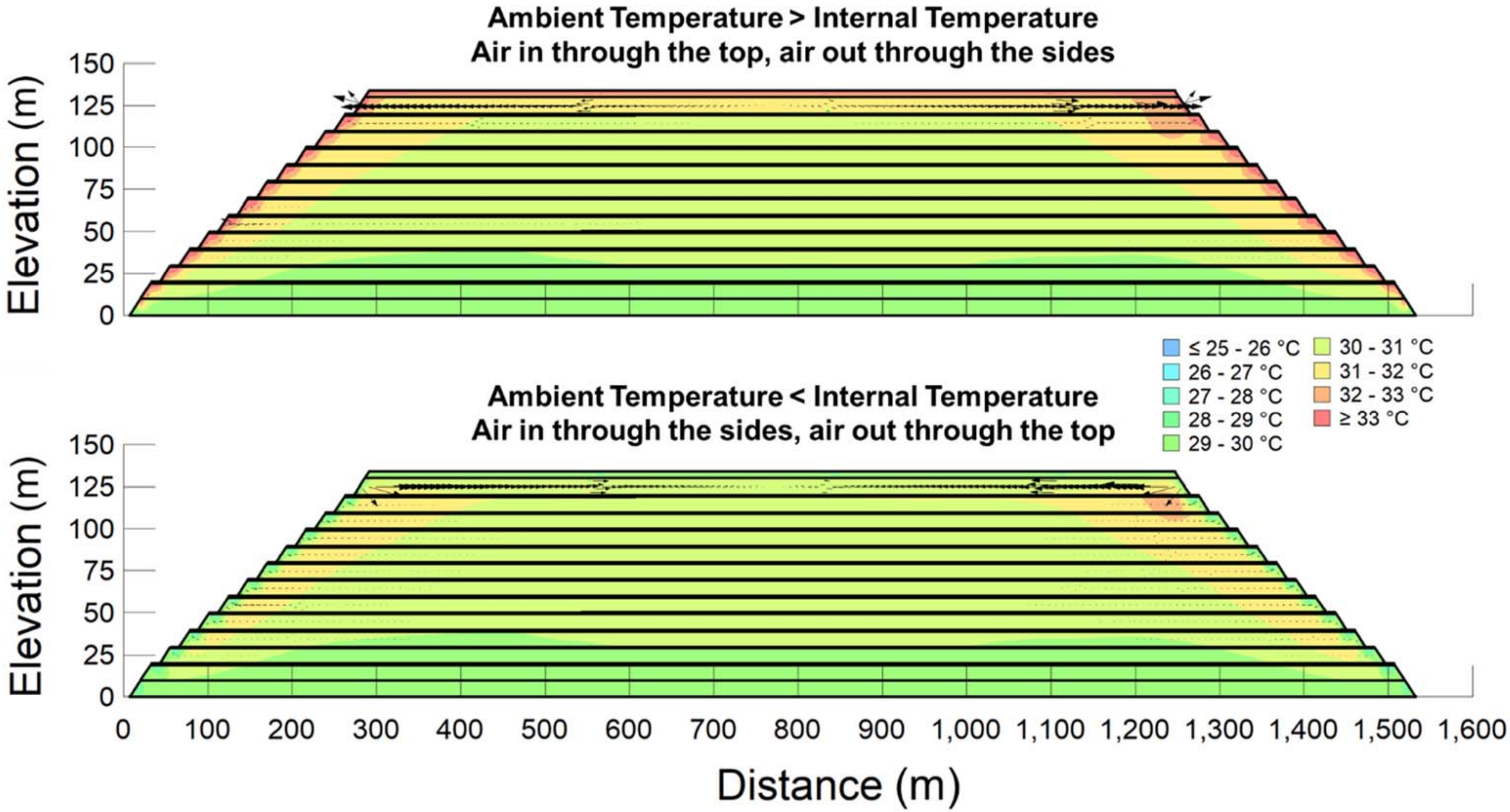

Figure 5-6: Air flux vectors in Scenario 1B at Year 25 when ambient temperature is greater or less than the internal temperature.

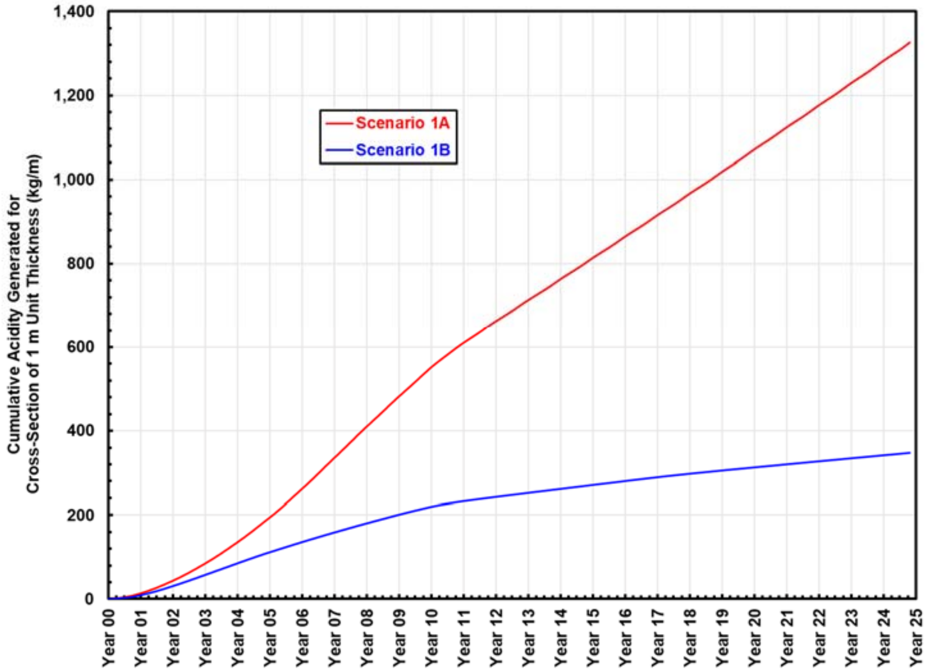

Figure 5-7: Comparison of cumulative acidity generation (normalized to a 1 m thick slice of the respective cross-section) for the different construction methods in Scenario 1.

5.3 Acidity Generation Model – Scenario 2A

The cross-section for Scenario 2A is that of an end-dumped, ridgeline-mined, valley fill, angle of repose MRS (Figure 5-8). The climate data used was a temperate climate based on a site with a Dfc Koppen-Geiger classification, with temperatures varying seasonally from -5 to 25°C and infiltration occurring due to spring freshet and rainfall in the summer. The material properties from Scenario 1A were used for Scenario 2A, with the bulk of the MRS composed of lower density material and the upper 5 m composed of moderate density material. The first lift was constructed over 2 years, after which it was wrapped by another end-dumped lift that was constructed over the remainder of the construction period. The MRS reached a total height of approximately 300 m, with a lateral extent of approximately 1250 m.

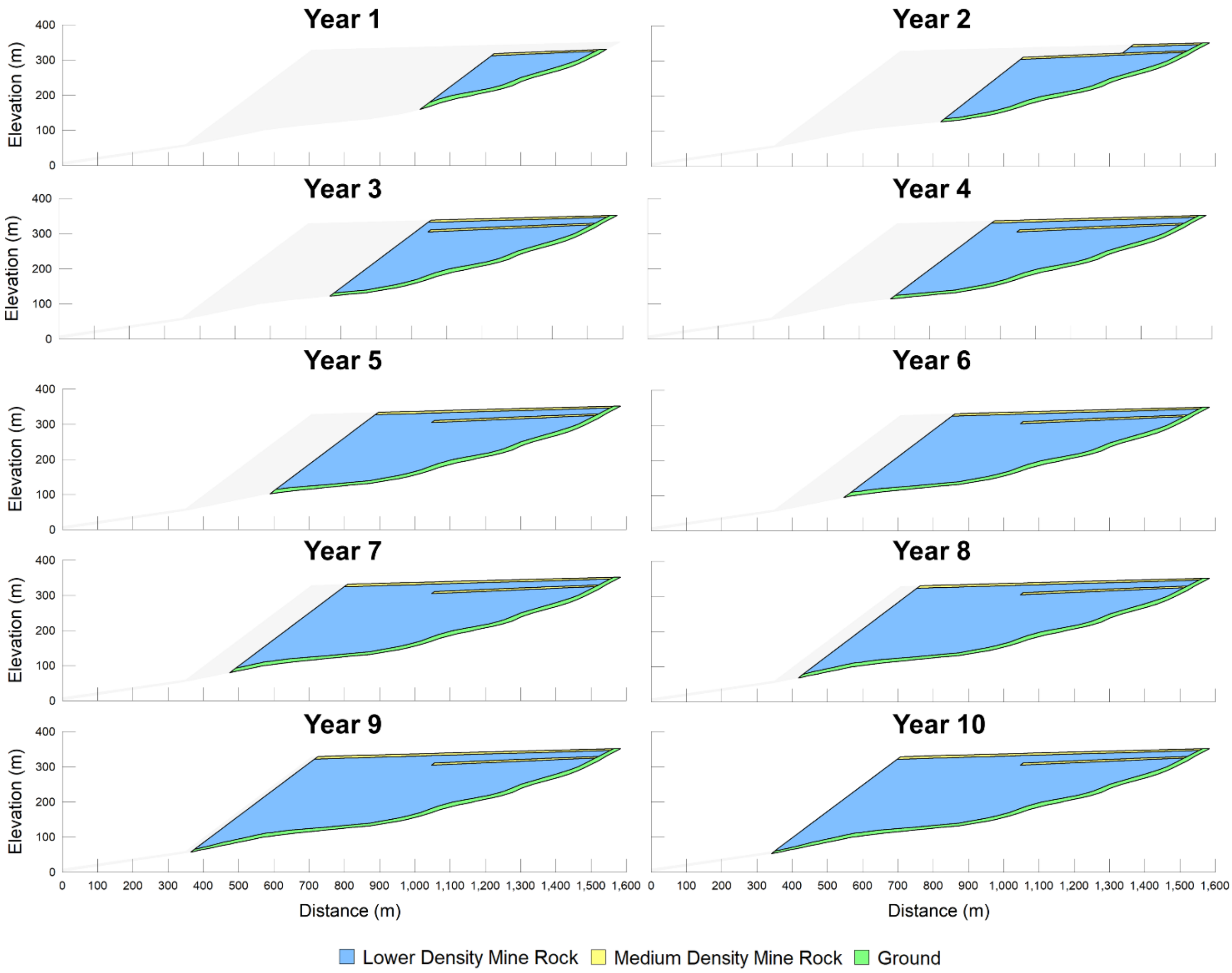

Figure 5-8: Cross-section and construction sequencing of Scenario 2A.

As in Scenario 1, the initial pore gas O_2 at greater depths was gradually consumed within the MRS as sections were covered (Figure 5-9). The suboxic region continued to expand after Year 10 and reached an equilibrium between Year 15 and Year 20. At this point, the suboxic region covered approximately 30% of the MRS.

Accumulation of heat due to ongoing oxidation reactions became evident at Year 15 near the top region of the MRS. The region of elevated temperature continued to expand for the duration of the model runtime and had not reached a steady state after Year 25, indicating the temperature would continue to rise, and continued increase in gas transport is likely to occur over time.

The air fluxes in Scenario 2A illustrate the high potential for strong gas advection and O_2 penetration into the MRS (Figure 5-10). Air was able to penetrate at least 300 m into the front of the MRS. Temperature differentials greatly influenced air direction and magnitude. In the summer, the internal air dropped and exited through the toe while pulling in air through the top of the MRS. In the winter, the internal air rose through the top and pulled in air through the sides. This trend demonstrates a clear ability for air to be continuously cycled in Scenario 2A. This also supports the observation of continued oxidation causing increased temperatures in the outer shell of the MRS. This model also lacks a distinct rubble zone at the base of the MRS which is typical of this construction method. A rubble zone is expected to enhance air flow capacity through the MRS and suggests this model could be conservative with respect to potential oxidation reactions.

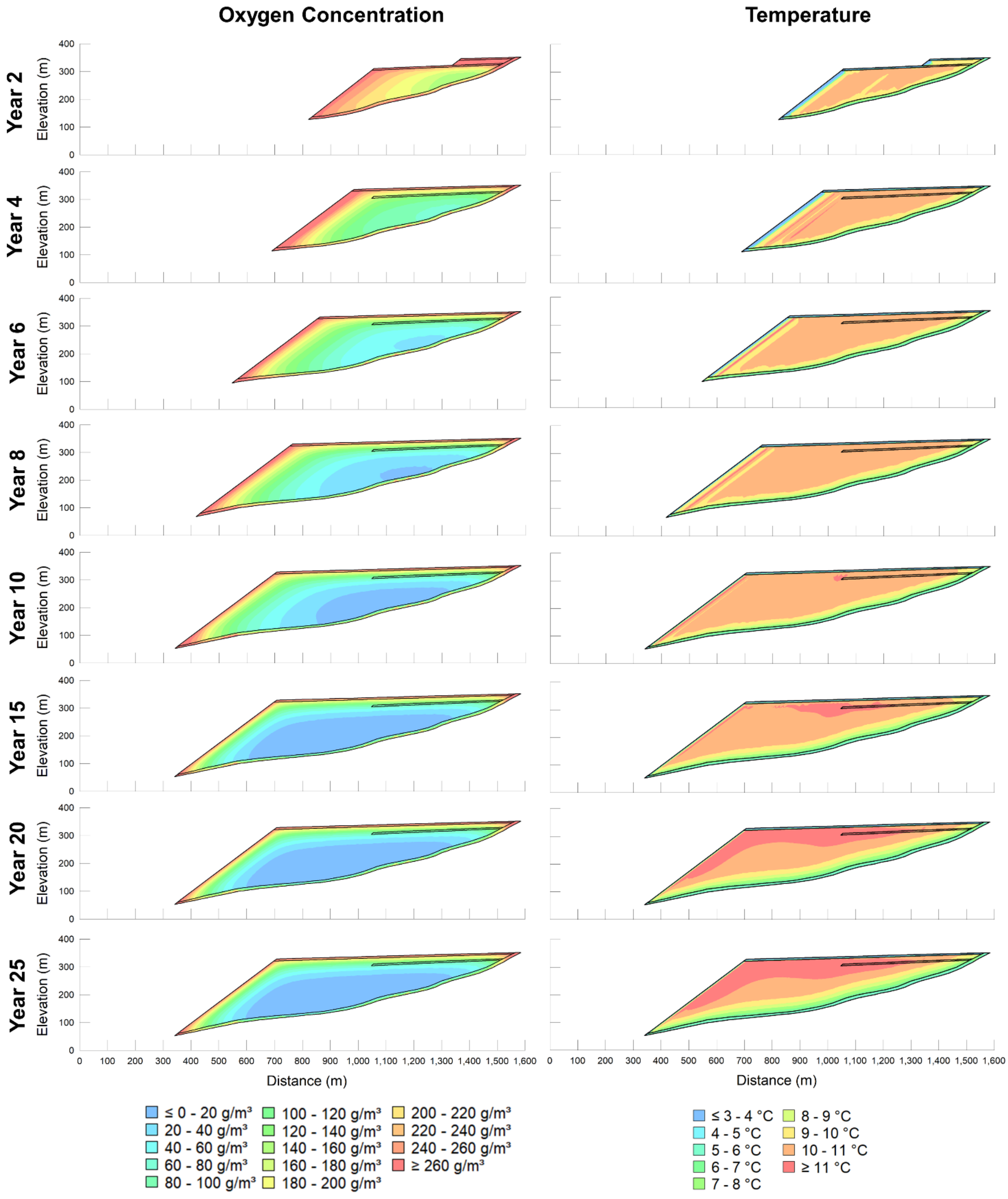

Figure 5-9: Progression of O_2 concentration and temperature profiles in Scenario 2A over 25 years.

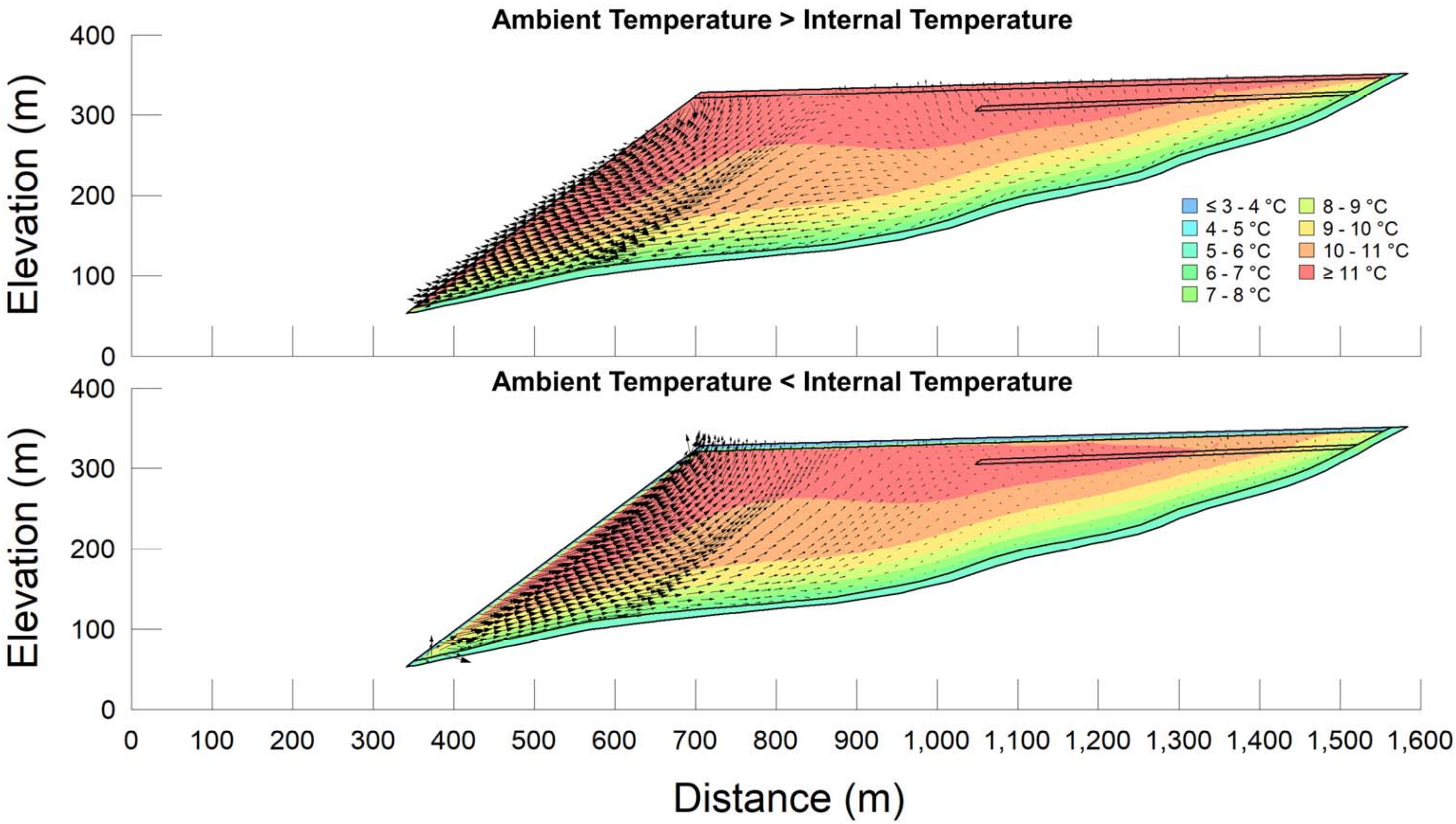

Figure 5-10: Air flux vectors in Scenario 2A at Year 25 when ambient temperature is greater or less than the internal temperature.

5.4 Acidity Generation Model – Scenario 2B

Scenario 2B used a similar footprint as Scenario 2A but was constructed from the bottom of the valley up with 10 m lifts containing 1 m thick engineered layers to control vertical gas transport (Figure 5-11). The material properties from Scenario 1B were applied for the shorter lifts and engineered layers to remain consistent. As before, the construction sequencing involved placement of equal volumes of rock in both Scenario 2A and 2B.

Like Scenario 2A, the initial pore gas O_2 was consumed over multiple years and established a suboxic zone (Figure 5-12). At Year 25, over 60% of the MRS was suboxic, compared to 30% in Scenario 2A. The internal temperature was controlled mostly by the ambient temperature at which it was placed. The vertical gas management layers limited advective gas transport, and therefore limited heat transfer. As such, temporary zones of higher temperatures exist due to residual heat from when the material was placed. This is illustrated by the shrinking hot spots with time (Figure 5-12). Only the outer 10 m were affected by the seasonal variations in temperature. A small zone of active oxidation (indicated by the circular region of higher temperature) was present in the top left of the MRS after 25 years but was much smaller than the active oxidation zones present in Scenario 2A. The relatively stable internal temperature is indicative of decreased oxidation as a result of greatly reduced air-flow capacity into the MRS.

The decreased potential for gas transport in Scenario 2B is illustrated by the air flux vectors in the model (Figure 5-13). Like Scenario 1B, gas transport into the MRS is limited by the shorter lift heights and vertical gas management layers, resulting in diffusion being the dominant mechanism for O_2 supply to the MRS. Temperature changes still resulted in advective transport in the top lift of the MRS, but these fluxes were small relative to Scenario 2A (Figure 5-10).

As with Scenario 1, comparing acidity generation between Scenario 2A and 2B illustrates the relative benefits provided by the improved construction methods (Figure 5-14). Acidity generation over 25 years decreased by approximately 75% (the same value as Scenario 1, only by coincidence) by incorporating shorter lifts, vertical gas management, and base-up construction, while rates of acidity generation decreased by 80% from Scenario 2A and Scenario 2B.

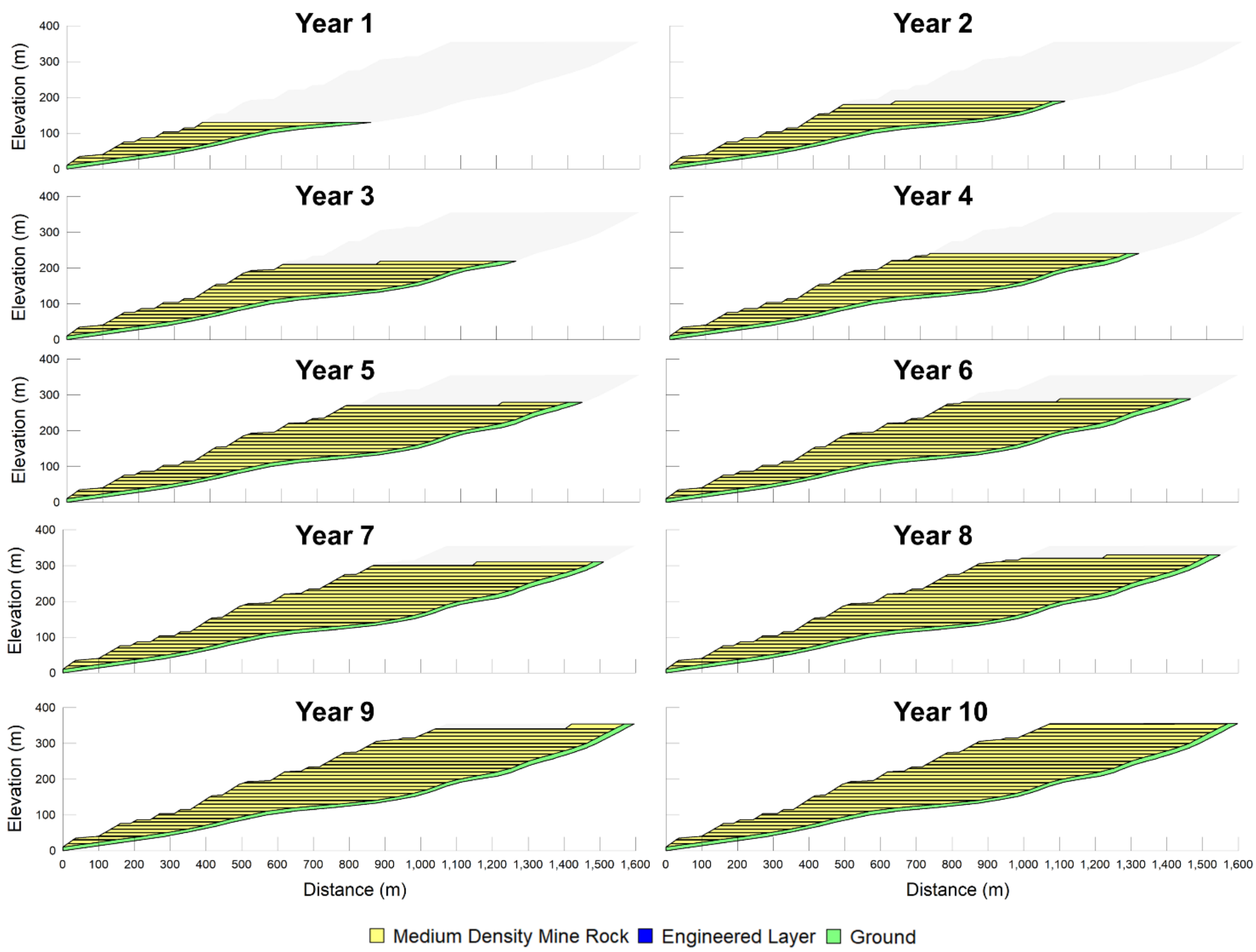

Figure 5-11: Cross-section and construction sequencing of Scenario 2B.

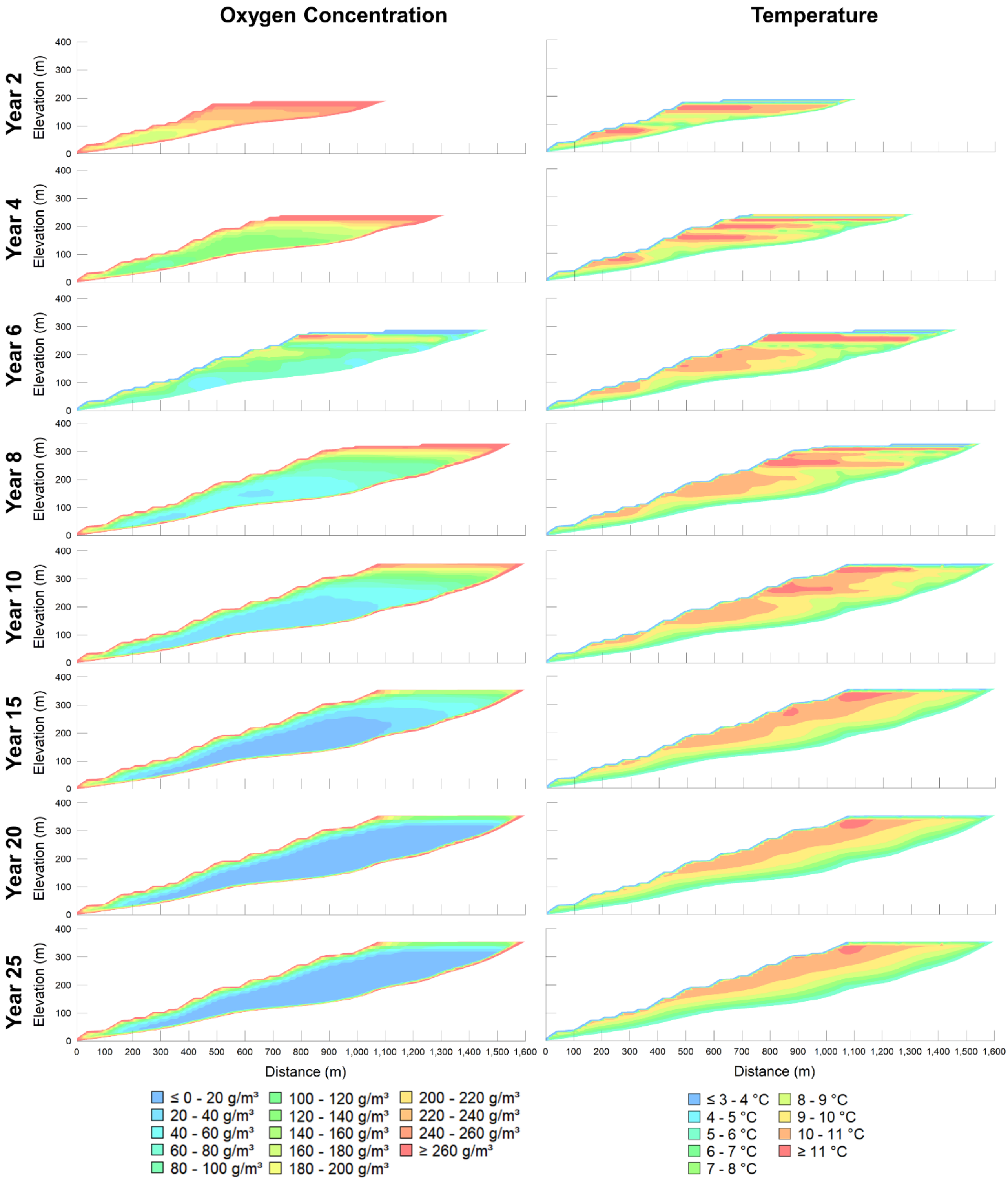

Figure 5-12: Progression of O_2 concentration and temperature profiles in Scenario 2B over 25 years. Material borders are omitted for clarity.

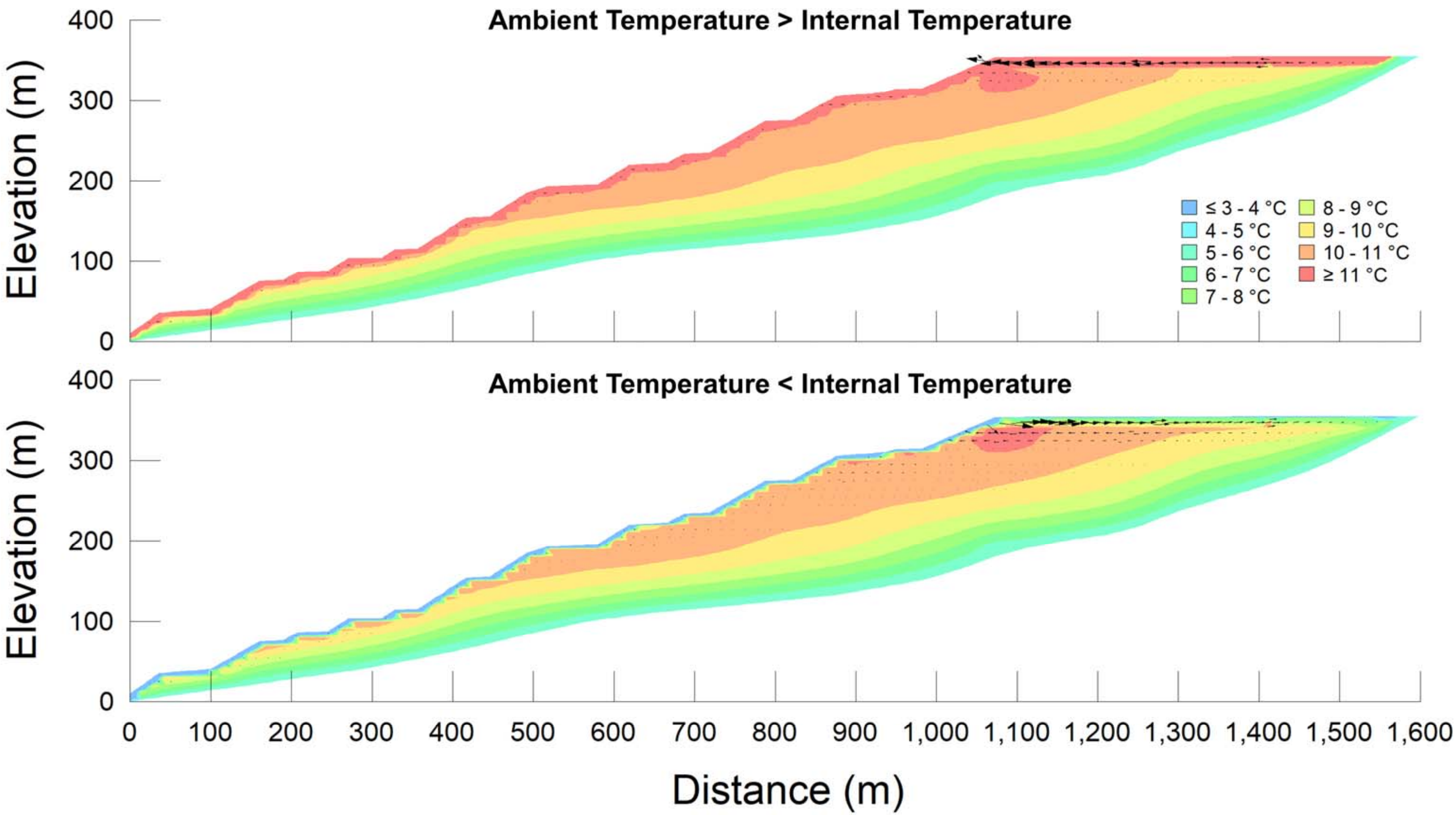

Figure 5-13: Air flux vectors in Scenario 2B at Year 25 when ambient temperature is greater or less than the internal temperature. Material borders omitted for clarity.

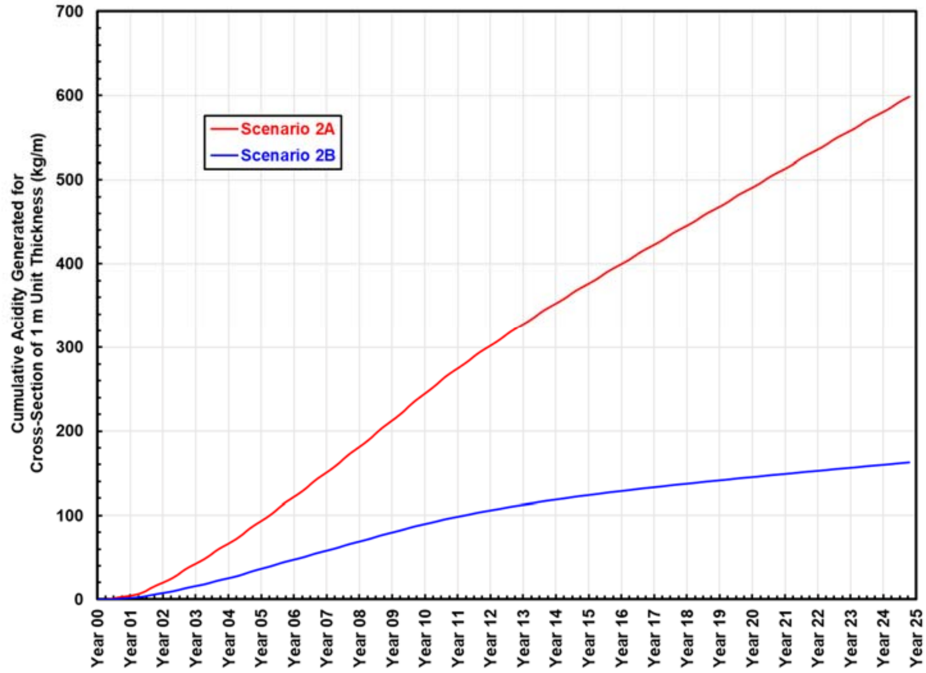

Figure 5-14: Comparison of cumulative acidity generation (normalized to a 1 m thick slice of the respective cross-section) for the different construction methods in Scenario 2.

5.5 Summary of Acidity Generation Models

The acidity generation models from Scenario 1 and 2 demonstrate the physical mechanisms that govern air movement through MRSs constructed with different methods. The results from these models illustrate that acidity loads generated by an MRS can be effectively lowered by building the MRS differently.

The chosen scenarios considered end-dumped MRSs in different climates and topographical settings, which were then built using improved construction methods. MRSs constructed through end-dumping had higher air-flow capacity and enabled a continual supply of O_2 through advective gas transport. Shorter lifts, vertical gas management layers, and base-up construction decreased the air-flow capacity of the MRS, which limited O_2 re-supply primarily as a result of diffusion. These construction changes resulted in approximately 75% decreases in acidity generation in both of the modelled scenarios, and 80 to 85% decreases in acidity generation rates in the post-closure phase.

An important consideration for these results is the dependence of site-specific parameters on the economic feasibility of the improved construction methods. In the case of Scenario 1, which was situated in an open-pit mine setting, the OPEX may not be drastically greater for short lifts constructed from the base-up compared to larger end-dumped lifts, simply because construction of the MRS will start from the bottom in both scenarios and the centroid for haul distance likely has not changed to a great extent.

In the case of Scenario 2, which was situated near a ridgeline mine (at the top of a mountain), base-up construction would require haul trucks to transport mine rock from the top of the mountain down to the base of the stockpile. These transportation costs would significantly change the OPEX of Scenario 2 assuming traditional hauling methods. This, however, opens up the opportunity for other hauling methods (eg. conveyors) that could mitigate increasing operating costs. Other site-specific parameters (eg. climate, mine rock texture, and reactivity) will influence the benefits realized from the various improved construction methods and the economics of implementing them into an MRS. The myriad of scenarios that could occur for a given mine site illustrates the utility of being able to numerically model the directional changes of a given construction method compared to conventional methods to better inform engineering decisions.

6. ASSESSMENT OF BENEFITS AND LIMITATIONS OF IMPROVED METHODS

6.1 Overview

An assessment of the likely geochemical benefits and limitations of each improved MRS construction method under varying physicochemical conditions is provided in Table 6-1.

In addition to the specific water quality benefits of the improved MRS construction methods, broader benefits can be realized by reducing acidity (acid plus metal) loads, including significant human health and safety benefits such as:

- Reduced severity and risk of interactions (eg. ingestion and contact with skin) with acidic waters and waters containing elevated metals;
- Reduced risk of generating elevated concentrations of toxic gases (eg. CO_2 and H_2S) from the MRS due to neutralisation of acidity by carbonate minerals generating CO_2 or passive treatment systems generating H_2S.
- Reduced risk of the generation of low O_2 conditions due to sulfide mineral oxidation consuming O_2;
- Reduced chronic health effects of poor water quality in downstream communities using water impacted by ARD / AMD; and
- Reduced risk of immediate and long-term effects of corrosion of site infrastructure (eg. culverts, bridge abutments, etc.)

The HSE benefits to be potentially gained from building improved MRS may not always represent a financial gain but will demonstrate progressive actions towards safety culture of a mine site, which is important to both mine workers and regulators. These benefits can also be valuable during environmental assessment and permitting to demonstrate the actions being taken to manage HSE for a proposed mining project.

The social license to operate is becoming increasingly critical to viability of a project in the mining industry and the reputation of a company. This license is generally intangible, evolves over time, and most specifically applies to local communities near mining operations. Now, more than ever, a key component to 'obtaining' and 'maintaining' a social license to operate is implementing environmentally sustainable mining practices that encompass the entire mining cycle. Companies with a good environmental track record are likely to be perceived with a positive reputation and will likely see less social resistance, and perhaps even approval, for a new project. There is large potential value to a company's social license to operate by demonstrating that ARD / AMD from a mine can be reduced by building an improved MRS.

6.2 Improved MRS Construction Methods at Brownfield Sites

The six improved MRS construction methods discussed in this report are introduced as proactive approaches to be implemented at greenfield sites. While some of the improved approaches inherently demand proactive rock placement, some methods can also be applied retrospectively at operating mines. The potential application of each of the improved construction techniques to a brownfield site is discussed briefly below. It is assumed that the brownfield site is operating and has an MRS with the following typical characteristics:

- End dumped;
- Contains NAF and PAF materials but without selective placement;

- Tip head heights of > 15 m;
- Coarse basal rubble zone;
- No engineered gas management layers;
- No cover system installed yet;
- Poor quality seepage from toe and recharge to groundwater beneath MRS.

Decrease tip head heights

Tip head heights can be altered at any stage of a mine life, but while such changes may partly improve water quality outcomes for the newly disposed mine rock, they are unlikely to significantly improve the geochemical behaviour of an existing stockpile. This conclusion partly depends on where the new tip heads are located relative to the existing angle of repose, end-dumped slope.

Decrease tip head heights and install engineered gas management layers

If the tip head heights are lowered or not, the application of engineered gas management layers (eg. 1 to 3 m thick) can be expected to provide some additional control on oxygen resupply to existing, end-dumped sulfidic wastes. The application (and compaction) of horizontal gas management layers across the top of existing MRSs can be expected to retard vertical gas movement into or from the mine rock. Further benefits can be expected from angle-of-repose gas management layers for retarding lateral gas flow. The relative benefits of such gas management layers will be site (and materials) specific but they are not expected to provide a complete solution.

Encapsulated PAF cells

In most situations, it is not possible to fully encapsulate the PAF material in an existing end-dumped MRS, particularly if the PAF materials were not selectively placed within identifiable and/or accessible cells. Hence this method is not specifically applicable to brownfield sites. Possible exceptions to this may be if there was a known source of suitable encapsulation material and/or if a large material re-handling operation was conducted. In general, if the encapsulated cell is well documented, one can look to minimise net percolation at the surface that will eventually result in seepage through the cell by placement of a lower net percolation cover system. The benefits, and when these benefits can be realised when using such an approach are strongly influenced by the wetting up / draining down evolution of the MRS.

Paddock dumping and base-up, thin lift construction methods

While thin lift, base-up construction methods are normally proposed as an alternative to end dumping methods, they have been anecdotally used to enclose the outer surface of existing (problematic) end-dumped MRSs in order to retard gas migration and improve drainage / seepage quality. In this way, the thin-lift, base-up stockpile construction method is acting as an external encapsulation zone for the end dumped material, providing the benefit of controlling both lateral and vertical gas movement whilst achieving routine mine rock stockpiling. The potentially substantial width (eg. 10 to 50 m) of thin lift, base-up external encapsulation layers are expected to render them far more efficient for retarding gas movement than the thin gas management layers described above. This method could easily accommodate the selective disposal of both NAF and PAF materials within the enclosing thin-lift, base-up zone. Significant water quality improvements are likely with this combination construction method, relative to end-dumping alone.

Strategic placement of oxygen consuming materials

The targeted identification and use of oxygen consuming NAF materials could also be applicable at brownfield sites, particularly if they are used as part of the thin-lift, base-up external encapsulation zone described above.

Sulfide passivation

The sulfide passivation approach is probably the only improved method that can be applied with equal ease at either brownfield or greenfield sites. At brownfield sites, the effectiveness of sulfide passivation will be lowered with larger lift heights and higher batter surface areas. Total acidity load reductions of up to 50% may be possible under ideal conditions at brownfield sites, but greater acidity load reductions will likely depend on the application of other improved construction methods (described above).

Table 6-1: Assessment of the benefits and limitations of improved MRS construction methods relative to conventional end-dumping methods.

Parameter	Variable	No change	Oxygen Control					
			Geotechnically focused methods				Geochemically focused methods	
		End dump	Lower lift height	Lower lift height and install air disruption layers (horizontal / repose slope)	Encapsulated PAF cells	Paddock dumping and thin lift from base up	Placement of O_2 consuming NAF	Sulfide passivation
Topography	Ridgeline, valley fill	Pro: Cost-effective, haul distances minimized. Con: Large tip-head heights maximize particle segregation and therefore optimise gas management and acidity generation. HSE risks such as working around dump faces with significant vertical drops, higher dust generation, greater momentum of large rocks.	Pro: Decreasing tip head heights reduces propensity for particle segregation, which may result in some reduction in acidity generation. Mitigation of HSE risks such as working around dump faces with significant vertical drops, higher dust generation, greater momentum of large rocks. Con: Topography may not allow for staged lifts to be easily constructed. Increased haulage costs to construct multiple lifts. Decreasing tip head heights increases the number of (air entry) rubble zones at base of each lift, although rubble zones will be smaller. This method in this setting should generally not be implemented in isolation but rather in combination with other improved methods (on a site-specific basis) to increase effectiveness.	Pro: Decreasing tip head heights reduces propensity for particle segregation, which helps to lower gas movement. Mitigation of HSE risks such as working around dump faces with significant vertical drops, higher dust generation, greater momentum of large rocks. Con: Topography may not allow for staged lifts to be easily constructed. Increased haulage costs to construct multiple lifts. Decreases in tip head heights may be largely ineffective if ARD / AMD risk classification and selective placement is not practiced. This method in this setting should generally not be implemented in isolation, but rather in combination with other improved methods (on a site-specific basis) to increase effectiveness.	Pro: Encapsulation methods (top, sides and base) have the potential to slow gas movement into PAF wastes. Con: Encapsulation will not be possible if ARD / AMD risk classification and selective placement is not being conducted. Topography may not allow for individual cells to be easily constructed. High tip head heights will complicate encapsulation methods. Increased haulage costs to construct cells. Will need to be combined with other improved construction methods such as the strategic placement of O_2 consuming NAF material.	Pro: Very significant reduction in gas movement and hence acidity generation rates. Optimal water retention due to lack of internal structure thereby maximising carbonate dissolution and enhancing neutralisation via silicate dissolution. Assuming selective placement of NAF / PAF wastes, this method could be used in isolation. Mitigation of HSE risks such as working around dump faces with significant vertical drops, higher dust generation, greater momentum of large rocks. Con: Bottom-up placement requires increased haulage costs for ridgeline mining scenarios.	Pro: ARD / AMD risk classification and selective placement of waste materials will improve water quality outcomes by retarding the migration of O_2 into PAF wastes. More sophisticated placement of high sulfide and low sulfide NAF materials will further retard O_2 entry into PAF materials. Con: Selective placement may be more challenging in ridgeline settings. Higher waste placement costs may be associated with ridgeline mining scenarios. This strategy should generally not be implemented in isolation but rather in combination with other methods discussed here (on a site-specific basis).	Pro: Can be applied to an end-dumped MRS retroactively. Needs to be combined with other improved placement methods to mitigate elevated construction costs of these methods in a hilltop setting. Assists in situations where there has been no selective placement of PAF/NAF materials. Con: Steep slope of an end-dumped MRS increases the complexity of installation issues when trying to place alkaline materials only above PAF materials. This method should not be implemented in isolation, but rather in combination with other methods discussed here (on a site-specific basis).
	Contour, valley fill	Pro: Cost-effective, haul distances minimized. Con: Large tip-head heights maximize particle segregation and therefore optimise gas migration and acidity generation. HSE risks such as working around dump faces with significant vertical drops, higher dust generation, greater momentum of large rocks.	Pro: Decreasing tip head heights reduces propensity for particle segregation. Mitigation of HSE risks such as working around dump faces with significant vertical drops, higher dust generation, greater momentum of large rocks. Con: Topography may not allow for staged lifts to be easily constructed. Increased haulage costs to construct multiple lifts. Con: Increase in the number of (air entry) rubble zones at base of each lift. Decreases in tip head heights may be largely ineffective if ARD / AMD risk classification and selective placement is not practiced. This method will likely need to be combined with other improved methods to be effective.	Pro: As above. Con: As above.	Pro: As above. Con: As above.	Pro: As above. Con: Bottom-up placement requires increased haulage costs for contour mining scenarios.	Pro: As above. Con: Selective placement may be quite challenging in contour settings. Higher waste placement costs may be associated with contour mining scenarios.	Pro: Can be applied to an end-dumped MRS retroactively. Needs to be combined with other improved placement methods to mitigate elevated construction costs of these methods in a hilltop setting. Assists in situations where there has been no selective placement of PAF/NAF materials. Con: Steep slope of an end-dumped MRS increases the complexity of installation issues when trying to place alkaline materials only above PAF materials. This method should not be implemented in isolation, but rather in combination with other methods discussed here (on a site-specific basis).

Parameter	Variable	No change	Oxygen Control					
			Geotechnically focused methods				Geochemically focused methods	
		End dump	Lower lift height	Lower lift height and install air disruption layers (horizontal / repose slope)	Encapsulated PAF cells	Paddock dumping and thin lift from base up	Placement of O_2 consuming NAF	Sulfide passivation
	Flat terrain	Pro: Larger end-dumped lifts will decrease overall haul distances. Geotechnically straightforward. Con: Large tip-head heights maximize particle segregation, gas movement and acidity generation. Benefits of haul cost savings are lower relative to valley fill end-dumping. HSE risks such as working around dump faces with significant vertical drops, higher dust generation, greater momentum of large rocks.	Pro: Decreasing tip head heights reduces propensity for particle segregation. Topography allows for lift height to be more easily controlled. Mitigation of HSE risks such as working around dump faces with significant vertical drops, higher dust generation, greater momentum of large rocks. Con: Increased haul costs to construct multiple lifts. Increase in the number of (air entry) rubble zones at base of each lift. Decreases in tip head heights may be largely ineffective if ARD / AMD risk classification and selective placement is not practiced. This method will likely need to be combined with other improved methods to be effective.	Pro: Implementing smaller lift head heights will be less complicated for a mine in flat terrain. Con: Increased haulage costs to construct multiple lifts. Decreases in tip head heights may be largely ineffective if ARD / AMD risk classification and selective placement is not practiced. This method will likely need to be combined with other improved methods to be effective.	Pro: Encapsulation methods (top, sides and base) have the potential to slow gas movement into PAF wastes. Encapsulated cells are likely to be most cost-effective in flat terrains. Haulage costs unlikely to be significantly different relative to conventional disposal methods. Con: Encapsulation will not be possible if ARD / AMD risk classification and selective placement is not being conducted. Will need to be combined with other improved construction methods such as the strategic placement of O_2 consuming NAF material.	Pro: As above. Base-up construction is a more economically competitive construction method for mine sites in flat terrains.	Pro: ARD / AMD risk classification and selective placement of waste materials will improve water quality outcomes by retarding the migration of O_2 into PAF wastes. More sophisticated placement of high sulfide and low sulfide NAF materials will further retard O_2 entry into PAF materials. Flat terrains tend to simplify the implementation of simple or sophisticated selective waste placement programs.	Pro: Can be applied to an end-dumped MRS retroactively. Needs to be combined with other improved placement methods to mitigate elevated construction costs of these methods in a hilltop setting. Assists in situations where there has been no selective placement of PAF/NAF materials. Larger footprint of flat terrain MRS (generally) will simplify surface area coverage of alkaline materials. Con: This method should not be implemented in isolation, but rather in combination with other methods discussed here (on a site-specific basis).
Climate	Arid	Pro: Low rainfall may extend the period before AMD/ARD is released. Con: Lower rainfall may decrease degree of saturation and therefore increase gas movement and acidity generation.	Pro: Decreased particle segregation could benefit the inherently low degree of saturation present in arid climates by partially lowering acidity generation. Con: This method will likely need to be combined with other improved methods to be effective.	Pro: Decreasing the segregation of wastes and installing air disruption layers will at least partially mitigate the low degree of saturation conditions inherent in arid climates. Con: Decreases in tip head heights and air disruption layers may be largely ineffective if ARD / AMD risk classification and selective placement is not practiced. This method will likely need to be combined with other improved methods to be effective.	Pro: Encapsulating layer will help mitigate the potential for increased air permeability due to low degree of saturation if it is compacted. Con: May not be able to rely on moisture content to assist with controlling air flow. Waste scheduling will influence the effectiveness of encapsulation methods.	Pro: Compaction and layering will allow moisture to be retained longer in low-rainfall climates. This assists with retarding gas movement as well as optimising carbonate and silicate neutralisation.	Pro: ARD / AMD risk classification and selective placement of waste materials will improve water quality outcomes by retarding the migration of O_2 into PAF wastes. More sophisticated placement of high sulfide and low sulfide NAF materials will further retard O_2 entry into PAF materials.	Pro: While low infiltration rates in arid climates will slow the introduction of alkalinity to an MRS, the significant accumulation of secondary acid salts over an extended period prior to flushing may enhance passivation when alkalinity is finally introduced. Con: This method should not be implemented in isolation, but rather in combination with other methods discussed here (on a site-specific basis).
	Temperate	Con: Seasonal and diurnal temperature fluctuations may enhance barometric pumping and acidity generation.	Pro: Decreased particle segregation could partially mitigate temperature driven convection cycles caused by seasonal ambient temperature fluctuations. Con: This method will likely need to be combined with other improved methods to be effective.	Pro: Decreasing the segregation of wastes and installing air disruption layers in temperate climates should enhance the effect of seasonally high moisture conditions, thereby lowering acidity generation. Con: Decreases in tip head heights and air disruption layers may be largely ineffective if ARD / AMD risk classification and selective placement is not practiced. This method will likely need to be combined with other improved methods to be effective.	Pro: The effectiveness of encapsulation cells should be improved in temperate climates. Con: May not be able to rely on moisture content to assist with controlling air flow. Waste scheduling will influence the effectiveness of encapsulation methods.	Pro: Compaction and layering will allow moisture to be retained longer in low-rainfall climates. This assists with retarding gas movement as well as optimising carbonate and silicate neutralisation. Con: Greater runoff from MRS will need to be managed.	Pro: If placed correctly, MRS with internal convection cycles due to ambient temperature fluctuations will have O_2 consumed before it reaches PAF material. Con: Oxygen consuming NAF material will be consumed faster if air permeability is high.	Pro: Variable infiltration rates may be beneficial in delivering alkalinity faster and deeper into a MRS. Con: Potentially low infiltration rates in temperate climates may slow the passivation rate of sulfides. This method should not be implemented in isolation, but rather in combination with other methods discussed here (on a site-specific basis).

Parameter	Variable	No change	Oxygen Control					
			Geotechnically focused methods				Geochemically focused methods	
		End dump	Lower lift height	Lower lift height and install air disruption layers (horizontal / repose slope)	Encapsulated PAF cells	Paddock dumping and thin lift from base up	Placement of O_2 consuming NAF	Sulfide passivation
	Tropical	Pro: High rainfall may increase degree of saturation in wastes and therefore decrease gas migration and acidity generation. Smaller temperature differentials will tend to decrease barometric pumping, air movement and acidity generation. Con: High rainfall may increase the rate of acidity flushing.	Pro: Decreased particle segregation will decrease seepage rates through a stockpile in high-rainfall climates. Smaller temperature fluctuations will tend to decrease barometric pumping and gas movement. Con: Possible seepage from top of each additional lift. This method will likely need to be combined with other improved methods to be effective.	Pro: Decreasing the segregation of wastes and installing engineered gas disruption layers in tropical climates should maintain relatively high degrees of saturation in lifts, thereby substantially lowering acidity generation. Con: Possible seepage from top of horizontal air disruption layers could be expected, depending on slope on air disruption layers. This method will likely need to be combined with other improved methods to be effective. Potential geotechnical stability issues may arise with high water contents and finer-textured disruption layers.	Pro: Both PAF and encapsulating materials will maintain high degree of saturation in tropical climates, improving the performance of the encapsulation process. Con: Waste scheduling will influence the effectiveness of encapsulation methods.	Pro: Compaction and layering in climates with high infiltration potential will enhance benefits already obtained by a high degree of saturation. Con: Greater runoff from MRS will need to be managed.	Pro: Higher degree of saturation will limit O_2 transport to PAF materials and allow O_2 consuming materials to develop suboxic conditions. Oxygen consuming NAF materials will have a longer lifespan.	Pro: High infiltration rates of tropical climates are ideal for rapidly passivating sulfide surfaces. Con: Rate of loss of alkaline material may be high due to enhanced dissolution rates created by high infiltration rates.
Mine rock texture	Coarse	Con: Gas movement optimised and therefore acidity generation maximised. Segregation will be less important if dealing with uniformly coarse materials.	Con: The benefits of lower segregation may be lessened in coarser textured materials, as there is inherently more air volume in coarser textured materials. This may allow air movement to still occur to an extent. Difficult to predict interplay between decreased segregation and increase number of smaller segregated zones. This method will likely need to be combined with other improved methods to be effective.	Pro: Engineered gas management layers should partially mitigate the increased air flow capacity inherent to coarser textured material, leading to decreased acidity generation rates. Con: These layers may be more difficult to create if only coarse textured material is available. This method will likely need to be combined with other improved methods to be effective.	Pro: Encapsulating coarser-textured PAF could greatly reduce air availability to otherwise high air permeability material. Con: A finer textured encapsulation layer is usually required and may not be readily available if on-site materials are generally coarse. Compaction alone may not be enough if the cover material is coarse-textured. Encapsulation may need to be combined with other improved construction methods.	Pro: This method offers a valuable strategy for at least partially managing normally unavoidably high gas migration. Con: Compaction of coarser textured material may only be partially successful. Additional construction costs may outweigh benefits from limited compactability. This method will likely need to be combined with other improved methods for coarse textured mine waste.	Pro: This strategy can be implemented in conjunction with one or more other strategies to incrementally lower O_2 access to PAF materials. Con: Coarser-textured material may allow faster O_2 resupply, consuming O_2 consuming sulfides in NAF materials faster.	Pro: Coarser-textured material will favour higher seepage rates of alkalinity into the MRS. Lower surface area of more coarse-textured material means less alkalinity is required to passivate the same mass of sulfide. Con: Potential for preferential flow paths to form, causing regions of un-passivated sulfides to remain. However, these zones may not contribute to acidity release if they have been isolated from water migration pathways. This method should not be implemented in isolation, but rather in combination with other methods discussed here (on a site-specific basis).
	Medium	Con: Assuming well graded materials, segregation of end-dumped medium textured materials could be high, thereby optimising gas migration and acidity generation.	Pro: Assuming well graded materials, this method may mitigate particle segregation caused by larger lift heights, and therefore at least partially decrease acidity generation. Con: This method will likely need to be combined with other improved methods to be effective.	Pro: Engineered gas management layers should partially mitigate risk of increased air flow capacity if there is variability in the medium textured material, leading to decreased acidity generation rates. Con: Diminishing benefits expected if placed material is finer textured. This method will likely need to be combined with other improved methods to be effective.	Pro: Compaction of medium textured encapsulation layer to necessary specifications for air permeability requirement should be achievable.	Pro: Layering and compaction of such materials can be expected to provide significant gas movement control benefits. Minimising infiltration and enhancing water retention will improve carbonate and silicate neutralisation. Con: This method will likely need to be combined with other improved methods for medium textured mine waste.	As above.	As above.

Parameter	Variable	No change	Oxygen Control					
			Geotechnically focused methods				Geochemically focused methods	
		End dump	Lower lift height	Lower lift height and install air disruption layers (horizontal / repose slope)	Encapsulated PAF cells	Paddock dumping and thin lift from base up	Placement of O_2 consuming NAF	Sulfide passivation
	Fine	Pro: Impact of particle segregation from end-dumping may be less extreme. Con: Difficult to attain the higher bulk density that is possible with finer-textured materials as some segregation is likely to occur. Increased point source dust emissions from finer materials being dumped from large heights.	Pro: Easier to attain the higher bulk density that is possible with finer-textured materials, therefore decreasing gas movement and acidity generation. Mitigation of point source dust emissions from finer materials being dumped from smaller heights. Con: This method will likely need to be combined with other improved methods to be effective.	Pro: Availability of finer-textured material makes construction of these layers easier, and likely more effective at lowering acidity generation rates. Mitigation of point source dust emissions from finer materials being dumped from smaller heights. Con: Finer textured waste material inherently possesses decreased air flow capacity, therefore cost savings may be minimal. This method will likely need to be combined with other improved methods to be effective.	Pro: Finer textured materials likely to be beneficial for limiting gas-flow through the encapsulation layer. May decrease the need for comprehensive compaction of encapsulation materials. Under some circumstances, it may not need to be combined with other improved construction methods.	Pro: Expected to be very effective at lowering gas migration and therefore acidity generation. Easier to attain the higher bulk density than is possible with coarser-textured materials, therefore decreasing gas migration. Mitigation of point source dust emissions from finer materials being dumped from smaller heights. Con: Compaction, which is necessary for structurally stable stockpiles, will deliver diminishing returns with finer textured materials.	Pro: Finer-textured material will inhibit O_2 transport and complement O_2 consuming layers in minimizing PAF exposure to O_2. Oxygen consuming NAF materials will have a longer lifespan. Con: The method still needs to be implemented in conjunction with other improved MRS construction methods.	Pro: Slower and more uniform flow of seepage may ensure alkalinity is delivered more evenly to sulfide surfaces. Con: Higher surface area of finer textured materials requires more alkalinity and therefore longer time frames to passivate sulfide surfaces. This method should not be implemented in isolation, but rather in combination with other methods discussed here (on a site-specific basis).
Mine rock geochemistry	High acidity generation rate	Pro: Oxygen can be consumed quickly, leading to the potential for rapid onset of suboxia. Con: Susceptible to accelerated oxidation as O_2 can be readily re-supplied via coarse rubble zones. Difficult to maintain suboxia if O_2 can be easily re-supplied. Acidity generation will likely be kinetically limited, rather than O_2 limited as O_2 can be readily supplied due to particle segregation. This can lead to very high acidity generation rates. Potential for low O_2 / elevated H_2S gases to be transported out of the pile.	Pro: Decreased grainsize segregation will at least partially decrease O_2 resupply to highly reactive materials. Oxygen can be consumed quickly, leading to the potential for rapid onset of suboxia. Con: Potential for greater diffusion-based oxidation as more (temporary) surface area is created constructing shorter lifts. This method will likely need to be combined with other improved methods to be effective.	Pro: Decreased air flow will limit O_2 availability to highly reactive materials. Oxygen can be consumed quickly, leading to the potential for rapid onset of suboxia. Diffusion-based oxidation could be lowered if the layer is placed quickly. Containment of potentially hazardous pore gases resulting from high reactivity. Con: Decreases in tip head heights and air disruption layers may be largely ineffective if ARD / AMD risk classification and selective placement is not practiced. This method will likely need to be combined with other improved methods to be effective.	Pro: Encapsulation helps to lower gas flow into PAF materials, thereby decreases acidity generation rates. Oxygen can be consumed quickly, leading to the potential for rapid onset of suboxia. Con: High acidity generation rates can lead to high chemical potential (diffusion) gradients, which retard the effectiveness of encapsulating materials.	Pro: Almost complete lack of segregation. Oxygen can be consumed quickly, leading to the potential for rapid onset of suboxia. Higher moisture retention and compaction will slow down O_2 availability to reactive materials. Con: This method may need to be combined with other improved methods for high acidity generating materials mine waste.	Pro: Oxygen can be consumed quickly, leading to the potential for rapid onset of suboxia. Additional O_2 consuming NAF material will increase extent of suboxia without generating acid. Con: The method still needs to be implemented in conjunction with other improved MRS construction methods.	Pro: Oxygen can be consumed quickly, leading to the potential for rapid onset of suboxia, lowering the need for passivation. High acidity generation rates could also facilitate rapid passivation. Con: High acidity generation rates may exceed neutralisation capacity of alkalinity generating materials, and only provide partial passivation. This method should not be implemented in isolation, but rather in combination with other methods discussed here (on a site-specific basis).
	Low acidity generation rate	Pro: Effects of particle segregation may be partially mitigated by less reactive material. Con: Acidity generation will likely be kinetically limited, rather than O_2 limited as O_2 can be readily supplied due to particle segregation. This can lead to high acidity generation rates.	Pro: Diffusion-based oxidation caused by the increased (temporary) surface area created when constructing shorter lifts will be less extreme. Con: This method will likely need to be combined with other improved methods to be effective at significantly decreasing acidity generation.	Pro: Similar to above. Con: As above.	Pro: Encapsulation retards gas movement and decreases acidity generation rates. Con: Decreasing acidity generation rates has the effect of increasing the duration of ARD / AMD release.	Pro: As above. Con: As above.	Pro: Oxygen consuming NAF layers will help establish suboxic conditions faster, without generating ARD / AMD. Con: The method still needs to be implemented in conjunction with other improved MRS construction methods.	Pro: Greater opportunity to passivate sulfide grains before they can generate too much acidity. Careful choice of alkalinity producing materials will avoid the possibility of overdosing pore water. Con: This method should not be implemented in isolation, but rather in combination with other methods discussed here (on a site-specific basis).

7. LITERATURE REVIEW ON APPLICATION OF IMPROVED METHODS

The improved MRS construction methods discussed in this report include approaches that are currently in limited and sporadic use, as well as emerging technologies that have been demonstrated at small to large scale but have yet to be demonstrated at full scale.

Published references or public domain examples of the improved MRS construction methods are provided and discussed below. Other relevant unpublished examples are introduced as generic case studies to demonstrate the growing interest in, and uptake of, improved MRS construction methods.

7.1 Lower Lift Heights

7.1.1 Cypress Coal Mine, New Zealand

MRSs constructed by coal mining in the Brunner Coal Measures (BCM) on the South Island of New Zealand have the potential to release ARD / AMD. Due to high rainfall, some sites in this region generate high fluxes of ARD / AMD. Construction of several MRSs with lower lift heights in this region, however, has demonstrated a decrease in pore space O_2 concentrations and subsequent ARD / AMD release.

At the Cypress Northern engineered landform (MRS) at the Cypress Mine, acid forming sandstones (of the BCM) and mudstones (Kaiata Mudstone) were used to construct an MRS with 5 m lifts. Horizontal probes monitor O_2 concentrations up to 25 m into the MRS. Oxygen concentrations dropped sharply, reaching concentrations < 1 vol.% beyond 4 m horizontally into the lift (Pope et al., 2016). These monitoring data demonstrate only limited advective gas transport is occurring for lower lift heights. The initial pore space O_2 is consumed by the PAF material and cannot be resupplied at a rate high enough to maintain elevated O_2 concentrations. Diffusion-based O_2 ingress is likely the source of elevated O_2 concentration near the surface of the MRS.

7.1.2 Stockton Mine, New Zealand

The McCabes engineered landform (MRS) at the Stockton Mine was constructed with 6 m lifts, and also monitored with horizontal O_2 probes. The O_2 profiles in this set of monitoring data are similar to the Cypress Northern engineered landform, with O_2 concentration sharply decreasing below 1 vol.% after the first 2 m horizontally into the lift.

Water quality from these specific MRSs with lower lift heights were not measured. However, the suboxic conditions in all but the surface layers of the lifts are expected to significantly limit the rates of sulfide oxidation. The only appreciable source of ARD / AMD would likely arise from diffusion of O_2 into the surface layers.

7.1.3 Reddale Coal Mine, New Zealand

The Ferndale MRS at the Reddale Coal Mine on the West Coast of New Zealand is also constructed from the BCM and contains material that was expected to generate ARD / AMD (Olds et al., 2016). The Ferndale MRS was constructed with 4 m lifts, along with a 15 mm layer of limestone, as part of the ARD / AMD management plan. Oxygen probes were installed up to 30 m horizontally into every second lift. As with the other MRS constructed with lower lift heights from the BCM, pore gas O_2 concentrations decreased rapidly below 5 vol.% at depths greater than 8 m into the lifts shortly after construction (up to 44 days). Oxygen concentrations in the outer 8 m of the lift ranged from 1 to 9 vol.%. Additional material was placed on top of the lift, leading to compaction by heavy vehicle traffic in the upper portion of each lift. After this compaction, the MRS zones containing higher O_2 concentrations shrunk to 4 m into the lift. Acidity generation is therefore likely only occurring in the outer oxic shell of the MRS. Three years of water quality monitoring data in a creek downstream from the Reddale Coal Mine have shown that the pH of the creek has remained circumneutral and comparable to pre-mining conditions. The lack of low-pH drainage from the Ferndale MRS has been attributed to the shorter lift height, trafficked-layer compaction and the addition of limestone layers.

7.1.4 Iron Ore Mine in Western Australia

An iron ore mine located in the arid and hot Pilbara region of Western Australia has multiple MRSs composed of reactive pyritic, carbonaceous shales, constructed using various techniques including both tall and short end-dumped lifts. In a study by Pearce et al., (2016), monitoring stations were placed in an MRS constructed from a single 30 m end-dumped lift, and in an MRS constructed with 8 m end-dumped lifts with a 2 m paddock dumped interim covers on top of each lift.

Oxygen profiles from the larger, single lift MRS (Figure 7-1) show that the stockpile is well oxygenated at the base as a result of the coarse basal rubble zone. In the top half of the MRS, O_2 concentrations do not decrease below 14 vol.%, demonstrating the ability for air to be resupplied despite the high O_2 consumption rates of the material. The MRS constructed from smaller lifts and with paddock dumped layers contained much lower pore gas O_2 concentrations (Figure 7-2). The base of each lift still generally contained the highest O_2 concentrations, demonstrating that segregation still likely occurred during the end-dumping. However, O_2 concentrations only reached a maximum of 15 vol.% and were generally below 10 vol.% throughout the MRS. The paddock dumped layers contained the lowest O_2 concentrations.

The O_2 concentration data in both MRSs were also linked to ambient and internal temperatures and demonstrated a dependence of advective gas flow on the presence of a temperature gradient between the inside of the stockpile and the surrounding environment. This temperature gradient was still able to drive air through the MRS with shorter lifts; however, the relative O_2 concentrations were less than those in the MRS with larger lifts. The MRS constructed with engineered layers was not numerically modelled before the MRS's were constructed. Hence, design of the engineered layers was conceptual, and it is likely that the relatively dry climate conditions at the site contributed to a higher air permeability than expected. This demonstrates that, site-specific evaluation is required to properly implement these measures, and that additional mitigation techniques may be required to minimize O_2 ingress into MRS located in extreme climates.

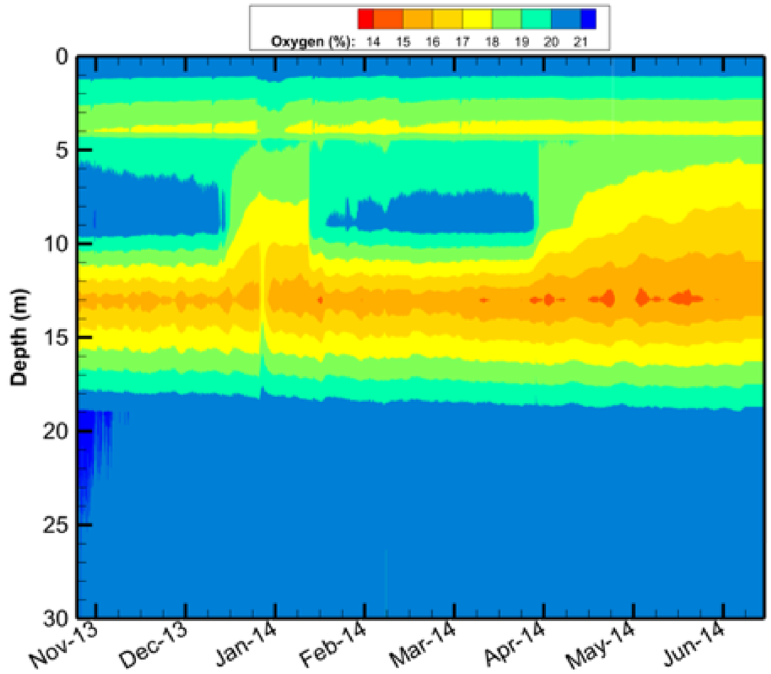

Figure 7-1: Pore gas O_2 concentration profile in a 30 m end-dumped MRS composed of a single lift (after Pearce et al., 2016).

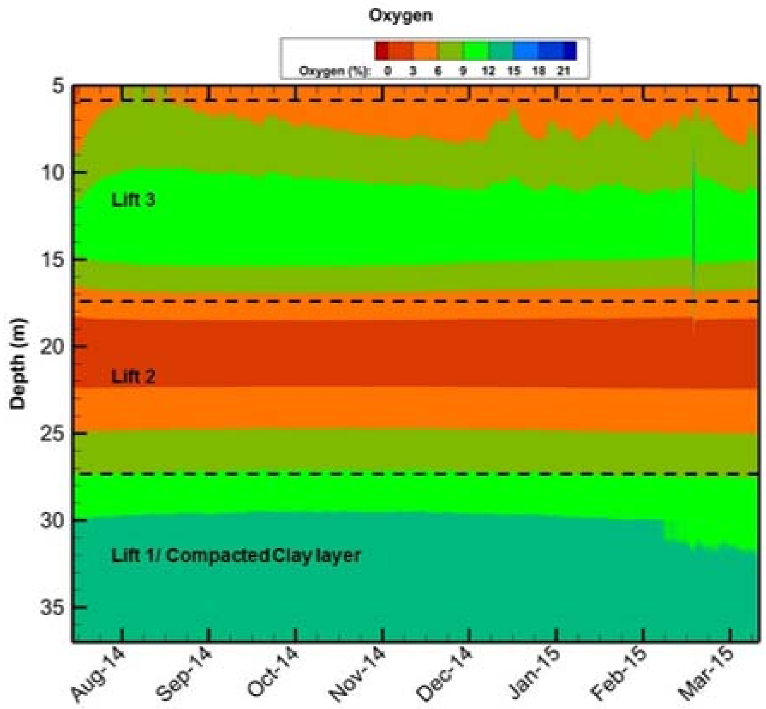

Figure 7-2: Pore gas O_2 profile in an MRS constructed with 8 m end-dumped lifts and 2 m paddock dumped layers (after Pearce et al., 2016).

7.2 Engineered Layers to Manage Vertical Gas Transport

7.2.1 Reddale Coal Mine, New Zealand

The Reddale coal mine was previously discussed in Section 7.1.3 as an example of a site that has constructed an MRS with lower lift heights to limit gas transport by advection. Compaction of the surface of each lift occurred by heavy vehicle traffic (ie. dozers and dump trucks). The field saturated hydraulic conductivity (k_{fs}) of non-compacted layers were measured to be ~1 x 10^{-6} m/s, while the k_{fs} of trafficked layers was measured ~1 x 10^{-7} to 1 x 10^{-8} m/s, indicating that trafficked layers can be over an order of magnitude lower in k_{fs} as compared to non-compacted mine rock (Olds et al., 2016). Combined with shorter lifts, the trafficked layers helped reduce advective gas transport as evidenced by continuously low O_2 concentrations in the pore spaces (Section 7.1.3).

7.2.2 Gold Mine, Tanzania

In some cases, vertical gas transport management can occur unintentionally. An MRS at a gold mine in Tanzania (a tropical savanna climate with a bimodal wet season and a distinct dry season) contains an average of 3 wt.% sulfur with 40 wt.% of the mine rock classified as PAF. The MRS at this site is approximately 100 m high with a footprint of 2 km^2. A 0.3 m clay layer was placed on top of the MRS to reduce truck tire damage during construction.

Generation of ARD / AMD would be expected in this setting; however, after more than 10 years, only one seep with water quality issues (elevated sulfate) of any significance was observed. The clay layer inadvertently appears to have inhibited vertical (advective) gas transport through the MRS, thus substantially decreasing sulfide oxidation. Elevated rainfall rates may cause a higher degree of saturation in this clay layer and assist with inhibition of gas transport. It is still possible, however, that ARD / AMD has yet to reach the toe of the 100 m MRS, therefore more detailed assessment is needed to verify the apparent benefits of vertical gas control at this site.

7.2.3 Greenhills Operations Coal Mine, Canada

The Greenhills Operations coal mine is located in the Elk Valley, BC, Canada. End-dumped MRSs in this region are not PAF but do contain elevated sources of soluble nitrate from blast residues and Se (selenium) associated with sulfide oxidation (Dockrey et al., 2015). As a result, seepage from MRSs in the Elk Valley characteristically contain elevated nitrate and Se. A potential treatment option for these seepages is to maintain suboxic conditions within the MRS in order to facilitate reduction of nitrate to ammonia and prevent sulfide oxidation (and therefore Se release), as well as facilitate bio-reduction of existing aqueous Se. However, these end-dumped MRSs are well oxygenated.

A by-product of coal processing called coarse coal reject (CCR) is generated on site and generally has a smaller grainsize than ROM material (Figure 7-3). The finer particles sizes of CCR increases the water retention characteristics of the material, thereby potentially reducing air permeability further. Stockpiles of CCR are placed in lifts at Greenhills Operations and while the CCR piles do not represent a true engineered layer system, monitoring data of pore gas O_2 concentrations (Figure 7-4) demonstrate key concepts of managing gas transport using finer-textured material. Suboxic conditions occur 5 to 15 m into the CCR stockpile, with variations resulting from seasonal effects. Carbon dioxide accumulates in the pore gas due to organic carbon oxidation and demonstrates the relatively slow re-supply of fresh air to the stockpile. The suboxic conditions have caused a demonstrable improvement in water quality with respect to nitrate and Se (Dockrey et al., 2015). Seepage from the CCR stockpile confirms attenuation of both nitrate and Se within the CCR as a result of the reducing (suboxic) conditions.

While not a deliberate or true engineered layer system, the monitoring data illustrate a decrease in pore gas O_2 concentrations, which appear to be aided by the decreased air flow capacity preventing re-supply of O_2, as a result of decreasing bulk air permeability within an MRS. These data provide field evidence that reducing air flow capacity simply by using finer-textured materials that are produced on site can improve water quality outcomes.

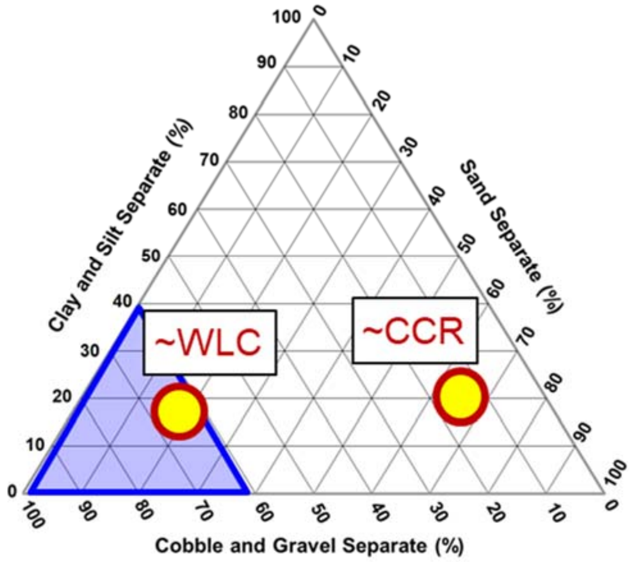

Figure 7-3: Textural triangle demonstrating the texture differences between typical mine rock (from West Line Creek; WLC) placed in the Elk Valley and CCR.

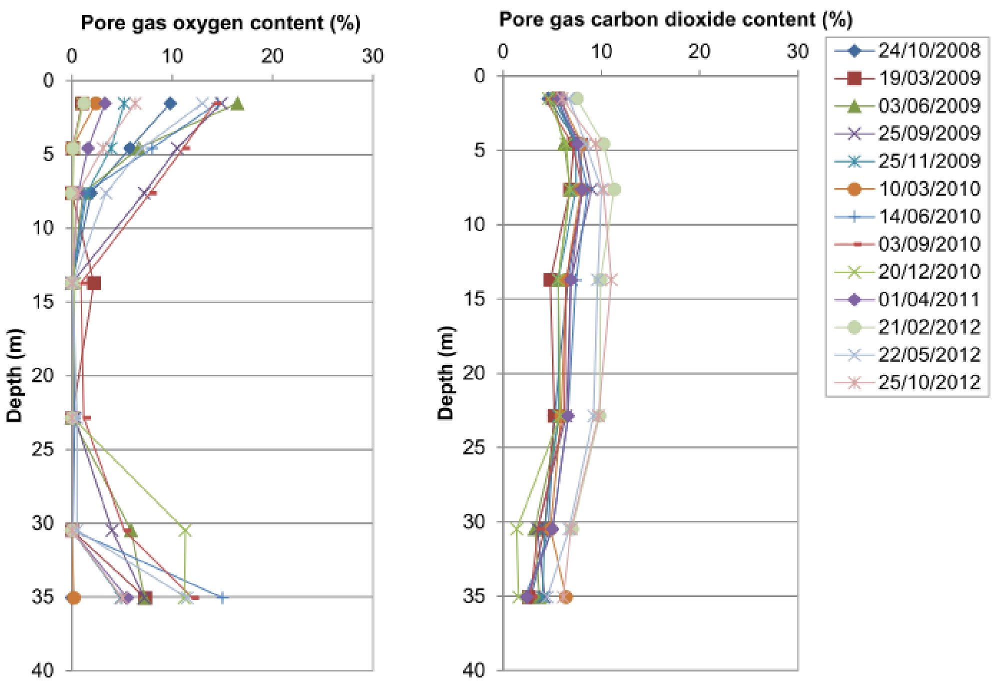

Figure 7-4: Pore gas concentration profiles of a CCR pile at Greenhills Operations (after Dockrey et al., 2015).

7.2.4 Rosebery Base Metal Mine, Australia

Discussed below in Section 7.3.1.

7.2.5 Coal Mine in Eastern Australia

A large coal mine in a temperate region of eastern Australia extracts 25-30 million tonnes of coal per year for power generation and produces 18 million tonnes of overburden material over the same period. The overburden immediately above the coal contains widespread authigenic marcasite (FeS_2; a polymorph of pyrite), which generates small quantities of ARD / AMD within the pit, but significant tonnages from the overburden stockpile. The stockpile is constructed in 20 m high, end-dumped tip heads. The unconsolidated nature of parts of the overburden and the ~700 mm of annual rainfall requires that a 1-3 m thick traffic compacted layer of clay be placed on top of each lift to ensure all-weather access to the tip head for the dump stackers.

While detailed water quality records for runoff and seepage from the overburden stockpile are sporadic, and acidity load discharge assessments often rely on calculations of treatment reagent costs, noteworthy changes in discharge water quality over time often cannot be discerned. Annual acidity loads discharged from the overburden stockpile have remained roughly unchanged at 200 to 400 tonnes H_2SO_4 per year for the last 10-15 years, despite an annual increase in overburden of 18 million tonnes. This acidity load discharged from the stockpile is believed to be largely derived from the mass of marcasitic (pyritic) rock exposed to atmospheric oxygen within near surface overburden materials at any one time.

While the traffic compacted clay layers placed on the overburden are primarily installed to ensure traffic access to the tip heads, they are believed to be acting as large-scale engineered gas management layers that are effectively sealing at least the horizontal surface of each lift, thereby limiting vertical gas transport and substantially limiting ARD / AMD formation.

7.3 Paddock Dumping and Base-up Construction

Miller (2009) identified a small number of sites that were currently using atmospheric O_2 control techniques to limit ARD generation. Included in this list were the Martha Mine in New Zealand, the Golden Cross Mine, New Zealand, the Phu Kham Copper-Gold Mine in Lao PDR, the Ban Houayxai Gold Mine in Lao PDR and the Kelian Gold Mine on Indonesia. These sites generally included thinner lift, base up construction and encapsulation techniques. More sites are beginning to employ these techniques in MRS construction (see below).

Taylor et al., (2016) describes the MRS construction methods and expected benefits of using base-up, thin-lift compaction techniques.

7.3.1 Rosebery Base Metal Mine, Australia

The Tasmanian EPA informed MMG's underground base metal operation in Rosebery that no more PAF material was to be disposed to the surface. A strategy was developed to identify material with low, positive net acid producing potential (PAF) and to amend it with limestone when it was brought to the surface to ensure that the waste was NAPP negative and therefore NAF. This process fulfilled regulatory requirements at low cost and converted the amended PAF into a non-acid forming, but O_2 consuming, material. The new NAF material was known to have the potential to produce NMD, and hence O_2 control was a key approach for minimising NMD.

Following stockpile construction trials, the full-scale stockpile consisted of the following ARD / AMD management components (MMG, 2016):

- Installation of a thin finer-grained limestone aggregate layer over legacy PAF mine wastes to act as an oxygen ingress control and add some alkalinity;
- Placement of only O_2 consuming, new NAF mine rock; and
- Creation of the stockpile from the base up in compacted thin lifts, with each lift separated by a compacted finer-grained limestone layer for managing air flow capacity and alkalinity addition.

The relatively high annual rainfall at Rosebery (~2100 mm) helps to maintain a high degree of saturation within the limestone layers and mine rock, facilitating limitation of air flow capacity. The base up, thinner lift, compacted construction also optimises carbonate and silicate neutralisation, and limits leachate release.

Early stage gas and water quality monitoring demonstrate that the stockpile design was very successful (MMG, 2016), but more recent data has yet to be made public.

7.3.2 Escarpment Coal Mine, New Zealand

BCM's Barren Valley engineered landform (MRS) at the Escarpment mine was constructed using paddock dumping with short lift heights of 2 m. Two sets of horizontal O_2 probes were installed at two elevations. As in the other MRSs constructed with shorter lifts from BCM materials (Section7.1.1), O_2 concentrations decreased below 1 vol.% horizontally into the lift (Figure 7-5) (Pope et al., 2016). Placement of a second lift on top of the first lift and subsequent installation of a monitoring station two days after the lift was constructed allowed the consumption of pore gas O_2 to be observed. The initial O_2 concentrations were near atmospheric. One month later, O_2 concentrations ranged from <1 vol.% to 7 vol.%. Two months later, all internal O_2 concentration measurements were < 1 %.

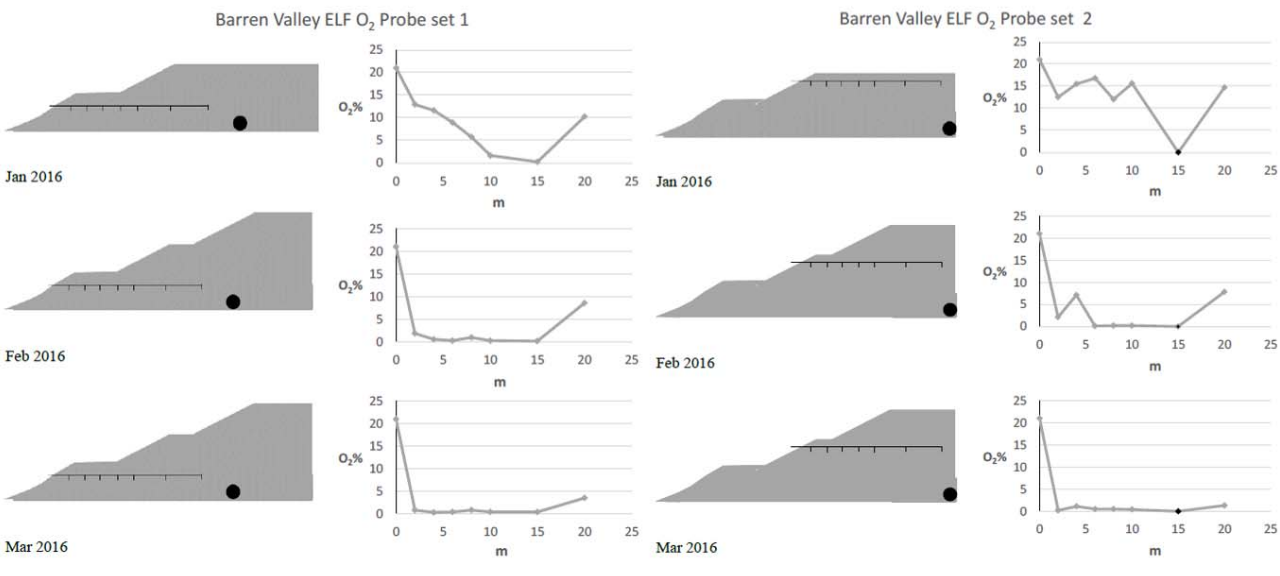

Figure 7-5: The extent of O_2 probes into the Barren Valley engineered landform and O_2 concentrations in the first (left) and second (right) O_2 probe sets (modified after Pope et al., 2016).

7.3.3 Telfer Copper-Gold Mine, Australia

Following concerns regarding seepage water quality from PAF mine rock at the Telfer Gold Mine in the Great Sandy Desert of the Eastern Pilbara, Western Australia, staff altered their conventional end-dumped construction methods to include paddock dumping, base up construction, and PAF encapsulation with lower air permeability, highly weathered NAF materials. This change in strategy was directed towards improving mine rock management to achieve progressive rehabilitation goals and minimise double handling of mine rock. No specific data on water quality improvements have been published.

Figure 7-6 shows preparation of paddock dumps, and also highlights the darker (sulfide bearing) wastes being surrounded (encapsulated) with more weathered, clay-rich materials.

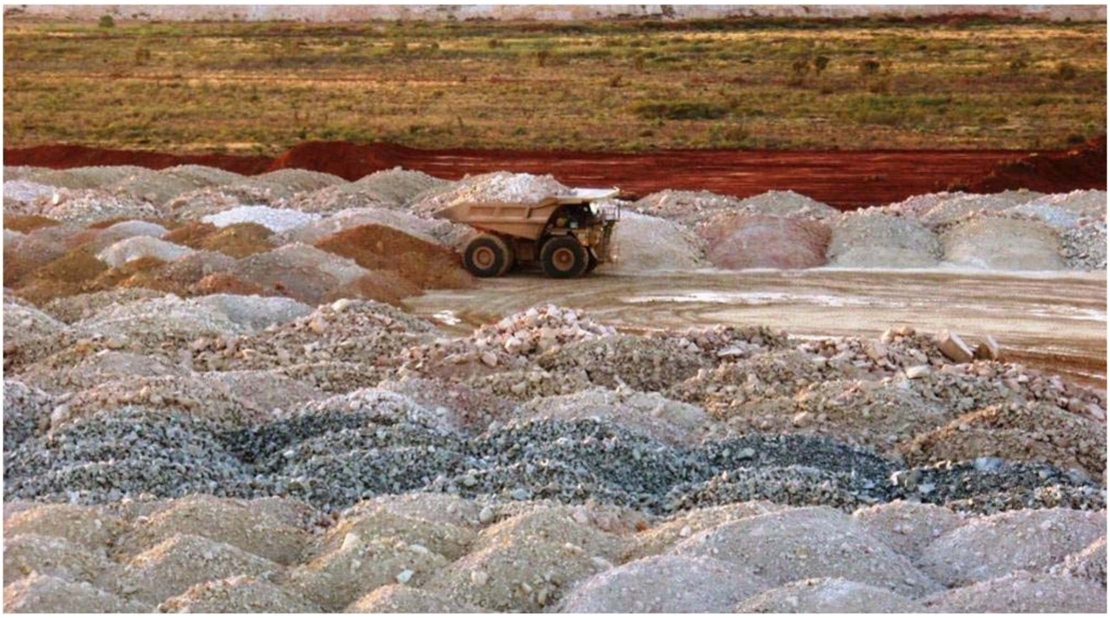

Figure 7-6: Paddock dumping MRS construction method, with darker coloured paddocks representing the fresher, sulfidic PAF rock, thereby also demonstrating encapsulation.

7.3.4 Martha Gold Mine, New Zealand

The Martha Gold Mine on the north island of New Zealand is one of the earliest documented sites that identified serious ARD / AMD issues and actively developed and implemented a range of highly effective management strategies, including construction methods designed to limit O_2 access to sulfidic wastes (Miller, 2009; Garvie et al., 2012; Garvie et al., 2014).

The Martha mine waste rock management strategy is sophisticated and includes compaction of thinner lifts to manage gas transport, careful encapsulation of PAF wastes with lower air permeability NAF and controlled carbonate blending (Garvie et al., 2012).

The documented water quality improvements from the range of management measures are very significant and occur over a sustained period (Garvie et al., 2012).

7.4 Encapsulation

7.4.1 Phu Kham Copper-Gold Mine, Lao PDR

The Phu Kham copper-gold operation is located in the tropical climate of PDR Lao and utilises mine rock as construction material for their tailings storage facility embankments where a large portion of this material is classified as PAF (Miller et al., 2012). Encapsulation of PAF material with NAF material is used to mitigate the risks of ARD / AMD within the embankment.

Mine rock from the pit block model is geochemically classified in-pit and scheduled for placement in the embankment. Cells of PAF material are encapsulated within compacted layers of NAF material during construction of the embankment. PAF layers are compacted in lifts of 6 m and are then covered with a 1 m layer of NAF material.

The encapsulated layers are compacted to a specified density and moisture content to minimize gas transport and a QA/QC program verifies that target specifications are being met. Because the Phu Kham site is located in a tropical climate, annual rainfall is high and allows for higher moisture contents in the encapsulating layers to be maintained. Horizontal pore gas monitoring arrays and vibrating wire piezometers (for pore pressure and temperature measurements) are installed in PAF cells to monitor encapsulation performance. Pore gas O_2 concentrations in the PAF cells generally decrease to zero within weeks or months and remain low (Figure 7-7), demonstrating the desired performance of the encapsulation layers.

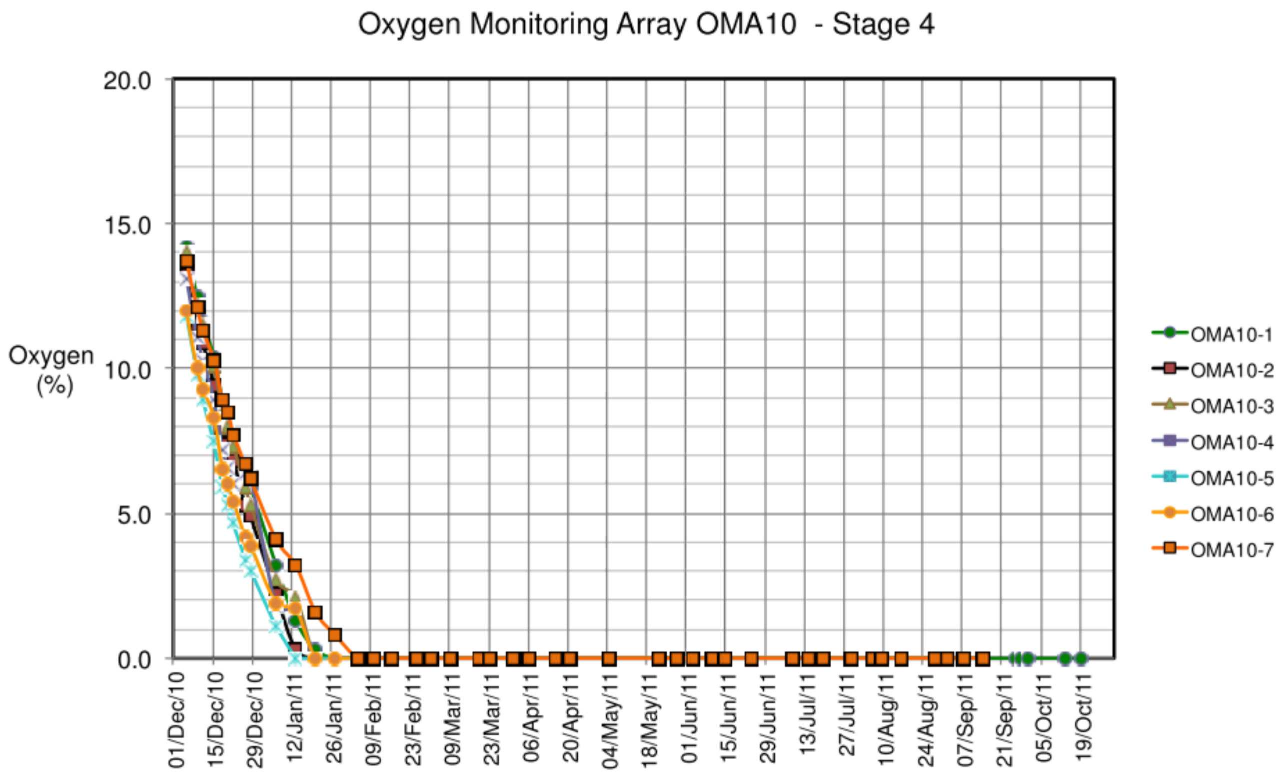

Figure 7-7: Oxygen pore gas profiles of monitoring arrays installed in PAF cells at Phu Kham (after Miller et al., 2012). OMA10-1 is installed furthest from the sealing layer, OMA10-7 is installed closest to the sealing layer.

Embankment seepage chemistry is also monitored. Water quality measurements from nearly three years of monitoring indicate minimal impact on seepage chemistry (eg. pH, sulfate, dissolved metals). While pore gas O_2 concentrations are the most direct way to monitor MRS construction performance, seepage chemistry represents the direct risks to potential receptors. Continual collection of seepage with low impacts from sulfide oxidation will further demonstrate encapsulation as a viable technique.

7.4.2 Tropical Rainforest Mine in Northern Sumatra, Indonesia

Encapsulation of PAF material is also being used in another tropical mine site in Northern Sumatra, Indonesia (Pearce et al., 2017). At this site, PAF layers are constructed in lifts of 8 m and are covered with a 2 m thick finer-textured encapsulating layer on the top and sides of each lift. The engineered layers for compaction are run-of-mine and classified as PAF.

Pore gas monitoring of encapsulation cells has shown that low and stable O_2 concentrations are maintained throughout the encapsulation cell, even as shallow as 0.5 m depths. Temperature monitoring shows that the internal temperatures are stable, which indicates a lack of exothermic oxidation reactions. This demonstrates that O_2 transport into the system is likely diffusion dominated. The degree of saturation measured at different points in the cells remains high throughout the available monitoring period. The wet climate is advantageous for controlling gas transport as available air space is drastically reduced. Encapsulated layers are quickly wetted up by the rainfall before being sealed by subsequent lifts of mine rock, allowing the internal degree of saturation to remain high and limit gas transport. pH measurements obtained from drill core through the main body of the embankment were near neutral pH throughout the depth profile, possibly suggesting a lack of oxidation as a result of the encapsulation method, although it is noted that some of the PAF material contains considerable ANC.

This case study demonstrates that encapsulation can be an effective construction method in managing ARD / AMD risk, especially if the local climate can be used to the advantage of the operator.

7.5 Oxygen Consumption

7.5.1 Rosebery Base Metal Mine, Australia

Discussed above under Section 7.3.1.

7.6 Sulfide Passivation

7.6.1 Grasberg Copper-Gold Mine, Indonesia

Sulfide passivation has not been trialled at full scale at any mine site. Miller et al., (2003) and Andrina et al., (2003) reported the first successful large-scale trial of an alkalinity generating cover at the Grasberg Copper-Gold Mine in the Papua Province of Indonesia. A 100,000 tonne dump was designed to assess a range of AMD management strategies, including limestone blending and limestone capping. One of the pads containing 25 wt.% blended limestone was also capped with a 2 m thick limestone cover following construction of the 20 m thick pads containing varying configurations of PAF (ranging from 2 to 5 wt.% S) and blended limestone. The water chemistry of leachate from each of the test pads was monitored regularly over several years (Miller et al., 2009; Miller et al., 2006; Andrina et al., 2006).

A significant improvement was recorded in the pH of waters exiting the limestone-covered pad within 2.5 years, and improvements continued over at least 10 years. These improvements were largely attributed to armouring and passivation of preferential flow paths and sulfide grains by neutralization precipitates. The armouring process was achieved by maintaining near-neutral conditions in pore waters due to dissolution of limestone, both associated with blended limestone and alkalinity released from a limestone-rich cover material. Excavation of one of the limestone-covered pads revealed an irregular reaction/precipitation front moving down through the mine rock. This reaction front is believed to follow preferential fluid pathways (Miller et al., 2009).

Key factors contributing to short-term success of the limestone cover at the Freeport mine include high annual rainfall (3,000 to 5,000 mm) that results in continuous and significant dissolution of the limestone, as well as the high proportion of carbonate within the mine rock (blended) and cover system (2 m thick limestone cover). A comparable response rate is considered far less likely in areas of lower rainfall due to very low solubility and slow dissolution rate of limestone.

The Grasberg example suggests that the ability of alkalinity generating cover materials to sustainably lower acidity discharges from MRSs can be significant under relatively unique conditions (very high rainfall and carbonate-rich mine rock and cover). Use of limestone under lower rainfall conditions would likely be successful but would be considerably slower. However, alkaline amendments with the potential to achieve similar improvements, in similar time frames, in the quality of seepage at mine sites in essentially any climatic setting were not identified at that time.

7.6.2 Brukunga Pyrite Mine, Australia

The South Australian state government is responsible for the management and remediation of the legacy Brukunga Pyrite Mine, near Nairne, approximately 40 km to the east of Adelaide. In the process of assessing the benefits of various remediation strategies, a series of 1,000 tonne mine rock stockpiles was established on site to test the relative benefits of various mine rock treatment methods on discharge water quality (Brett et al., 2011; Scott et al, 2011; Taylor et al., 2009; Stimpfl et al., 2009).

The test pads included various limestone blends and two separate alkalinity cover trials to assess the benefits of sulfide passivation. The trials were conducted over an 18-month period. The discharge water quality from each test pad was compared with an untreated baseline stockpile of PAF rock. One of the alkaline covers was constructed from precipitated calcium carbonate (PCC) and the other was prepared from carefully calcined caustic magnesia. The performance of the alkaline covers in passivating sulfides was determined by comparing the acidity loads from the baseline test pad with the reduced acidity loads from each of the treated test pads. The alkalinity released from the individual PCC and caustic magnesia covers by interaction with irrigation water was subtracted from the reduction in the acidity load from the test pads, so that only the effect of the sulfide passivation was revealed. Acidity load reductions attributed to passivation only were up to 50% for both alkalinity cover test pads. The shape of the test pads, with broad uncapped batters, restricted the influence of the alkalinity cover materials to the flat tops of the pads. In addition, the widespread distribution and abundance of existing jarosite, a sparingly soluble secondary acid salt, that is not sensitive to oxygen or subject to passivation, limited the benefit of the demonstration.

The substantial water quality benefits of thin alkaline caps over the highly sulfidic rock material suggest that sulfide passivation could play an important role in retarding acidity generation at many sites, regardless of the rainfall.

7.6.3 Savage River Iron Ore Mine, Australia

Following the success of Miller et al., (2003), Grange Resources, owners of the Savage River Iron Ore Mine on the west coast of Tasmania, Australia, noted some improvements in discharge water quality from one of their mine rock stockpiles. This stockpile, referred to as B-Dump, was known to be one of the key sources of ARD / AMD from the site. B-Dump was rehabilitated in 2006 by the previous owner of the site, and records indicated that part of the stockpile had been capped with high ANC rock materials.

Grange Resources decided to conduct a forensic geochemical assessment of the alkaline cover materials and underlying PAF rock to better understand the likely cause of the water quality improvements (Hughes et al., 2009; Hutchison et al., 2009; Li et al., 2011; Li et al., 2012).

Careful analysis of acidity generation rates from the PAF materials and alkalinity generation rates from the high ANC cover materials confirmed that reduction of acidity (acid plus metal) loads from the PAF materials significantly exceeded the alkalinity generating capacity of the alkaline materials. Li et al., (2012) concluded that the water quality improvements were related to passivation of pyrite crystal surfaces at high levels in the PAF material via the surficial precipitation of iron oxide bearing precipitates. The precipitation was thought to be related to the migration of weakly alkaline water percolating from the high ANC cover down into the PAF material and interacting with acid salts surrounding pyrite grains. It was also concluded (Li et al., 2012) that the estimated acidity generation and (typically very slow) alkalinity generation rates (associated with the low solubility and slow dissolution kinetics of dolomite in rainwater) indicated that the passivation front would take several years to migrate fully into the PAF materials to expand the zone of influence of passivation.

As previously noted, however, application of enhanced alkalinity generating materials (PCC or specialised caustic magnesia) can be expected to dramatically accelerate water quality improvements achieved via sulfide passivation.

8. FAILURE MODES AND EFFECTS ANALYSIS OF IMPROVED METHODS

A failure modes and effects analysis (FMEA) is a top down systematic approach to risk appraisal and identification of controls. The aim is to foresee the potential risks associated with a system and build redundancy or mitigation measures as required, but also identify and prioritize studies to address risks. The analysis can be used as a tool to support and communicate adopted strategies and to determine whether further research or analysis may be required. An FMEA draws on the knowledge and experience of experts to identify and assess failure modes and to develop controls to reduce the likelihood of a particular failure or consequence occurring.

An FMEA provides evaluators with the ability to perform a systematic and comprehensive evaluation of potential failure modes of the design / plan in order to identify potential hazards. The FMEA can be used to evaluate the potential for failures arising from a 'Base Case' that could result in environmental impacts, legal and other obligations, effects to the reputation with stakeholders, and HSE concerns. A risk profile can be developed for each area of concern. Once the failure modes and measures with the highest risk have been identified, it is possible to consider mitigation or alternative designs to reduce risks, and or further study / research to reduce risk. FMEAs are therefore an essential part of any risk- and liability-reduction program.

For this study, the objective of conducting an FMEA was to identify overarching risks associated with a conventional MRS. The same failure modes were assessed for improved construction methods in the same MRS setting to communicate, using a risk-based framework, how these improved methods can reduce or mitigate risks associated with a conventional MRS. The detailed FMEA results worksheets are provided in Appendix C.

8.1 FMEA Workshop Method

Three FMEA sessions were conducted to evaluate risks of a conventional MRS and how improved construction methods could mitigate those risks. Prior to the FMEA workshop, the evaluating question and the failure modes were defined. The 'base case' conventional MRS was chosen to be the setting used for Scenario 2A from the modelling program (an end-dumped MRS in a ridgeline mining setting; Section 5.3).

An FMEA was conducted on Scenario 2A using the evaluating question to assess risk for a series of high-level potential failure modes. Two subsequent FMEAs using the same evaluating question and failure modes were conducted on an 'improved' MRS that, which utilizes the improved construction methods that have been identified in this study. The first 'improved' evaluation was conducted on Scenario 2B from the modelling program (an MRS constructed from the bottom-up, using shorter (10 m) lifts, and layers to manage vertical gas movement; Section 5.4). The second 'improved' evaluation built upon Scenario 2B by adding the remaining improved construction methods incrementally (ie. encapsulation, gas consuming layers, and sulfide passivation) to create a Scenario 3C. Appendix B describes the FMEA method in detail.

8.2 FMEA Workshop Outcomes

8.2.1 Evaluating Question

The evaluating question guides the process of the FMEA by providing an overarching question to be applied when ranking each potential failure mode. The question is reflective of site or landform specific closure objectives. For this FMEA workshop, the question was defined as:

"What conditions could lead to geochemical failure of the applied MRS construction method, whereby 'failure' refers to inadequate spatial extent of suboxia conditions and/or increased treatment requirements?"

8.2.2 Development of Potential Failure Modes

A list of potential failure modes for the site was developed by the Project Team (Appendix C). While the failure modes that arise from an FMEA workshop are site-specific, the purpose of this risk assessment was to evaluate failure modes that would likely be present at any site. The failure modes list is meant to be comprehensive; however, there are always unknown hazards, and the combination of hazards increases the complexity.

8.2.3 Assumptions

Multiple assumptions were required to provide a common setting and understanding for how each failure mode would be evaluated. The overarching assumptions for each scenario were as follows:

- Geochemical risk classification characterisation of the mine rock has been conducted;
- It is assumed that geochemical classification control on the basis of drill core sampling / testing, GPS on haul trucks, and signage will be used at the site;
- There is operational awareness on site to ensure mine rock management is emphasized;
- NAF rock will be placed in the 20 to 50 m outer shell region (top and side);
- Runoff will be managed before it can reach any PAF material;
- There is an understanding of distribution and scheduling of the PAF and NAF mine rock;
- The ratio of PAF:NAF is 25:75;
- Monitoring data will be acquired from the MRS once operational; and
- The regulatory system is equal at all sites (in reality, regulatory requirements are site-specific).

8.2.4 Scenario 2A

FMEA outcomes for Scenario 2A (Figure 5-8) identified an overarching trend of the potential risks of a conventional MRS. Many of the failure modes demonstrate the inability for a conventional MRS to create adequate suboxic conditions necessary to prevent sulfide oxidation and ARD / AMD. The greatest risk was most often the consequence costs relating to water treatment. In the immediate-term, the opportunity exists to use existing water treatment facilities that are typically on-site during operations to manage poor water quality that results from a given failure mode, resulting simply in increased OPEX. In the short- and long-term timeframes, which represent the closure and post-closure periods, respectively, water treatment becomes more costly. The long-term consequence cost was often ranked to be catastrophic as the construction and operation of multiple water treatment plants, and enhancement / replacement of water conveyance and storage facilities required could likely exceed $100 million. Management of additional treatment sludges would also need to be considered. The consequence costs of these failure modes were ranked with high levels of confidence because increased long-term OPEX and CAPEX costs (treatment in perpetuity) are a current reality that occurs in the mining industry. This outcome highlights a key driver for this project.

Failure modes leading to catastrophic consequence costs included PAF materials being incorrectly placed due to inaccurate static geochemical characterization, PAF materials incorrectly placed within the predicted zone of suboxia due to poor quality control for mine rock segregation, inadequate static and kinetic geochemical characterization, and inadequate geotechnical characterization, all leading to the evaluating question.

While many of the failure modes result in generation of oxidation products that could cause significant environmental consequences, it was decided that the site would be required to address any water quality issues resulting from the failure mode. Therefore, environmental risks were almost always ranked as medium or less. The risk was instead transferred to the consequence costs of collecting and treating the water to ensure environmental risks were managed appropriately.

The failure mode that was most likely to be delayed by regulatory approval involved a problematic mine rock schedule of PAF and NAF delivery to the MRS. Following the assumption that we understand the distribution and scheduling of PAF and NAF mine rock, a scenario could occur where NAF material is arranged in the deposit such that it must be mined first with no way of changing the schedule for a favourable outcome. Because it was assumed we know the schedule will be problematic, regulators could delay permitting until a suitable plan to handle the mine rock is arranged. With an end-dumped MRS, a mine rock management plan would require significant rehandling of the material to ensure the entirety of PAF is not placed on the outer shell of the MRS. Designing a cost-effective handling plan that would satisfy regulators would be challenging without using the improved methods. This failure mode, along with others, presents the opportunity for improved methods to mitigate risks of conventional methods.

8.2.5 Scenario 2B

Scenario 2B considers the same MRS as Scenario 2A, except it is constructed from the bottom-up, in short lifts (10 m), and with vertical gas management layers (Figure 5-11).

Many of the failure modes centred on incorrect geochemical / geotechnical characterization, improper PAF / NAF placement, or incorrect or insufficient modelling information resulting in the evaluating question occurring. In all cases where the highest risk rating in Scenario 2A was high or very high, the highest risk rating was decreased to medium in Scenario 2B. The greatest improvement to risk ratings due to implementing the improved methods was a decreased likelihood of the failure mode actually causing inadequate suboxia or water treatment requirements. This improvement was especially pronounced in the short- and long-term whereby monitoring of the MRS during construction will inform adaptive management during MRS construction (eg. internal MRS, O_2 concentrations, MRS hydraulic characteristics, and quality control and assurance for placement of the engineered layer). The feedback of the monitoring data to refine the design is a critical form of risk mitigation.

Consequence costs were almost always reduced by at least one risk rating as well. It was assumed that a zone of suboxia would cover approximately 80% of the MRS in Scenario 2B, resulting in an estimated 5 to 10x reduction in generated acidity. If a specific failure mode were to occur, suboxia would be diminished but would likely generate less acidity than as compared to Scenario 2A for the same failure mode. As such, consequence costs for each failure mode were generally improved in Scenario 2B.

In Scenario 2A, a failure mode existed whereby a problematic schedule of PAF / NAF material in the mine block model led to a risk of regulatory approval delays due to the difficulties in developing a management plan for a conventional MRS. Constructing shorter lifts and managing vertical gas transport decreases the inherent risks of oxidation of large sections of PAF material. It is possible that a regulator would look at this management plan as favourable risk mitigation; however, because it is a relatively new construction method, a regulator may require increased financial assurance to address their uncertainty, thereby increasing the consequence cost.

Two additional failure modes relating to the ability to construct the gas management layer (either through incorrect quality control or insufficient material availability) were defined for Scenario 2B. The likelihood and consequence costs of the failure of gas management layers resulted in a long-term, high-risk rating due to potential treatment costs. Performance monitoring of the layers in the immediate-term could help mitigate this risk; however, this failure mode presents an opportunity for additional construction methods to mitigate the risk.

An important caveat for this risk assessment, however, is the low level of confidence in the majority of these rankings. Because of the general lack of commercial-scale application and performance of the improved construction methods relative to what we know about conventional methods, it is challenging to rank the failure modes with confidence There will likely be a generational time frame to adopt these techniques until enough commercial-scale in-service performance data is collected to increase confidence in using these improved methods for risk mitigation. It will be necessary to conduct field trials, assess monitoring data, and construct commercial-scale MRSs to be able to confidently assess the failure mode risks using these technologies.

The FMEA outcomes of Scenario 2B demonstrate the viability of several of the improved construction methods to help mitigate risks associated with conventional MRS construction. The cumulative effect of mitigating risk from several failure modes should be considered in any cost-benefit analysis being used to assess these technologies.

8.2.6 Scenario 2C

Scenario 2C built on the construction methods of Scenario 2B by adding encapsulation, O_2 consuming layers, and sulfide passivation to the MRS. This scenario allowed the risks from Scenario 2A and 2B to be mitigated further. Like Scenario 2B, nearly all risk rankings were made with a low level of confidence.

In general, the short- and long-term risk ratings for failure modes consisting of PAF / NAF placement issues were decreased due to the effects of sulfide passivation as the long-term consequence costs were reduced. In small-scale tests at existing sites, at least 50% reduction in acidity has been observed, providing a basis for consequence costs reductions. While sulfide passivation almost always helped mitigate consequence costs, this method functions best as a fail-safe for other construction methods rather than a singular construction method. The failure mode of sulfide passivation itself failing was identified as a low risk because of the presence of the other improved construction methods. However, without the other construction methods to rely on, the risk rating of sulfide passivation failure would increase significantly.

The greatest risk rating for Scenario 2B was failure of the gas management layers. Oxygen consuming layers would mitigate the likelihood of gas management layer failure leading to increased oxidation. Sulfide passivation beyond the short-term adds another layer of risk mitigation and brought these failure modes from a high to a medium risk rating.

Encapsulation and O_2 consuming layers can be used to manage a problematic schedule of PAF / NAF material. Scenario 2C consists of selectively placing PAF material within layers to isolate it from O_2 and is favourable for scenarios where the amount of mined PAF material is disproportionally higher than the mined NAF material.

Additional failure modes centred around not having the correct type of NAF material or not having sufficient amounts of NAF material for encapsulation or O_2 consumption layers were also developed. In these cases, consequence costs would increase in the immediate term to make up for the lack of NAF materials or to generate the materials on site. This would also place a reliance on sulfide passivation and the technologies implemented in Scenario 2B which also provide risk mitigation. The presence of these other construction methods brings down the likelihood of these failure modes.

The dependence of encapsulation and O_2 consuming layers on availability of geotechnical characterization of the engineered layer material was also identified as a potential risk. For example, if O_2 is able to move through encapsulation layers easier than expected because the encapsulation layer material is coarser-textured than expected, more and/or different encapsulating material may be required. Similarly, the required thickness of an O_2 consuming layer will be dependent on the texture of the material, as the texture will control the rate at which O_2 flows through the consumption layer. These factors did not change the overall risk assessment, but they do provide additional factors to consider in the engineering design of the MRS using these methods.

The magnitude of risks mitigated by Scenario 2C was generally less than the magnitude of risks mitigated by Scenario 2B. If a different combination of construction methods were used in Scenario 2B, it is probable that a different risk ranking would emerge. However, it should be emphasised that the FMEA should be used to identify what failure modes present the greatest risk, to inform on which construction methods would best mitigate those risks, and work that is required prior to implementation. The FMEA can be iterated on itself until an acceptable level of risk is achieved.

8.2.7 Summary of FMEA Outcomes

In general, the highest risk ratings for each failure mode decreased in severity from Scenario 2A through to 2C. Figure 8-1 shows the frequency of each risk rating for failure modes common to each scenario in each timeframe. A clear decrease in high and very high risk ratings occurs from Scenarios 2A to 2B and 2C, with many of the failure modes being ranked at medium. Furthermore, there is an increase in low risk ratings in Scenarios 2B and 2C.

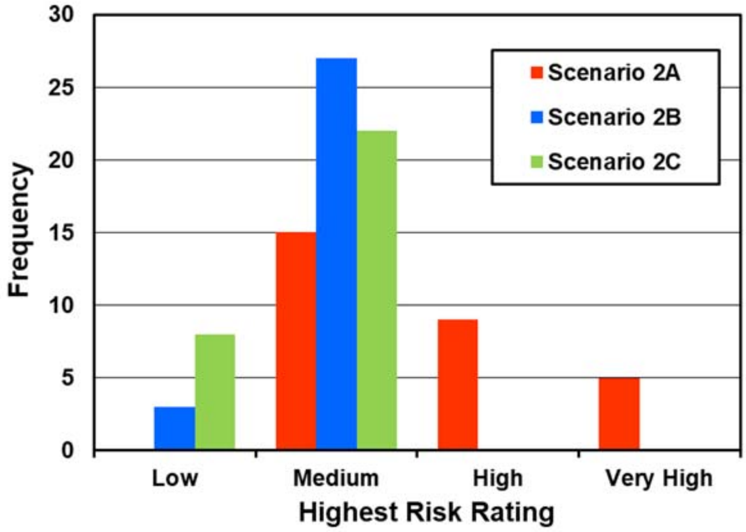

Figure 8-1: Frequency of risk ratings for all timeframes and for failure modes common to Scenarios 2A, 2B, and 2C.

The benefits of the improved construction methods are especially important for the long-term (post-closure) phase of the MRS. The long-term risk ratings for Scenario 2A were often high or very high for failure modes relating to operational segregation, modelling, material characterization, and geotechnical failure (Table 8-1). These long-term risk ratings decreased to medium for Scenarios 2B and 2C, demonstrating an effective mitigation of risk with the improved construction methods. There are diminishing returns for risk mitigation by incorporating all of the improved construction methods into one MRS, as the majority of risk ratings remained the same between Scenarios 2B and 2C.

Table 8-1: Highest long-term risk-ratings for failure modes common to Scenarios 2A, 2B, and 2C and categorized by a high-level failure mode type.

Failure Mode #	Failure Mode Type	Highest Long-Term Risk Rating		
		2A	2B	2C
1	Operational Segregation	Medium	Medium	Medium
2		Very High	Medium	Low
3		Very High	Medium	Low
10	Modelling	High	Medium	Medium
11		High	Medium	Medium
12	Material Characterization	Very High	Medium	Medium
13		Very High	Medium	Medium
14		Very High	Medium	Medium
17	Geotechnical Failure	High	Low	Low
18		Medium	Low	Low

The FMEA process demonstrates that risks associated with conventional end-dumped MRSs can be progressively lowered by adoption of a combination of the improved construction methods identified in this study, and that further assessment of cost-benefits of these methods is warranted.

9. CONCLUSIONS

Key conclusions from this work include:

- Multiple long-term quantitative studies at (confidential) client sites by Earth Systems indicate that mined PAF rock typically contributes to around 60 to 80% of a site's total acidity load at closure, with a further 20 to 30% of acidity load associated with TSFs, and relatively minor contributions from other ARD / AMD sources (eg. underground mine void wallrock, open cuts, heap leach facilities and other stockpiles). A published example is Scott et al. (2011) at the Brukunga mine site.
- MRS construction is currently based on optimising development and extraction of a site's ore resources, while also managing geotechnical risk associated with the MRS. Hence, it is the industry norm that MRSs are constructed using the end-dump placement method.
- End-dumping results in coherent grainsize segregation and distinctive depositional layering, with concentration of larger rock fragments in a 'rubble' zone at the base of each lift. As a result:
    - Gas transport within a typical MRS can be dominated by advection; the result is high air flow and oxygen supply rates deep into the MRS.
    - Increased gas flow can accelerate ARD / AMD generation and release rates.
- The action of end-dumping creates an MRS with internal structure that optimises sulfide oxidation, minimises carbonate and silicate neutralisation and hence, exacerbates ARD / AMD generation and release.
- Oxygen supply to sulfidic rock is the key limiting factor for ARD / AMD generation at most sites, unless they are in hyper-arid environments. Hence, to manage ARD / AMD risk, gas flow mechanisms should be considered when developing ARD / AMD management strategies for MRS.
- There is substantive, and growing, evidence that ARD / AMD management strategies for MRSs that are largely focussed on collection and treatment of MRS effluent (ie. MRS toe and basal seepage) is not sustainable. Application of cover systems to manage oxygen ingress and/or NP into an MRS serve to regulate the extent of collection and treatment required; however, the time frame from when the influence of a cover system at the base/toe of an MRS is fully realized often requires extended collection and treatment requirements.
- This study has identified and summarised improved MRS construction methods that build on industry's recent learnings related to challenges and costs associated with a heavy reliance on treatment of mine effluent to manage ARD / AMD.
- A total of six (6) broad categories of improved MRS construction methods were assessed in this study. Four (4) of the methods are focussed on geotechnical engineering approaches, and two (2) are geochemically focused methods:

Lower lift heights:	Lowering tip head heights to reduce the influence of segregation within an end-dumped MRS, and thereby reduce internal MRS air flow capacity.
Engineered layers:	Installation of horizontal or angle-of-repose engineered layers in an end-dumped MRS to facilitate vertical and lateral gas management.
Base-up, layered / compacted:	Building an MRS from the base-up via paddock dumping in compacted, thin lifts simultaneously retards air flow capacity and enhances carbonate and silicate neutralisation.
Encapsulation:	Encapsulating potentially acid forming (PAF) material with material that can achieve and maintain low air permeability to manage vertical

	and lateral gas transport within and to the PAF rock, thereby lowering acidity generation. Encapsulation related methods can be applied proactively (greenfield sites) and retrospectively (brownfield sites).
Oxygen Consuming Materials:	Strategic placement of sulfidic NAF materials around PAF mine material (eg. encapsulation style) can limit O_2 from reaching PAF material, as it is being at least partially consumed in the oxidising NAF layer, often without generating metalliferous drainage.
Sulfide Passivation:	Sulfide passivation installations require placement of relatively thin layers of specialised alkalinity generating materials above all PAF materials, often as a component of a cover system. Alkalinity slowly flushes into the MRS via infiltrating surface water and can passivate sulfide grains with neutralisation precipitates, thereby limiting ongoing oxidation.

- In summary, improved MRS construction methods can limit availability of oxygen to sulfidic mine rock, by either:
  - Regulating gas movement in PAF material;
  - Influencing pore gas oxygen concentrations via manipulated oxygen consumption; and/or
  - Coating sulfide grains to limit reaction with oxygen.
- Some of these improved construction methods can be applied retrospectively at brownfield sites.
- Additional methods have been identified in this study (Appendix D); these are considered "evolving" technologies and have not been assessed in detail.
- Numerical modelling of acidity generation from conventional and improved MRS construction methods illustrated the ability for the improved methods to limit air-flow capacity. Key outcomes from the modelling were:
  - Gas flow through an MRS can be controlled by placing layers in a way that decreases air permeability;
  - Controlling gas flow decreased O_2 concentrations within the MRSs and decreased acidity generation by approximately 75% over 25 years, and decreased acidity generation rates by 80 to 85% in the post-closure phase;
  - Decreases in acidity generation by varying the construction of the MRS is site-specific; however, positive directional changes in acidity generation are conceptually demonstrated with the modelling method presented in this report; and
  - Decreases in acidity generation also correlate to decreased leaching of other elements associated with sulfide minerals that may be of concern for a site.
- A comprehensive and accurate physical and geochemical characterisation and classification system coupled with the formulation of an ARD / AMD risk block model and a mine rock handling strategy is integral to all of the improved MRS construction methods.
- Case studies using published and unpublished data from active mine sites illustrate that water quality benefits can be achieved, and that the potential exists, for increased MRS construction costs to be offset by lower closure costs and closure bonding.
- Each improved MRS construction techniques has strengths and weaknesses that are influenced by site specific conditions, such as climate, topography, rock geochemistry, and rock texture.

- It is likely that application of any one of these improved methods in isolation will not be sufficient to achieve the necessary water quality improvements in most cases. The best water quality outcomes are predicted to be associated with the carefully considered, and site-specific, application of multiple improved MRS construction techniques.
- The FMEA process demonstrated that risks associated with conventional end-dumped MRSs can be progressively lowered by adoption of a combination of the improved construction methods identified in this study, and that further assessment of cost-benefits of these methods is warranted.
- Benefits to mine site water quality associated with existing full-scale applications of various improved construction methods provides strong evidence to support their broader application.
- Some of the improved methods have only been implemented at small to medium demonstration scales but also show very considerable promise, and new full-scale demonstrations are warranted.

10. NEXT STEPS

Key recommendations include:

1. Clarify the benefits of the improved MRS construction methods by developing a conceptual, and then detailed approach that uses current life-of-mine mine-planning tools, and mine-life-cycle costs, to compare conventional and improved MRS construction costs. Apply this approach to existing and potential MRSs on a site-specific basis to quantify cost-benefit.
2. Use information collated to this point to develop an early stage 'Decision Tree Tool' that can provide initial guidance on selection of appropriate MRS construction methods on a site-specific basis.
3. Develop conceptual and enhanced models of existing MRSs where internal (gas, temperature, etc.) and external (flow, water quality, etc.) data is available. 'Mine' this data to develop understanding for site-specific controls on performance, which can be transferred to opportunities at other sites, or if one could have a 'second' chance at building the same MRS, but differently.
4. Identify opportunities at existing problematic (brownfield) or potentially problematic (greenfield) mine sites to conduct large-scale trials to improve water quality outcomes from existing end-dumped materials by strategic use of improved MRS construction methods.
5. Identify opportunities to construct full-scale improved MRSs where site-specific factors have been considered at a conceptual level (eg. Decision Tree Tool) to inform a reasonable approach.
6. Identify opportunities to instrument and monitor existing MRSs to further evaluate the presence and spatial scale effect of MRSs that have been constructed 'differently', using methods discussed herein, but perhaps for reasons other than ARD / AMD management.
7. Fund targeted field demonstrations of emerging technologies in a range of climates, geologies and terrains in order to add to the toolkit of improved MRS construction methods.
8. Develop a series of recorded webinars that summarise the key outputs of this study for dissemination to all INAP member companies once cost opportunities have been analysed in the next phase.

11. REFERENCES

Andrina, J, Miller, S, Neale, A. 2003. 'The design, construction, instrumentation and performance of a full-scale overburden stockpile trial for mitigation of acid rock drainage, Grasberg Mine, Papua Province, Indonesia', in T Farrell, G Taylor (eds), Proceedings of the Sixth International Conference on Acid Rock Drainage, Cairns, Australia, 14–17 July 2003, 123–132.

Andrina, J., Wilson, G. W., Miller, S., and Neale, A., 2006, Performance of the acid rock drainage mitigation waste rock trial dump at Grasberg Mine. The 7th International Conference on Acid Rock Drainage (ICARD), March 26-30, 2006, St. Louis MO. R.I. Barnhisel (ed.). Published by the American Society of Mining and Reclamation (ASMR), 3134 Montavesta Road, Lexington, KY 40502.

Brett, D., O'Kane, M., Scott, P., Taylor, J., McLeary, M. and Williams, D., 2011, A water-covered waste dump in an arid climate? A remediation concept for Brukunga Mine. Mine Closure Conference proceedings, September 18-21, 2011, Lake Louise, Alberta, Canada.

Claridge, F.B., Nichols, R.S., Stewart, A.F., 1986. Mine waste dumps constructed in mountain valleys. CIM Bulletin. 79–87.

DIIS, 2016, Preventing Acid and Metalliferous Drainage. Leading Practice Sustainable Development Program for the Mining Industry. Australian Federal Government Department of Industry, Innovation and Science.

Dockrey, J., Martin, A., Stockwell, J., Kennedy, C., Day, S. 2015. Role of Nitrate in the Remobilization and Attenuation of Selenium in Coal Mine Waste. MEND Report 10.3.

Elberling, B. 2005. Temperature and oxygen control on pyrite oxidation in frozen mine tailings. Cold Regions Science and Technology. 41(2), 121-133.

Garvie A, Miller S, Fransen P, Ruddock J and Haymont R., 2012. Early and Prolonged Limitation of AMD Production via Waste Landform Construction. In 'Proceedings of the 9th International Conference on Acid Rock Drainage'. Ottawa, Ontario, Canada. 20-26 May 2012. (Eds WA Price, C Hogan and G Tremblay).

Garvie, A., Linklater, C., Chapman, J., and Watson, A., 2014, Overall acid production rates in mine wastes. Proceedings of the Eighth Australian Workshop on Acid and Metalliferous Drainage (Eds H Miller and L Preuss), pp.111-124. Adelaide, 29 April-2 May.

GEOSLOPE International Ltd. 2018. Add-In: Gas Consumption and Exothermic Reactions. Website: https://www.geoslope. com/learning/support-resources/add-ins/exothermic-reaction.

Herasymuik, G. 1996. Hydrogeology of a Sulphide Waste Rock Dump. M.Sc. Thesis. University of Saskatchewan, Saskatoon, Saskatchewan, Canada.

Hughes, A., Dineen R. and Kent S. 2009. Environmental performance of the Savage River rehabilitation project. In 'Proceedings of the 8th International Conference on Acid Rock Drainage' (8th ICARD). Skellefteå, Sweden. website http://www.proceedingsstfandicard-2009.com. pp.1–12.

Huminicki, D.M.C., Rimstidt, J.D. 2009. Iron oxyhydroxides coating of pyrite for acid mine drainage control. Applied Geochemistry. 24, 1626-1634.

Hutchison B, Brett D, Kent S and Ferguson T., 2009. Acid rock drainage management and remediation through innovative waste rock management techniques and mine planning at Savage River. In 'Proceedings of the 8th International Conference on Acid Rock Drainage' (8th ICARD), Skellefteå, Sweden. Website: http://www.proceedings-stfandicard-2009.com. pp. 1–10.

Lefebvre, R., Hockley, D., Smolensky, J., Lamontagne, A. 2001. Multiphase transfer processes in waste rock piles producing acid mine drainage. 2. Applications of numerical simulation. Journal of Contaminant Hydrology. 52, 165-186.

Li J, Kawashima N, Kaplun K, Schumann R, Smart R.St.C, Hughes A, Hutchison B and Kent S., 2012. Investigation of alkaline cover performance for abatement of ARD from waste rock dumps at Savage River Mine. In 'Proceedings of the 9th Int. Conf. Acid Rock Drainage' (9 ICARD). Ottawa, Canada. 21–25 May, 2012. www.mendnedem.org.

Li J., Kawashima N., Schumann R., Hughes A., Hutchison B., Kent S., Kaplun K., Ciccarelli J. M. and Smart RStC., 2011, Assessment of alkaline cover performance for abatement of ARD from waste rock dumps at Savage River Mine. In 'Proceedings of the Seventh Australian Workshop on Acid and Metalliferous Drainage, Emerging Trends in Acid and Metalliferous Drainage Management'. Indooroopilly Qld, Australia. pp. 241–253 (JKTech Pty Ltd: Indooroopilly, QLD, Australia).

Mahmood, F., Barbour, S., Kennedy, C., Hendry., M.J. 2017. Nitrate release from waste rock dumps in the Elk Valley, British Columbia, Canada. Science of the Total Environment. 605-606, 915-928. http://dx.doi.org/10.1016/j.scitotenv.2017.05.253.

Meints, C. and Aziz, M. 2018. Equity mine – 25 Years of Closure. 25th British Columbia MEND Metal Leaching/Acid Rock Drainage Workshop. Vancouver. 2018.

MEND, 2013. Review of Mine Drainage Treatment and Sludge Management Operations, MEND Report No. 3.43.1.

Miller, S., 1995, Geochemical indicators of sulfide oxidation and acid generation in the field. Conference: Proceedings. Second Australian acid mine drainage workshop, Charters Towers (Australia), 28-31 Mar 1995.

Miller, S., 2009, Leading practice solutions for acid rock drainage prevention and control: A key to achieving a sustainable future for mineral resource development. Proceedings of the Eighth Australian Workshop on Acid and Metalliferous Drainage (Eds H Miller and L Preuss), pp.51-66.

Miller, S., Rowles, T., Millgate, J., Pellicer, J., Morris, L., Gaunt, J., 2012. Integrated Acid Rock Drainage Management at the Phu Kham Copper Gold Operation in Lao PDR, in: 9th ICARD. Ottawa, Canada.

Miller, S., Rusdinar, Y., Smart, R., Andrina, J., and Richards, D., 2006, Design and construction of limestone blended waste rock dumps – Lessons learned from a 10 year study at Grasberg. The 7th International Conference on Acid Rock Drainage (ICARD), March 26-30, 2006, St. Louis MO. R.I. Barnhisel (ed.). Published by the American Society of Mining and Reclamation (ASMR), 3134 Montavesta Road, Lexington, KY 40502.

Miller, S., Smart, R., Andrina, J., Neale, A. and Richards, D., 2003. Evaluation of limestone covers and blends for long-term acid rock drainage control at the Grasberg Mine, Papua Province, Indonesia. p. 133-141. In: Proceedings Sixth International Conference on Acid Rock Drainage. (Cairns, QLD, July 12-18, 2003). The Australian Institute of Mining and Metallurgy, Melbourne.

MMG, 2016, Sustainability Report. Corporate Sustainability Report in the public domain for shareholders and other stakeholders.

Morin, K.A., Gerencher, E., Jones, C.E., Konasewich, D.E., 1991. Critical Literature Review of Acid Drainage from Waste Rock. MEND Rep. 1.11.1.

Olds, W., Weber, P., Pizey, M.H., Pope, J. 2016. Acid mine drainage analysis for the Reddale Coal Mine, Reefton, New Zealand. New Zealand Journal of Geology and Geophysics.

Pearce, S., Lehane, S., Pearce, J., 2016. Waste material placement options during construction and closure risk reduction — quantifying the how, the why and the how much, in: Fourie, A., Tibbet, M. (Eds.), Mine Closure 2016. Perth, Australia, pp. 685–700.

Pearce, S., Barteaux, M., Grohs, K., Hertrijana, J., Purnamasari, H., Orr, M., Nugraha, C., 2017. Progressive Management of AMD Risk During Construction of an Integrated Waste Storage Landform - A Case Study at Martabe Gold Mine, Indonesia, in: IMWA 2017. Lappeenranta, Finland. pp. 610-617.

Pope, J., Weber, P., Olds, W. 2016. Control of acid mine drainage by managing oxygen ingress into waste rock dumps at bituminous coal mines in New Zealand, in: IMWA 2016. Freiberg, Germany.

Ray, D. and Kent, S., 2004. Savage River Rehabilitation Project: Strategic Plan. Minerals Council of Australia Sustainable Development Conference Proceedings, Melbourne, Australia. Source at www.minerals.org.au/environment/SD04/papers.

Scott, P., Taylor, J., McLeary, M. and Grindley, P., 2011. Acidity load contributions from highwall sources at the Brukunga Mine. Proceedings of the 7th Australian Workshop on Acid and Metalliferous Drainage (Eds. LC Bell and B. Braddock), 21-24 June 2011, Darwin, NT, pp. 295-3.

Stimpfl, M., Carrigan, M. L., McLeary, M. B. and Taylor, J. R., 2009. Approaches to acid and metalliferous drainage management - Implications of short-term trials for long-term remediation, in A. B. Fourie & M. Tibbett (eds), Proceedings of the Fourth International Conference on Mine Closure, Australian Centre for Geomechanics, Perth, pp. 273-264.

Taylor, J. R., Pape, S. M., David, B. S. and Muchan, J. A., 2016. Waste rock pile construction to lower closure and relinquishment costs. Life-of-Mine 2016 Conference, Brisbane, Queensland, 28-30 September.

Taylor, J., Guthrie, B., Murphy, N. and Waters, J., 2006. Alkalinity Producing Cover Materials for Providing Sustained Improvement in Water Quality from Waste Rock Piles. The 7th International Conference on Acid Rock Drainage (ICARD), March 26-30, 2006, St. Louis MO. R.I. Barnhisel (ed.) Published by the American Society of Mining and Reclamation (ASMR), 3134 Montavesta Road, Lexington, KY 40502.

Taylor, J., Pape, S., Davis, B., Muchan, J., 2018. Waste Rock Pile Construction to Lower Closure and Relinquishment Costs. Life of Mine 2016 Conference, Brisbane, QLD, 28-30 September 2016

Taylor, J., Stimpfl, M., McLeary, M. and Grindley, P., 2009. Alkalinity generating cover materials for Sustainably Lowering Acidity Loads from Waste Rock Piles – Field Demonstration. Conference proceedings in Securing the Future and 8th ICARD, June 22-28, Skelleftea, Sweden.

Thomas, C., and O'Grady, T. 2018. Closure Activities – Progress over the last 10 years, Britannia Mine. 25th British Columbia MEND Metal Leaching/Acid Rock Drainage Workshop. Vancouver, BC, Canada.

Tran, A.B., Miller, S., Williams, D.J., Fines, P., Wilson, G.W., 2003. Geochemical and Mineralogical Characterisation of Two Contrasting Waste Rock Dumps — The INAP Waste Rock Dump Characterisation Project, in: 6th ICARD. Cairns, QLD, pp. 12–18.

Wels, C., Lefebvre, R., Robertson, A.M., 2003. An Overview of Prediction and Control of Air Flow in Acid-Generating Waste Rock Dumps, in: 6th ICARD. Cairns, QLD, pp. 639–650.

Wilson, W., 2011. Rock Dump Hydrology: An overview of full-scale excavations and scale-up experiments conducted during the last two decades, in: Proceedings of the Seventh Australian Workshop on Acid and Metalliferous Drainage. pp. 307-322.

Zhou, Y., Short, M. D., Li, J., Schumann, R. C., Smart, R, St. C., Gerson, A. R., and Qian, G., 2017. The formation of Aluminate Doped Surface Passivating Layers on Pyrite for Effective Acid and Metalliferous Drainage Control. Proceedings of the 9th Australian Acid and Metalliferous Drainage Workshop. Editors L. C. Bell, M. Edraki and C. Gerbo. 20-23 November, Burnie, Tasmania, 2017.

APPENDIX A

Numerical Modelling Method

The acidity generation model was constructed and simulated using the GeoStudio 2019 suite of numerical modelling software. To capture the important processes that govern acidity generation in an MRS, SEEP/W, TEMP/W, AIR/W, and CTRAN/W were coupled to simulate the hydrogeology, heat transfer, air flow, and mass transfer in a typical MRS. A gas consumption and exothermic reaction add-in was included in the model to account for O_2 consumption and heat generation from oxidation reactions, as well as to allow for the calculation of acidity generation via O_2 consumption (GEOSLOPE 2018).

Four generalized scenarios were developed as settings for the acidity generation models. Two sites with different settings and climates were chosen, with each MRS constructed using either conventional (end-dumped) or improved construction methods. These scenarios consisted of different climates, mining topographies, placement techniques, and material properties (Table 5-1). Over 1,000 scenarios can be generated from this matrix; therefore, feedback from INAP was incorporated into choosing the specific properties for each scenario (Table 5-2) to ensure that they were based on scenarios that are common or likely to occur.

Scenario 1 considers an MRS located in an arid climate and an open pit mine setting with moderate textured and higher reactivity mine rock. The conventional construction (Scenario 1A) in this setting might use top-down end-dumping with large lifts (> 30 m). Alternatively, the improved construction (Scenario 1B) in this setting was chosen to be constructed by bottom-up construction, smaller lifts (< 10 m) and contains compacted layers between lifts to manage vertical gas transport.

Scenario 2 considers an MRS located in a temperate climate and a ridgeline (valley fill) mine setting with moderate textured and higher reactivity mine rock. Like Scenario 1A, the conventional construction (Scenario 2A) in this setting might use top-down end-dumping with large lifts (> 30 m). Alternatively, the improved construction (Scenario 2B) in this setting was chosen to be constructed by bottom-up construction, smaller lifts (< 10 m) and contains compacted layers between lifts to manage vertical gas transport. Each model considered a 10 year construction period and was then modelled out for an additional 15 years to simulate the performance of the completed MRS. During the construction period, mine rock was 'added' to the stockpile quarterly. The volume of mine rock between the conventional and improved methods were kept equal during construction to ensure an equal basis existed for comparing performance differences.

Daily climate data (ie. temperature and rainfall) from real sites were used for the climate functions in the model. For consistency, the same set of material properties were used for each scenario. These properties were sourced from real material property data and included:

- Volumetric water content functions;
- Hydraulic conductivity functions;
- Air conductivity functions;
- Bulk gas diffusion coefficient functions;
- Material thermal conductivities;
- Material specific heat capacities; and
- Oxidation rate (modelled first-order reaction rate approximately equivalent to 1×10^{-8} kg O_2 / t / s);

The metric chosen for comparing relative outcomes of each scenario is the acidity generated per unit thickness of the MRS cross-section. This metric allows us to compare the acidity generated (which acts as an analogue for oxidation and encompasses both acid and "latent" acidity from metals) between scenarios with the same cross-sectional areas, and therefore same volume of mine rock placed.

While the model does capture many of the important processes, there are certain limitations in the current version of the model:

- Time steps were one day in length, and did not allow for diurnal changes to be modelled;
- There is no consumption term for sulfide minerals. As such, acidity generation in the model will continue indefinitely;
- Acidity neutralizing components are not considered in the model;

It is assumed that all O_2 consumption is due to pyrite oxidation and follows first-order reaction rate kinetics (Lefebvre et al., 2001):

$$\frac{dC}{dt} = -kC$$

Where C is the mass concentration of O_2, t is time, and k is the bulk reaction rate coefficient which accounts for the effective diffusion porosity of this material. This reaction rate is a function of temperature, and the temperature dependent relationship developed by Elberling (2005) was used in the model. Energy is generated by O_2 consumption at a rate of 360 kJ/mole of O_2. The change in energy at each node and timestep is converted into a boundary heat flux to calculate the change in temperature. Detailed calculations are provided by GEOSLOPE (2018).

Acidity generation was calculated from the sum of O_2 consumption within the cross section over time. Oxygen consumption at each time step and node was calculated using the integrated first order rate law and adjusted for the effective diffusion porosity (θ_{eq}):

$$\frac{\Delta m_{O2}}{V} = \theta_{eq} C_t \left(e^{(k\Delta t)} - 1\right)$$

Where m_{O2} is the mass of O_2 at the time step, V is the volume of the node, C_t is the mass concentration of O_2 at the start of the current time step, and Δt is the time step. The change in concentration is multiplied by the area of the node to yield a change in mass per unit thickness. The sum of O_2 consumption was calculated at each node over time. Assuming the complete net reaction of pyrite oxidation:

$$FeS_2 + \frac{15}{4}O_2 + \frac{7}{2}H_2O \rightarrow Fe(OH)_3 + 2SO_4^{2-} + 4H^+$$

Pyrite oxidation generates 1.07 moles of acidity per mole of O_2 consumed or 0.034 g of acidity per g of O_2. The mass of O_2 consumed in the model can be converted to acidity generated using this relationship.

APPENDIX B

Failure Modes and Effects Analysis Method

The FMEA method applied to Scenarios 2A, 2B and 2C, is outlined below.

B.1 Timeframe

Timeframes for assessment must be defined, as the consequence associated with a given failure mode is dependent on the timeframe in which it occurs. During the FMEA workshop three generalized timeframes for assessment were defined:

- Immediate-term: Permitting, planning, design, construction, and the operation years (10 years);
- Short-term: Closure period (> 10 years);
- Long-term: Post-closure period.

B.2 Risk Definitions

The FMEA assessment of 'risk' uses the traditional combination of likelihood and consequences. The goal is to provide an assessment of potential for, or likelihood of, failure of structures, equipment, or processes. The analysis technique evaluates the effects of such failures on the larger systems of which they form a part, and on the surrounding ecosystems.

The term 'risk' encompasses both the concepts of likelihood of failure (Section B.3), or 'expected' frequency of failures, and 'severity' of the expected consequences if such events were to occur (Section B.4). Separate assessments were made for the likelihood and consequences for each failure mode. A risk matrix was then used to assign a risk ranking to each failure mode based on likelihood and consequence values (Figure B-1).

		Consequence Severity				
		Insignificant (I)	Minor (Mi)	Moderate (Mo)	Major (Ma)	Catastrophic (C)
Probability	Very High (VH)	Medium	Medium	High	Very High	Very High
	High (H)	Low	Medium	High	High	Very High
	Moderate (M)	Low	Medium	Medium	High	High
	Low (L)	Low	Low	Medium	Medium	Medium
	Very Low (VL)	Low	Low	Low	Low	Medium

Figure B-1: Risk matrix for the FMEA evaluation.

Some failure modes will represent ‘acceptable’ risk, while others which rank in the ‘high’ and ‘very high’ levels should be viewed as unacceptable and steps should be taken to reduce or mitigate these risks. The ‘medium’ level is acceptable if it is ‘as low as reasonably practical’ (ALARP). In other words, the cost involved to reduce the risk further would be grossly disproportionate to the benefit gained. The ‘low’ risk designation is broadly acceptable.

B.3 Likelihood Definitions

The risk matrix for ‘likelihood’ classes were developed for the FMEA workshop are presented in Table B-1.

Table B-1: Definition of likelihood classes for FMEA.

Probability	Probability of Occurrence
Very High (VH)	Happens often (Expected)
High (H)	Could easily happen
Moderate (M)	Could happen and has happened elsewhere
Low (L)	Has not happened but could happen
Very Low (VL)	Conceivable but only at extreme circumstances

B.4 Consequences / Severity of Effects Definitions

The assessment of the severity of effects (or consequences) of specific failure modes should be based on evaluations or analysis of expected responses to failure. The estimated consequence for a given failure mode is based on a professional judgement of the anticipated impact of that specific failure. Consequence categories assessed during the FMEA workshop are summarized in Table B-2.

Table B-2: Definition of consequence categories for the FMEA.

Consequence Categories	Insignificant (I)	Minor (Mi)	Moderate (Mo)	Major (Ma)	Catastrophic (C)
Environment Effects	No observable impact to ecosystem functionality	Minor effect to ecosystem functionality, temporary displacement / impairment of species	Deleterious effect to ecosystem functionality, long-term displacement / impairment of species	Extensive deleterious effect to ecosystem functionality, permanent displacement / impairment of species	Serious impairment to ecosystem functionality, loss of species from the region
Consequence Cost (NPV)	< $1M	$1M-$10M	$10M-$50M	$50M-$100M	>$100M
Regulatory Approval	No change to the MRS permitting case / design	Less than one (1) year delay in approval	Delay project by one (1) year and additional conditions for permitting	Triggers a review panel and approval conditions, delays project by five (5) years	No acceptance

B.5 Level of Confidence Definition

The uncertainty associated with the assessment of likelihood and consequence for each failure mode was identified using the designations described in Table B-3. The level of confidence designation did not feed back into the overall risk ranking of a given failure mode but was included to identify risk tanking of failure modes that may not be well understood. Confidence level rankings were, in part, decided based on experience with the particular method in the field.

Table B-3: Level of confidence designations for the FMEA.

Confidence	Description
Low (L)	Do not have confidence in the estimate or ability to control during implementation.
Medium (M)	Have some confidence in the estimate or ability to control during implementation, conceptual level analyses.
High (H)	Have lots of confidence in the estimate or ability to control during implementation, detailed analyses following a high standard of care.

APPENDIX C

Failure Modes and Effects Analysis Results

The list of failure modes considered for the FMEA is outlined in Table C-1. Detailed FMEA results for Scenarios 2A, 2B and 2C, are presented on the following pages.

Table C-1: List of failure modes considered for the FMEA.

ID	Failure Mode Description
1	Problematic schedule of PAF/NAF delivery to MRS, leading to the Question.
2	PAF materials incorrectly placed due to inaccurate static geochemical characterization and AMD Risk Classification in mine block model, leading to the Question.
3	PAF materials incorrectly placed due to poor-quality control for mine rock segregation and placement, leading to the Question.
4	Insufficient NAF materials available to achieve encapsulation, leading to the Question.
5	Inappropriate NAF materials available to achieve encapsulation, leading to the Question.
6	Insufficient NAF materials available to achieve adequate oxygen consumption, leading to the Question.
7	Inappropriate NAF materials available to achieve adequate oxygen consumption, leading to the Question.
8	NAF materials incorrectly placed due to inaccurate static geochemical characterization and AMD Risk Classification in mine block model, leading to the Question.
9	NAF materials incorrectly placed due poor-quality control for mine rock segregation and placement, leading to the Question.
10	MRS design does not meet performance expectations (eg. inadequate extent of suboxia and/or longer time frame to achieve suboxia) due to incorrect modelling assumptions or methods, leading to the Question.
11	MRS design does not meet performance expectations due to insufficient model input information / supporting data, leading to the Question.
12	MRS design does not meet performance expectations due to inadequate static geochemical characterization and therefore AMD risk classification in mine block model, leading to the Question.
13	MRS design does not meet performance expectations due to inadequate kinetic geochemical characterization, leading to the Question.
14	MRS design does not meet performance expectations due to inadequate geotechnical characterization, leading to the Question
15	Engineered layers at top of lifts to manage vertical gas transport do not meet performance expectations due to inadequate quality control and assurance during construction, leading to the Question
16	Engineered layers at top of lifts to manage vertical gas transport do not meet performance expectations due to insufficient material availability, leading to the Question

ID	Failure Mode Description
17	MRS design does not meet performance expectations (eg. inadequate extent of suboxia and/or longer time frame to achieve suboxia) due to small-scale geotechnical stability failure of the landform leading to the Question
18	MRS design does not meet performance expectations due to large-scale geotechnical stability failure of the landform leading to the Question
19	Incomplete coverage of alkalinity generating material over surface of MRS, leading to the question.

Scenario 2A. Conventional MRS (End-dumped)

Question: What conditions could lead to the geochemical failure of the applied MRS construction method, whereby “failure” refers to inadequate spatial extent of suboxia conditions and/or increased treatment requirements.

Failure Mode ID	***Failure Mode Description***	***Timeframe***	***Likelihood***	***Consequences***						***Level of Confidence***	***Highest Risk Rating***	***Mitigation / Comments***
				Environment Effects		*Consequence Cost*		*Regulatory Approval*				
1	Problematic schedule of PAF/NAF delivery to MRS, leading to the Question.	Immediate	H	Mi	M	Mo	H	Mo	H	H	H	1. This FM assumes that the right rock is not coming out at the right time. 2. Problematic schedule assumes that we know where our PAF/NAF are. 3. Would likely need to re-handle the material in some manner, adding to the consequence cost. 4. Assumes there is no way to change the schedule for a favourable outcome. 5. Assumes we will figure out some way to handle the ore nonetheless. 6. Would need to consider utilizing improved MRS construction methods. 7. Additional time required for permitting, as we have already developed the block model. 8. In the short-term (closure), we have supposedly developed a management plan (without using improved methods). 9. Consequence cost in short-term will cover the re-handling / management. 10. Consequence cost in immediate term would be associated with additional treatment. 11. Regulatory approval for short-term, is minor because we have already committed to a closure plan / management plan in the immediate term. 12. Short-term level of confidence - it is possible that the consequence cost could slip into a higher category. 13. Long-term environmental effects may go up as you are not able to react as fast as when you were initially managing it. 14. Treatment in perpetuity and possible construction costs increase the consequence in the long-term. 15. Assumes this is a problem we are aware of from the outset and can plan accordingly, thereby reducing the likelihood in the long-term.
1		Short-term	H	Mi	M	Ma	H	Mi	M	M	H	
1		Long-term	L	Mo	M	C	M	Mi	L	M	M	
2	PAF materials incorrectly placed due to inaccurate static geochemical characterization and AMD Risk Classification in mine block model, leading to the Question	Immediate	M	Mi	M	Mi	M	Mi	M	M	M	1. Ensure that you had approximately 20-50 m of NAF rock placed on the outer shell (top and side). 2. Manage runoff before it could reach PAF. 3. Assumed that there is some understanding of distribution and scheduling of PAF/NAF rocks and selective placement of these rocks. 4. Standard practice to have grade-control, GPS on haul trucks and signage in the present, to ensure this is less likely. More geochemical studies happening nowadays. Not as common in the past however. 5. More awareness at an operational level. 6. Once operational, more emphasis on placement when monitoring data is acquired. 7. Assuming we have a recoverable / unrecovable seepage ratio of 75:25 in immediate time-frame. 8. Likely an initial lag phase with the PAF material generating acid. 9. Assuming an actual ratio of PAF/NAF of 25:75. This assumption should be revisited. 10. Mitigation during operations - annual auditing to cross-reference block model, characterizing materials on a continual basis, monitor any changes in geochemistry. 11. In short term, still have the ability to manage water quality, at an increased expense. 12. In the immediate and short-term, the chosen consequences are likely in the lower-end of their bounds. 13. The choice for moderate level of confidence is to communicate that more modelling / characterization is needed. 14. Consequence cost is an NPV cost. 15. Over $100M required for CAPEX of at least two additional WTPs and continual OPEX. 16. Long term - Captured increased risk to environmental effects as a result of increased likelihood and increased expenditure for treatment. 17. Management of treatment sludges would increase consequence costs; this would tip us into the catastrophic category if we weren't there already. Also would have it's own specific environmental effect to be managed. 18. Typical location for sludge storage would be in a pit, which would be a substantial cost for the current setting. 19. Long-term - high confidence because this is what occurs on an everyday basis in the mining industry.
2		Short-term	H	Mi	M	Mo	H	Mi	M	M	H	

Scenario 2A. Conventional MRS (End-dumped)

Question: What conditions could lead to the geochemical failure of the applied MRS construction method, whereby "failure" refers to inadequate spatial extent of suboxia conditions and/or increased treatment requirements.

Failure Mode ID	*Failure Mode Description*	*Timeframe*	*Likelihood*	*Consequences*						*Level of Confidence*	*Highest Risk Rating*	*Mitigation / Comments*
				Environment Effects		*Consequence Cost*		*Regulatory Approval*				
2		Long-term	VH	Mi	M	C	VH	Mi	M	H	VH	20. This outcome is the reason we are doing this project. 21. Global note - we are assuming that the regulatory system is equal world wide. In reality, this is very site-specific.
3	PAF materials incorrectly placed within the predicted zone of suboxia due to poor quality control for mine rock segregation and placement, leading to the Question	Immediate-Term	M	Mi	M	Mi	M	Mi	M	H	M	1. Using the same assumptions as failure mode 1. 2. Emphasis will be placed on quality control for mine rock separation and placement during operations to mitigate this faillue mode. 3. Incorrect placement due to QC should have similar consequences as incorrect geochemical characterization. 4. Level of confidence in the rankings is high because we have experience of this happening.
3		Short-Term	H	Mi	M	Mo	H	Mi	M	H	H	
3		Long-Term	VH	Mi	M	C	VH	Mi	M	H	VH	
4	Insufficient NAF materials available to achieve encapsulation, leading to the Question.	Immediate-Term			n/a		n/a		n/a			1. Failure mode does not apply to this scenario.
4		Short-Term			n/a		n/a		n/a			
4		Long-Term			n/a		n/a		n/a			
5	Inappropriate NAF materials available to achieve encapsulation, leading to the Question.	Immediate-Term			n/a		n/a		n/a			1. Failure mode does not apply to this scenario.
5		Short-Term			n/a		n/a		n/a			
5		Long-Term			n/a		n/a		n/a			
6	Insufficient NAF materials available to achieve adequate oxygen consumption, leading to the Question.	Immediate-Term			n/a		n/a		n/a			1. Failure mode does not apply to this scenario.
6		Short-Term			n/a		n/a		n/a			
6		Long-Term			n/a		n/a		n/a			
7	Inappropriate NAF materials available to achieve adequate oxygen consumption, leading to the Question.	Immediate-Term			n/a		n/a		n/a			1. Failure mode does not apply to this scenario.
7		Short-Term			n/a		n/a		n/a			
7		Long-Term			n/a		n/a		n/a			
8	NAF materials incorrectly placed due to inaccurate static geochemical characterization and AMD Risk Classification in mine block model, leading to the Question.	Immediate-Term			n/a		n/a		n/a			1. Failure mode does not apply to this scenario.
8		Short-Term			n/a		n/a		n/a			
8		Long-Term			n/a		n/a		n/a			
9	NAF materials incorrectly placed due poor-quality control for mine rock segregation and placement, leading to the Question.	Immediate-Term			n/a		n/a		n/a			1. Failure mode does not apply to this scenario.
9		Short-Term			n/a		n/a		n/a			
9		Long-Term			n/a		n/a		n/a			
10		Immediate-Term	M	Mi	M	Mo	M	Mi	M	H	M	1. Using the same assumptions as failure mode 1. 2. Seepage recovery will be increased if water quality becomes an issue, at the expense of consequence costs. 3. Consequence costs would be high to treat water as a result of the failure mode. 4. Are the assumptions / design parameters way off? Or are they just off by a bit? This may change how

Scenario 2A. Conventional MRS (End-dumped)

Question: What conditions could lead to the geochemical failure of the applied MRS construction method, whereby "failure" refers to inadequate spatial extent of suboxia conditions and/or increased treatment requirements.

Failure Mode ID	Failure Mode Description	Timeframe	Likelihood	Consequences: Environment Effects		Consequences: Consequence Cost		Consequences: Regulatory Approval		Level of Confidence	Highest Risk Rating	Mitigation / Comments
10	MRS design does not meet performance expectations (e.g., inadequate extent of suboxia and/or longer time frame to achieve suboxia) due to incorrect modelling assumptions, methods, or design parameters leading to the Question	Short-Term	M	Mi	M	Mo	M	Mi	M	H	M	[illegible] we view the likelihood ranking. 5. Not meeting performance expectations would still lead to catastrophic effects in terms of cost (long-term). 6. A time delay of acid generation will offset the severity until at least the short-term. 7. Mitigation: Test (calibrate) modelling assumptions with field data before and during construction.
10		Long-Term	M	Mi	M	C	H	Mi	M	H	H	
11	MRS design does not meet performance expectations due to insufficient model input information / supporting data, leading to the Question	Immediate-Term	M	Mi	M	Mo	M	Mi	M	H	M	1. Using the same assumptions as failure mode 1 and failure mode 3. 2. Insufficient modelling information could be climate data (rainfall, temperature), material properties (SWCCs), oxidation rates, etc. that would be important for modelling acid generation. 3. Mitigation: Refine model inputs as the MRS is being contructed. Adjust construction as the model refinements are made. 4. Likelihood of this occurring increases if the model inputs are not refined during construction.
11		Short-Term	M	Mi	M	Mo	M	Mi	M	H	M	
11		Long-Term	M	Mi	M	Ma	H	Mi	M	H	H	
12	MRS design does not meet performance expectations due to inadequate (i.e., not enough) static geochemical characterization and therefore AMD risk classification in mine block model, leading to the Question	Immediate-Term	H	Mi	M	Mi	M	Mi	M	M	M	1. Using same assumptions as failure mode 1. 2. Considers the possibility that there is more PAF than the original block model estimated. 3. Unexpectedly high amounts of PAF would definitely increase acidity generation in a conventional MRS.
12		Short-Term	H	Mi	M	Mo	H	Mi	M	M	H	
12		Long-Term	VH	Mi	M	C	VH	Mi	M	H	VH	
13	MRS design does not meet performance expectations due to inadequate kinetic geochemical characterization, leading to the Question	Immediate-Term	H	Mi	M	Mi	M	Mi	M	M	H	1. Using the same assumptions as failure mode 1. 2. Considers the possibility that either neutralization capacity cannot keep up with acid generation, or intrinsic oxidation rates are higher than expected. 3. This could result in higher acid generation rates due to slower neutralization rates. 4. Mitigation: Strategic placement of PAF material away from the outer shell or close to more neutralizing materials to minimize oxygen contact or promote more contract with alkalinity. 5. Oxygen ingress inherent to a conventional MRS will still likely generate more acidity with time despite mitigations.
13		Short-Term	H	Mi	M	Mo	H	Mi	M	M	H	
13		Long-Term	VH	Mi	M	C	VH	Mi	M	H	VH	
14	MRS design does not meet performance expectations due to inadequate or incorrect geotechnical characterization, leading to the Question	Immediate-Term	L	Mi	L	Mi	L	Mi	L	M	M	1. Using the same assumptions as failure mode 1. 2. Assuming geotechnical characterization refers to the material characterization of placed material's PSD and packed densities and their subsequent ability to control air permeability and degree of saturation. What we are seeing draining from the toe now does not necessarily reflect what will drain from the toe know (in terms of both seepage rates and water quality). 3. Considers the wetting up / draining down dynamics of the MRS. 4. Increased air flow through the conventional MRS will likely lead to the Question. 5. Due to the variabiliy of "inadequate geotechnical characterization", the confidence in this ranking is medium.
14		Short-Term	M	Mi	M	Mo	M	Mi	M	M	M	
14		Long-Term	H	Mi	M	C	VH	Mi	M	M	VH	
15	Engineered layers at top of lifts to manage vertical gas transport do not meet performance expectations due to inadequate or incorrect quality control and assurance during construction, leading to the Question	Immediate-Term			n/a		n/a		n/a			1. Failure mode does not apply to this scenario.
15		Short-Term			n/a		n/a		n/a			
15		Long-Term			n/a		n/a		n/a			
16	Engineered layers at top of lifts to manage vertical gas transport do not meet performance expectations due to insufficient material availability, leading to the Question	Immediate-Term			n/a		n/a		n/a			1. Failure mode does not apply to this scenario.
16		Short-Term			n/a		n/a		n/a			

Scenario 2A. Conventional MRS (End-dumped)

Question: What conditions could lead to the geochemical failure of the applied MRS construction method, whereby "failure" refers to inadequate spatial extent of suboxia conditions and/or increased treatment requirements.

Failure Mode ID	Failure Mode Description	Timeframe	Likelihood	Consequences: Environment Effects		Consequences: Consequence Cost		Consequences: Regulatory Approval		Level of Confidence	Highest Risk Rating	Mitigation / Comments
16	insufficient material availability, leading to the Question	Long-Term			n/a		n/a		n/a			
17	MRS design does not meet performance expectations (e.g., inadequate extent of suboxia and/or longer time frame to achieve suboxia) due to small-scale geotechnical stability failure of the landform leading to the Question	Immediate-Term	M	Mi	M	Mo	M	Mo	M	H	M	1. Using the same assumptions as failure mode 1. 2. A small scale geotechnical stability failure would lead to a portion of the MRS potentially being exposed to increased oxygen ingress. 3. In the immediate-term and short-term, may be possible to repair the failure, at increased costs, to mitigate environmental effects. 4. Any geotechnical stability issues would be treated seriously by regulators. 5. This could occur due to consumption of carbonates due to acid generation which could result in slumping. 6. Heavy rainfall or erosion could also lead to small scale slope failure.
17		Short-Term	M	Mi	M	Mo	M	Mo	M	H	M	
17		Long-Term	H	Mo	H	Mo	H	Mo	H	H	H	
18	MRS design does not meet performance expectations due to large-scale geotechnical stability failure of the landform leading to the Question	Immediate-Term	L	Mo	M	C	M	Ma	M	H	M	1. Using the same assumptions as failure mode 1. 2. A large scale geotechnical stability failure would lead to a large portion of the MRS potentially being exposed to oxygen ingress. 3 Any geotechnical stability issues would be treated seriously by regulators. 4. Due to some foundational failure, pore-water pressure build-up, or seismic failure 5. Cannot build an MRS if it is not proven to be geotechnically stable.
18		Short-Term	VL	C	M	C	M	Ma	L	H	M	
18		Long-Term	VL	C	M	C	M	Ma	L	H	M	
19	Incomplete coverage of alkalinity generating material over surface of MRS, leading to the question.	Immediate-Term			n/a		n/a		n/a			1. Failure mode does not apply to this scenario.
19		Short-Term			n/a		n/a		n/a			
19		Long-Term			n/a		n/a		n/a			

Scenario 2B. Smaller lift heights / vertical gas management / bottom up

Question: What conditions could lead to the geochemical failure of the applied MRS construction method, whereby “failure” refers to inadequate spatial extent of suboxia conditions and/or increased treatment requirements.

Failure Mode ID	Failure Mode Description	Timeframe	Likelihood	Consequences						Level of Confidence	Highest Risk Rating	Mitigation / Comments
				Environment Effects		Consequence Cost		Regulatory Approval				
1	Problematic schedule of PAF/NAF delivery to MRS, leading to the Question.	Immediate	M	Mi	M	Mo	M	Mi	M	L	M	1. Assuming the same setting as in Scenario 2A. 2. Assumes that NAF material comes out first. Add this to Scenario 2A comments as well. 3. In the immediate term, the regulatory approval will be more favourable since we are doing something about it, but because of the uncertainty we would have to set aside more money, therefore consequence costs would increase. 4. PAF material would be placed higher up in the MRS. Any acid generation and seepage would be delayed until it can flow through the rest of the MRS (possible 30+ years, and into the long-term). 5. Provides the opportunity to create a barrier / alkalinity / passivation during construction. 6. More oxygen and water management in the short-term would be required to prevent PAF oxidation that is now placed more at the top, contributing to consequence costs. 7. Not managing acidity generation as well we said we would. May need to add a cover system to control net percolation, to enable solubility controls. 8. Short term consquence cost likely at low end of major to account for a potential cover system. 9. Likely still treatment requirements in the long-term, leading to catastrophic consequence costs.
1		Short-term	L	Mi	L	Ma	M	Mi	L	L	M	
1		Long-term	L	Mo	M	C	M	Mi	L	M	M	
2	PAF materials incorrectly placed due to inaccurate static geochemical characterization and AMD Risk Classification in mine block model, leading to the Question	Immediate	M	Mi	M	Mo	M	Mi	M	L	M	1. Also consider applicable comments from Scenario 2A (conventional) FMEA. 2. Still making the effort to place NAF material near the outside of the MRS. 3. We would need to monitor internal gas concentration, temperatures, to demonstrate that we don't have additional gas moving in. We would have this data in the first 2-5 years. 4. We can adaptively change our construction of the layers based on this data to control oxygen. 5. Low confidence because it is a relatively "new" technology. There would need to be holistic modelling, commercial scale performance monitoring, field scale trials, etc. 6. We have done performance monitoring during operations and adapted how the MRS is being built based on the data. 7. Mitigation - Enhance the collection of recoverable seepage. 8. Mitigation - If the modelling were to show that there was high risk of oxidation if PAF material was placed near the front, then you can reduce lift height further. 9. Retroactively as part of closure, place NAF material on the front of the MRS, through wrapping the MRS and building up, or tipping over the edge and pushing it down. 10. Place a cover system to manage lateral gas transport. 11. These mitigations could be done in immediate or short-term. Immediate would be better to mitigate the risks in the most cost effective manner of placing material up front. 12. Another mitigation would be to just let it happen and enhance treatment capacity. 13. In short term, assume that we have executed a plan to mitigate this failure mode. 14. Assume that we have anywhere from 5-10x less acidity generated in the system through achieving >80% suboxia. 15. Assuming that in 20% of the oxic zones, we have to address the possibility that all PAF could be placed incorrectly. 16. Long-term consquence cost - there would be lower volumes / acidity to treat, so costs would be adjusted accordingly. 17. Building with shorter lift heights will typically be done by constructing from the bottom up. 18. We assume that we need to build from the bottom up to manage vertical gas transport. 19. There are other ways to achive vertical gas management (e.g., paddock dumping, lower air K layers on every layer). 20. Assumes that we will have active collect and treat systems during the operations phase. 21. Assumes that there is some generational time delay in the acceptance of these new technologies. There is low confidence at the moment from a regulatory point of view in "unproven" technologies. More commercial demonstration is needed to increase the confidence in these rankings.
2		Short-term	L	Mi	L	Mo	M	Mi	L	L	M	
2		Long-term	L	Mi	L	Mo	M	Mi	L	L	M	

Scenario 2B. Smaller lift heights / vertical gas management / bottom up

Question: What conditions could lead to the geochemical failure of the applied MRS construction method, whereby "failure" refers to inadequate spatial extent of suboxia conditions and/or increased treatment requirements.

Failure Mode ID	*Failure Mode Description*	*Timeframe*	*Likelihood*	*Consequences*						*Level of Confidence*	*Highest Risk Rating*	*Mitigation / Comments*
				Environment Effects		*Consequence Cost*		*Regulatory Approval*				
3	PAF materials incorrectly placed within the predicted zone of suboxia due to poor quality control for mine rock segregation and placement, leading to the Question	Immediate-Term	M	Mi	M	Mo	M	Mi	M	L	M	1. Using same assumptions as failure mode 1. 2. Incorrect placement should lead to the same consequences as inadequate static characterization (i.e., PAF material unexpectedly placed in oxic zones). 3. Assuming we have internal monitoring of gas concentrations, we can adaptively manage the placement to reduce the likelihood of this failure mode occurring beyond the immediate-term. 4. If we place the PAF out near the front of the MRS, the likelihood is higher. 5. Assumes that we have a high confidence of where that zone of suboxia extends to, and the geochemical characterization of the materials
3		Short-Term	L	Mi	L	Mo	M	Mi	L	L	M	
3		Long-Term	L	Mi	L	Mo	M	Mi	L	L	M	
4	Insufficient NAF materials available to achieve encapsulation, leading to the Question.	Immediate-Term			n/a		n/a		n/a			1. Failure mode does not apply to this scenario.
4		Short-Term			n/a		n/a		n/a			
4		Long-Term			n/a		n/a		n/a			
5	Inappropriate NAF materials available to achieve encapsulation, leading to the Question.	Immediate-Term			n/a		n/a		n/a			1. Failure mode does not apply to this scenario.
5		Short-Term			n/a		n/a		n/a			
5		Long-Term			n/a		n/a		n/a			
6	Insufficient NAF materials available to achieve adequate oxygen consumption, leading to the Question.	Immediate-Term			n/a		n/a		n/a			1. Failure mode does not apply to this scenario.
6		Short-Term			n/a		n/a		n/a			
6		Long-Term			n/a		n/a		n/a			
7	Inappropriate NAF materials available to achieve adequate oxygen consumption, leading to the Question.	Immediate-Term			n/a		n/a		n/a			1. Failure mode does not apply to this scenario.
7		Short-Term			n/a		n/a		n/a			
7		Long-Term			n/a		n/a		n/a			
8	NAF materials incorrectly placed due to inaccurate static geochemical characterization and AMD Risk Classification in mine block model, leading to the Question.	Immediate-Term			n/a		n/a		n/a			1. Failure mode does not apply to this scenario.
8		Short-Term			n/a		n/a		n/a			
8		Long-Term			n/a		n/a		n/a			
9	NAF materials incorrectly placed due poor-quality control for mine rock segregation and placement, leading to the Question.	Immediate-Term			n/a		n/a		n/a			1. Failure mode does not apply to this scenario.
9		Short-Term			n/a		n/a		n/a			
9		Long-Term			n/a		n/a		n/a			
10	MRS design does not meet performance expectations (e.g., inadequate extent of suboxia and/or longer time frame to achieve suboxia) due to incorrect modelling assumptions, methods, or design parameters leading to the Question	Immediate-Term	M	Mi	M	Mo	M	Mi	M	L	M	1. Using assumptions from failure mode 1. 2. If the modelling assumptions and design parameter were way off, it is possible that the Question could occur. 3. Depending on the magnitude or the incorrect parameters, long-term treatment costs could be quite high. 4. Mitigation: Refine modelling assumptions with monitoring data during construction, and update the construction appropriately. 5. Regulatory: we will have to demonstrate that these design conditions will work at the commercial scale, leading to a longer approvals stage.
10		Short-Term	L	Mi	L	Mo	M	Mi	L	L	M	
10		Long-Term	L	Mi	L	Ma	M	Mi	L	L	M	
11		Immediate-Term	M	Mi	M	Mo	M	Mi	M	L	M	1. Using assumptions from failure mode 1. 2. Short and long-term timeframes are less likely as issues arising from lack of modelling input should be rectified in the immediate-term. 3. Some modelling inputs may not be available until construction begins (immediate-term), which increases the

Scenario 2B. Smaller lift heights / vertical gas management / bottom up

Question: What conditions could lead to the geochemical failure of the applied MRS construction method, whereby “failure” refers to inadequate spatial extent of suboxia conditions and/or increased treatment requirements.

Failure Mode ID	***Failure Mode Description***	***Timeframe***	***Likelihood***	***Consequences*** *Environment Effects*		*Consequence Cost*		*Regulatory Approval*		***Level of Confidence***	***Highest Risk Rating***	***Mitigation / Comments***
11	MRS design does not meet performance expectations due to insufficient model input information / supporting data, leading to the Question	Short-Term	L	Mi	L	Mo	M	Mi	L	L	M	likelihood of the Question occurring due to this failure mode in the immediate-term. 4. Based on initial monitoring in the first few years, we will have the appropriate inputs for the last 75% of the MRS.
11		Long-Term	L	Mi	L	Ma	M	Mi	L	L	M	
12	MRS design does not meet performance expectations due to inadequate (i.e., not enough) static geochemical characterization and therefore AMD risk classification in mine block model, leading to the Question	Immediate-Term	M	Mi	M	Mo	M	Mi	M	L	M	1. Using assumptions from failure mode 1. 2. Construction method will ensure that, even if there is more PAF than expected, around 80% should remain suboxic, thereby making it less likely for the failure mode to cause the Question in the short and long-term. 3. A delay in suboxia in the immediate-term may make it more likely for the Question to occur.
12		Short-Term	L	Mi	L	Mo	M	Mi	L	L	M	
12		Long-Term	L	Mi	L	Mo	M	Mi	L	L	M	
13	MRS design does not meet performance expectations due to inadequate kinetic geochemical characterization, leading to the Question	Immediate-Term	M	Mi	M	Mo	M	Mi	M	L	M	1. Using assumptions from failure mode 1. 2. As in failure mode 4, suboxia in the short and long-term should mitigate mis-characterization of the geochemical kinetics. 3. In the immediate-term, faster acid generation or slower neutralization potential could lead to increased water treatment until suboxia can develop. 4. These mitigations that are being done in the immediate term to bring down the short and long term risks are site specific and will be evaluated further. (Apply this to all other FMs as well)
13		Short-Term	L	Mi	L	Mo	M	Mi	L	L	M	
13		Long-Term	L	Mi	L	Mo	M	Mi	L	L	M	
14	MRS design does not meet performance expectations due to inadequate or incorrect geotechnical characterization, leading to the Question	Immediate-Term	M	Mi	M	Mo	M	Mi	M	L	M	1. Using assumptions from failure mode 1. 2. Assuming geotechnical characterization refers to the material characterization of the engineering layers, and their PSD and packed densities and their subsequent ability to control air permeability and degree of saturation. 3. Mitigation: The mis-characterization will be rectified during construction. The likelihood of the failure mode causing the question in the short and long-term is therefore lower than the immediate-term. 4. If the on site materials for vertical gas management don't exist as expected, the immediate-term costs could be large. 5. We either have to find the materials on site, create the materials, or bring in the materials. These costs could be on the high end of the 10 - 50 million.
14		Short-Term	L	Mi	L	Mo	M	Mi	L	L	M	
14		Long-Term	L	Mi	L	Mo	M	Mi	L	L	M	
15	Engineered layers at top of lifts to manage vertical gas transport do not meet performance expectations due to inadequate or incorrect quality control and assurance during construction, leading to the Question	Immediate-Term	L	Mi	L	Mo	M	Mi	L	M	M	1. Using assumptions from failure mode 1. 2. As noted in failure mode 1, ongoing monitoring of gas concentrations will inform on performance. Adaptive management will mitigate this risk. 3. Likelihood of this occurring would be low in the immediate term, but will need to demonstrate a strong QCA program to regulators. 4. If the layers weren't constructed properly, it would require higher treatment costs or a cover system to mitigate in the long term. 5. This would be an opportunity to include a passivation layer at closure. 6. A note to add to all other FMs - if the regulators do not require additional permitting for the conventional scenario, then why would they hold the process up with these improved technologies.
15		Short-Term	M	Mi	M	Mo	M	Mi	M	M	M	
15		Long-Term	M	Mi	M	Ma	H	Mi	M	M	H	
16	Engineered layers at top of lifts to manage vertical gas transport do not meet performance expectations due to insufficient material availability, leading to the Question	Immediate-Term	M	Mi	M	Mo	M	Mi	M	M	M	1. Using assumptions from failure mode 1. 2. Insufficient material availability could strongly impact the development of suboxia. 3. It would be important to continue ongoing studies during construction to ensure enough materials are available for the duration of construction to mitigate this risk. 4. The consequence costs of creating or bringing in more material to manage gas transport would be large.
16		Short-Term	M	Mi	M	Mo	M	Mi	M	M	M	

Scenario 2B. Smaller lift heights / vertical gas management / bottom up

Question: What conditions could lead to the geochemical failure of the applied MRS construction method, whereby “failure” refers to inadequate spatial extent of suboxia conditions and/or increased treatment requirements.

Failure Mode ID	Failure Mode Description	Timeframe	Likelihood	Consequences						Level of Confidence	Highest Risk Rating	Mitigation / Comments
				Environment Effects		Consequence Cost		Regulatory Approval				
16		Long-Term	M	Mi	M	Ma	H	Mo	M	M	H	
17	MRS design does not meet performance expectations (e.g., inadequate extent of suboxia and/or longer time frame to achieve suboxia) due to small-scale geotechnical stability failure of the landform leading to the Question	Immediate-Term	M	Mi	M	Mo	M	Mi	M	L	M	1. Using assumptions from failure mode 1. 2. Low confidence because we are uncertain how stability issues would impact these relatively new constructions methods. 3. Small-scale slope failures could lead to localized oxic zones, thereby decreasing performance. 4. Treatment costs, plus potential slope repair costs to re-estabilish suboxia increase the consequence costs. 5. Due to limited experience, there is low confidence in this ranking and a stability analysis would be required. 6. This could occur due to consumption of carbonates due to acid generation which could result in slumping. 7. Heavy rainfall or erosion could also lead to small scale slope failure.
17		Short-Term	L	Mi	L	Mo	M	Mi	L	L	M	
17		Long-Term	VL	Mi	L	Mo	L	Mi	L	L	L	
18	MRS design does not meet performance expectations due to large-scale geotechnical stability failure of the landform leading to the Question	Immediate-Term	L	Mo	M	Mo	M	Mo	M	L	M	1. Using assumptions from failure mode 1. 2. Large-scale stability failure would compromise the suboxia conditions greatly. 3. Treatment would like be needed to be implemented quickly, at great cost. 4. Due to limited experience, there is low confidence in this ranking and a stability analysis would be required.
18		Short-Term	VL	Ma	L	Mo	L	Mo	L	L	L	
18		Long-Term	VL	Ma	L	Ma	L	Mo	L	L	L	
19	Incomplete coverage of alkalinity generating material over surface of MRS, leading to the question.	Immediate-Term			n/a		n/a		n/a			1. Failure mode does not apply to this scenario.
19		Short-Term			n/a		n/a		n/a			
19		Long-Term			n/a		n/a		n/a			
20	PAF materials incorrectly placed outside the predicted zone of suboxia due poor quality control for waste rock segregation and placement, leading to… the Question	Immediate-Term	H	Mi	M	Mo	H	Mi	M	L	H	
20		Short-Term	H	Mi	M	Ma	H	Mi	M	L	H	
20		Long-Term	H	Mi	M	C	VH	Mi	M	L	VH	

Scenario 2C. Use of 6 MRS improved construction technologies: Smaller lift height, air disruption layers, bottom-up, encapsulation (NAF around PAF), oxygen consuming materials (NAF around PAF), alkalinity releasing materials for pyrite passivation (top of MRS or PAF)

Question: What conditions could lead to the geochemical failure of the applied MRS construction method, whereby "failure" refers to inadequate spatial extent of suboxia conditions and/or increased treatment requirements.

Failure Mode ID	***Failure Mode Description***	***Timeframe***	***Likelihood***	*Consequences: Environment Effects*		*Consequences: Consequence Cost*		*Consequences: Regulatory Approval*		***Level of Confidence***	***Highest Risk Rating***	***Mitigation / Comments***
1	Problematic schedule of PAF/NAF delivery to MRS, leading to the Question.	Immediate	L	Mi	L	Mi	L	Mi	L	L	L	1. Assume same setting as Scenario 2A. 2. We are now selectively placing materials. 3. When the MRS is built, the PAF material has been managed through encapsulation, oxygen consuming materials, etc. 4. Many facets to this construction leading to low level of confidence.
1		Short-term	L	Mi	L	Mo	M	Mi	L	L	M	
1		Long-term	VL	Mo	L	C	M	Mi	L	L	M	
2	PAF materials incorrectly placed due to inaccurate static geochemical characterization and AMD Risk Classification in mine block model, leading to the Question	Immediate	M	Mi	M	Mo	M	Mi	M	L	M	1. Relying on NAF/PAF placement for encapsulation and oxygen consumption. 2. Immediate term consequences would not change from 2B. 3. From the beginning, doing monitoring to locate potential problem areas. 4. In the short-term, the pyrite passivation will start to kick in and reduce consequence cost. 5. In previous sites, there have been a minimum of a 50% reduction in acidity (in small-scale dumps). 6. Two of the three additions to 2C rely on knowing your PAF/NAF placement. 7. Long-term consequences costs are assumed to be on the high-end of minor, assuming that pyrite passivation takes full effect. 8. Note that the sloping geometry of the MRS will add to the difficulty / cost of pyrite passivation.
2		Short-term	L	Mi	L	Mi	L	Mi	L	L	L	
2		Long-term	L	Mi	L	Mi	L	Mi	L	L	L	
3	PAF materials incorrectly placed within the predicted zone of suboxia due to poor quality control for mine rock segregation and placement, leading to the Question	Immediate-Term	M	Mi	M	Mo	M	Mi	M	L	M	1. Same comments as FM#2, we are relying on passivation to control water quality.
3		Short-Term	L	Mi	L	Mi	L	Mi	L	L	L	

Scenario 2C. Use of 6 MRS improved construction technologies: Smaller lift height, air disruption layers, bottom-up, encapsulation (NAF around PAF), oxygen consuming materials (NAF around PAF), alkalinity releasing materials for pyrite passivation (top of MRS or PAF)

Question: What conditions could lead to the geochemical failure of the applied MRS construction method, whereby “failure” refers to inadequate spatial extent of suboxia conditions and/or increased treatment requirements.

Failure Mode ID	***Failure Mode Description***	***Timeframe***	***Likelihood***	***Consequences***						***Level of Confidence***	***Highest Risk Rating***	***Mitigation / Comments***
				Environment Effects		*Consequence Cost*		*Regulatory Approval*				
3		Long-Term	L	Mi	L	Mi	L	Mi	L	L	L	
4		Immediate-Term	M	Mi	M	Mo	M	Mi	M	L	M	1. This will make relying on encapsulation and oxygen consuming materials difficult. 2. If you know about the lack of NAF, consequence costs would increase in the immediate term to make up for the lack of NAF material, but not necessarily into the next cost bracket. 3. Again, assuming that passivation will manage water quality in the short and long term. 4. Also relying on the technologies implemented in 2B.
4	Insufficient NAF materials available to achieve encapsulation, leading to the Question.	Short-Term	L	Mi	L	Mi	L	Mi	L	L	L	
4		Long-Term	L	Mi	L	Mi	L	Mi	L	L	L	
5		Immediate-Term	M	Mi	M	Mo	M	Mi	M	L	M	1. Physical properties (e.g., too coarse textured) are not appropriate for controlling oxygen as an encapsulation layer, allowing oxygen into the PAF material. 2. Potential opportunity to manufacture a finer-textured material to reduce air permeability by adding water retention capacity, at an increased expense. 3. Less of a consequence cost of having to manufacture on site, rather than have insuffucient materials as in FM#4. 4. Material is still appropriate for oxygen consumption. 5. Also relying on the technologies implemented in 2B.
5	Inappropriate NAF materials available to achieve encapsulation, leading to the Question.	Short-Term	L	Mi	L	Mi	L	Mi	L	L	L	
5		Long-Term	L	Mi	L	Mi	L	Mi	L	L	L	
6		Immediate-Term	M	Mi	M	Mo	M	Mi	M	L	M	1. Relying on passivation and encapsulation. 2. Also relying on the technologies implemented in 2B.
6	Insufficient NAF materials available to achieve adequate oxygen consumption, leading to the Question.	Short-Term	L	Mi	L	Mi	L	Mi	L	L	L	
6		Long-Term	L	Mi	L	Mi	L	Mi	L	L	L	
7		Immediate-Term	M	Mi	M	Mo	M	Mi	M	L	M	1. Have inert NAF materials which do not consume oxygen (i.e., low or no sulfide) 2. Relying on passivation and encapsulation. 3. Also relying on the technologies implemented in 2B.
7	Inappropriate NAF materials available to achieve adequate oxygen consumption, leading to the Question.	Short-Term	L	Mi	L	Mi	L	Mi	L	L	L	

Scenario 2C. Use of 6 MRS improved construction technologies: Smaller lift height, air disruption layers, bottom-up, encapsulation (NAF around PAF), oxygen consuming materials (NAF around PAF), alkalinity releasing materials for pyrite passivation (top of MRS or PAF)

Question: What conditions could lead to the geochemical failure of the applied MRS construction method, whereby "failure" refers to inadequate spatial extent of suboxia conditions and/or increased treatment requirements.

Failure Mode ID	***Failure Mode Description***	***Timeframe***	***Likelihood***	***Consequences***						***Level of Confidence***	***Highest Risk Rating***	***Mitigation / Comments***
				Environment Effects		*Consequence Cost*		*Regulatory Approval*				
7		Long-Term	L	Mi	L	Mi	L	Mi	L	L	L	
8	NAF materials incorrectly placed due to inaccurate static geochemical characterization and AMD Risk Classification in mine block model, leading to the Question.	Immediate-Term	M	Mi	M	Mo	M	Mi	M	L	M	1. Equivalent to incorrect PAF placement. Relying on oxygen consumption / air-entry restriction, that will not occur. 2. Relying on passivation and 2B technologies.
8		Short-Term	L	Mi	L	Mi	L	Mi	L	L	L	
8		Long-Term	L	Mi	L	Mi	L	Mi	L	L	L	
9	NAF materials incorrectly placed due poor-quality control for mine rock segregation and placement, leading to the Question.	Immediate-Term	M	Mi	M	Mo	M	Mi	M	L	M	1. Relying on passivation and 2B technologies.
9		Short-Term	L	Mi	L	Mi	L	Mi	L	L	L	
9		Long-Term	L	Mi	L	Mi	L	Mi	L	L	L	
10	MRS design does not meet performance expectations (e.g., inadequate extent of suboxia and/or longer time frame to achieve suboxia) due to incorrect modelling assumptions, methods, or design parameters leading to the Question	Immediate-Term	M	Mi	M	Mo	M	Mi	M	L	M	1. In the immediate-term, the pyrite passivation will not be available to mitigate any consequences. 2. Assumes that because the design does not meet performance expectation, the 2B technologies aren't able to mitigate failure like in the previous failure modes. 3. Passivation will be slow to act, and improvements in the short-term would be minimal. 4. If performance is not being bet, passivation unlikely to provide a significant enough improvement in the long-term.
10		Short-Term	L	Mi	L	Mo	M	Mi	L	L	M	
10		Long-Term	L	Mi	L	Ma	M	Mi	L	L	M	
11	MRS design does not meet performance expectations due to insufficient model input information / supporting data, leading to the Question	Immediate-Term	M	Mi	M	Mo	M	Mi	M	L	M	1. Same comments as FM#10. 2. Passivation would give some improvement short-term, but unlikely to move the needle to a lower bracket.
11		Short-Term	L	Mi	L	Mo	M	Mi	L	L	M	

Scenario 2C. Use of 6 MRS improved construction technologies: Smaller lift height, air disruption layers, bottom-up, encapsulation (NAF around PAF), oxygen consuming materials (NAF around PAF), alkalinity releasing materials for pyrite passivation (top of MRS or PAF)

Question: What conditions could lead to the geochemical failure of the applied MRS construction method, whereby “failure” refers to inadequate spatial extent of suboxia conditions and/or increased treatment requirements.

Failure Mode ID	*Failure Mode Description*	*Timeframe*	*Likelihood*	*Consequences*						*Level of Confidence*	*Highest Risk Rating*	*Mitigation / Comments*
				Environment Effects		*Consequence Cost*		*Regulatory Approval*				
11		Long-Term	L	Mi	L	Ma	M	Mi	L	L	M	
12	MRS design does not meet performance expectations due to inadequate (i.e., not enough) static geochemical characterization and therefore AMD risk classification in mine block model, leading to the Question	Immediate-Term	M	Mi	M	Mo	M	Mi	M	L	M	1. Assuming we have a large zone of suboxia (around 80% of the total volume of the MRS). 2. Assuming encapsulation / and O2 consumption is not optimized. 3. Relying on passivation. 4. For this and other FM that rely on passivation, need to consider the difficulties of application on slopes and uncertainties of how much alkalinity it needed. Need to capture that this method needs to be used alongside other methods.
12		Short-Term	L	Mi	L	Mo	M	Mi	L	L	M	
12		Long-Term	L	Mi	L	Mo	M	Mi	L	L	M	
13	MRS design does not meet performance expectations due to inadequate kinetic geochemical characterization, leading to the Question	Immediate-Term	M	Mi	M	Mo	M	Mi	M	M	M	1. If everything is placed in the correct place (effective encapsulation / oxygen consumption), there is little risk of this occurring. 2. Confidence would actually go up because we are taking out the uncertainty of our kinetic geochemical characterization. 3. Inadequate kinetic characterization could lead to a miscalculation of required oxygen consuming thickness.
13		Short-Term	L	Mi	L	Mo	M	Mi	L	M	M	
13		Long-Term	L	Mi	L	Mo	M	Mi	L	M	M	
14	MRS design does not meet performance expectations due to inadequate or incorrect geotechnical characterization, leading to the Question	Immediate-Term	M	Mi	M	Mo	M	Mi	M	L	M	1. The texture of oxygen consuming layers or encapsulation layers will be affected by a mis-characterization of the physical properties (e.g., lower water retention capacity). 2. Encapsulation cells could be built too large if oxygen is able to move through more easily, reducing the effectiveness. 3. In oxygen consumption layers, possibility of consuming sulfide too fast. 4. Despite being a geochemical solution, the geotechnical aspect is also important in the success of those methods.
14		Short-Term	L	Mi	L	Mo	M	Mi	L	L	M	
14		Long-Term	L	Mi	L	Mo	M	Mi	L	L	M	
15	Engineered layers at top of lifts to manage vertical gas transport do not meet performance expectations due to inadequate or incorrect quality control and assurance during construction, leading to the Question	Immediate-Term	L	Mi	L	Mo	M	Mi	L	M	M	1. Provides the opportunity for the encapsulation, oxygen consumption, and passivation to mitigate risks.
15		Short-Term	L	Mi	L	Mo	M	Mi	L	M	M	

Scenario 2C. Use of 6 MRS improved construction technologies: Smaller lift height, air disruption layers, bottom-up, encapsulation (NAF around PAF), oxygen consuming materials (NAF around PAF), alkalinity releasing materials for pyrite passivation (top of MRS or PAF)

Question: What conditions could lead to the geochemical failure of the applied MRS construction method, whereby “failure” refers to inadequate spatial extent of suboxia conditions and/or increased treatment requirements.

Failure Mode ID	Failure Mode Description	Timeframe	Likelihood	Consequences						Level of Confidence	Highest Risk Rating	Mitigation / Comments
				Environment Effects		Consequence Cost		Regulatory Approval				
15		Long-Term	L	Mi	L	Mo	M	Mi	L	M	M	
16	Engineered layers at top of lifts to manage vertical gas transport do not meet performance expectations due to insufficient material availability, leading to the Question	Immediate-Term	L	Mi	L	Mo	M	Mi	L	M	M	1. Provides the opportunity for the encapsulation, oxygen consumption, and passivation to mitigate risks.
16		Short-Term	L	Mi	L	Mo	M	Mi	L	M	M	
16		Long-Term	L	Mi	L	Mo	M	Mi	L	M	M	
17	MRS design does not meet performance expectations (e.g., inadequate extent of suboxia and/or longer time frame to achieve suboxia) due to small-scale geotechnical stability failure of the landform leading to the Question	Immediate-Term	M	Mi	M	Mo	M	Mi	M	L	M	1. New technologies unlikely to improve the situation.
17		Short-Term	L	Mi	L	Mo	M	Mi	L	L	M	
17		Long-Term	VL	Mi	L	Mo	L	Mi	L	L	L	
18	MRS design does not meet performance expectations due to large-scale geotechnical stability failure of the landform leading to the Question	Immediate-Term	L	Mo	M	Mo	M	Mo	M	L	M	1. New technologies unlikely to improve the situation.
18		Short-Term	VL	Ma	L	Mo	L	Mo	L	L	L	
18		Long-Term	VL	Ma	L	Ma	L	Mo	L	L	L	
19	Incomplete coverage of alkalinity generating material over surface of MRS, leading to the question.	Immediate-Term	VL	I	L	Mi	L	I	L	M	L	1. Assumes 5 of 6 technologies are working properly. 2. In the immediate-term, alkalinity bearing materials will be placed on flat surfaces. 3. This is a supporting technology. 4. Note to self: make sure highest risk ranking column is corrected.
19		Short-Term	VL	I	L	Mi	L	I	L	M	L	

Scenario 2C. Use of 6 MRS improved construction technologies: Smaller lift height, air disruption layers, bottom-up, encapsulation (NAF around PAF), oxygen consuming materials (NAF around PAF), alkalinity releasing materials for pyrite passivation (top of MRS or PAF)

Question: What conditions could lead to the geochemical failure of the applied MRS construction method, whereby "failure" refers to inadequate spatial extent of suboxia conditions and/or increased treatment requirements.

Failure Mode ID	Failure Mode Description	Timeframe	Likelihood	Consequences: Environment Effects		Consequences: Consequence Cost		Consequences: Regulatory Approval		Level of Confidence	Highest Risk Rating	Mitigation / Comments
19		Long-Term	VL	I	L	Mi	L	I	L	M	L	

APPENDIX D

Additional Improved MRS Construction Methods not Evaluated in this Study

The improved MRS construction methods outlined in the previous sections include those methods that have at least been demonstrated in the field at a small to large scale. New technologies continue to be devised as new knowledge is obtained on the physical, chemical and mineralogical behaviour of waste materials and MRS. Those technologies that remain at the laboratory assessment stage have not been included in the methods assessed in this report. A brief summary is provided below on the thinking that is shaping these evolving MRS construction technologies.

Controlling Secondary Mineral Formation to Lower Acidity Loads

As sulfidic minerals decompose in the presence of atmospheric O_2, the acid that they produce routinely reacts with common rock forming minerals such as micas, feldspars, chlorite, amphiboles and pyroxenes, and is partially neutralised in the process. This often results in the formation of secondary sulfate-bearing, acidity-storing minerals. Most of the methods discussed in previous sections will enhance silicate neutralisation and therefore increase the production of secondary, acidity storing minerals. At legacy mine sites in excess of 100 years old, up to 50% of the acidity loads can actually be derived from secondary, acidity storing, non-sulfide minerals.

The most common secondary acidity storing mineral at most mine sites is jarosite ($KFe_3(SO_4)_2(OH)_6$). It is formed by routine reactions such as Reaction D.1 below:

$$3\,FeS_2 + 15/2\,O_2 + 9\,H_2O + KAl_3Si_3O_{10}(OH)_2 = KFe_3(SO_4)_2(OH)_6 + 3/2\,Al_2Si_2O_5(OH)_4 + 8\,H^+ + 4\,SO_4^{2-} \quad (D.1)$$

pyrite + oxygen + water + muscovite = jarosite + kaolinite + acid + sulfate ions

In this reaction, approximately 8.5% of the acid is neutralised by the muscovite (white mica / sericite) and 25% of the acidity that pyrite oxidation can create is stored in the jarosite precipitate. The abundance of either muscovite or k-feldspar makes this reaction very widespread in mineralised waste on a global basis. The low pH and high redox state of most ARD / AMD ensures that Fe^{3+} remains stable, thereby facilitating the formation of jarosite.

Reaction D.2 below shows that subsequent dissolution of jarosite in water can release the stored acidity. 1.5 moles of acid is released for every mole of jarosite dissolved, and this acidity generating reaction is no longer O_2 sensitive.

$$2\,KFe_3(OH)_6(SO_4)_2 + 6\,H_2O = 6\,Fe(OH)_3 + 2\,K^+ + 6\,H^+ + 4\,SO_4^{2-} \quad (D.2)$$

jarosite + water = ferrihydrite precipitate + potassium ions + acid + sulfate ions

There are only limited geochemical environments where jarosite remains unable to form. In such environments, its aluminium bearing equivalent (alunite: $KAl_3(SO_4)_2(OH)_6$) often forms, such as via the following reaction:

$$2\,FeS_2 + 9\,O_2 + 2\,H_2O + 2\,CH_2O + 2\,KAl_3Si_3O_{10}(OH)_2 = 2\,KAl_3(SO_4)_2(OH)_6 + 2\,FeCO_3 + 6\,SiO_2 \quad (D.3)$$

pyrite + oxygen + water + organic matter + muscovite = alunite + siderite + quartz

This reaction shows that in the presence of a reducing material, such as some form of organic matter, ferrous iron (aqueous Fe^{2+}) remains stable. In the absence of ferric iron (Fe^{3+}), jarosite cannot form. The benefit of forming alunite over jarosite is that the solubility of alunite is close to an order of magnitude less soluble than jarosite. Hence, any additive to the MRS than can promote or enhance reducing conditions can significantly lower acidity release rates from mine wastes. The primary challenge in this process is to utilise an organic matter compound that matches the life expectancy of the sulfide oxidation process (ie. 200-1,000 years). Whilst most forms of organic matter will only persist for up to a few years, more refractory carbon compounds are available, some natural and some anthropogenic.

In combination with MRS construction practices that enhance silicate neutralisation (ie. retard fluid and O_2 flow), the engineered formation of alunite over jarosite should offer major reductions in acidity release from mine wastes, particularly as they age.

Field evidence supporting this strategy is provided by exposures of Mt. McRae Shale in the Pilbara. The primary lithology is comprised of quartz, muscovite, pyrite and bituminous (apparently bioavailable) carbon. Oxidation of this lithology of geological time frames produces alunite-quartz rocks (up to 50 wt.% alunite), rather than jarosite-quartz rocks, as the bituminous carbon is predicted to prevent the formation of Fe^{3+}, which thereby favours alunite formation. Some other non-carbonaceous pyritic lithologies permit the formation of jarosite. There is negligible acidic drainage release from large wallrock exposures of alunite-quartz (weathered Mt. McRae Shale) lithologies, supporting the benefits of this proposed management measure.

Biochar Addition for Sustained ARD / AMD Abatement

The concept of using organic matter to maintain reducing conditions within mine wastes, thereby improving the stability of sulfides, or to consume O_2 before it can enter mine wastes, also designed to retard sulfide oxidation, has been widely trialled. In general, both of these techniques are logical and technically sound and have often proven to be temporarily successful. The key limitation to the long-term success of this approach is believed to be the discrepancy between the rate at which most forms of carbon decompose and the rate at which sulfides (principally pyrite) decompose. The bacterial oxidation of carbon, in most of its forms, in the presence of sufficient water, is on the order of weeks to months (eg. compost) to a few years (eg. woody waste, paper waste). Under such circumstances, unless the form of carbon addition is regularly re-applied, then it cannot last for the typical duration of sulfide oxidation (ie. 200-1,000 years). As routine intimate mixing of compost with mine rock is not possible post closure, and not economically viable even if were possible, then suitable alternative carbon compounds need to be identified.

Recent research by Earth Systems quantified that high temperature biochar material (produced by the pyrolysis of woody waste and other biomass) can take at least 1,000 years to decompose to CO_2. Such materials could be generated at many mine sites from local woody materials, packaging materials (eg. pallets), sewage sludge, spent activated carbon and possibly even tyre wastes.

The strategic blending of biochar with mine wastes, based on their reactive sulfide concentration and sulfide oxidation half-life, is predicted to assist with maintaining reducing conditions, partly due to the presence of organic carbon and partly due to the local consumption of O_2 by the biochar. Both of these processes should retard the rate of acidity generation from treated wastes.