Linking waste rock dump construction and design with seepage geochemistry: an integrated approach using quantitative tools

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Abstract

The characterisation and assessment of waste rock has been the subject of considerable research and many guidance documents have been published internationally. While these documents provide detailed information on the technical aspects of geochemical characterization of waste rock, there is not great detail into how to integrate these studies into engineering planning decisions around waste management options. These planning decisions require quantitative assessment to balance environmental management (risk) and operational constraints (cost). For example what is the risk/cost tradeoff for using different placement methods e.g. end tipping vs paddock dumping. Because current industry practice and the majority of guidance documentation focuses on only geochemical classification, there is a disconnect between the outputs of the studies and the operational requirements for a direct assessment of placement method such that risk and cost can be quantitatively assessed.

Defining the contributing factors to the risk/cost tradeoff posed by disposal of waste based on a specific waste management approach requires a broader technical assessment approach and directs these assessments towards a semi-qualitative and quantitative methodology. Quantitative methodologies show an increase in the confidence of these assessments by providing logical, measureable assessments.

To address the need for a qualitative risk/cost tradeoff assessment approach OKC has developed an assessment process based around a quantitative risk tool. This tool captures multifaceted inputs, and employs an analytical model to provide quantitative analysis and outputs. This method of assessment allows risk to be assessed on the basis of waste placement technique, and whole waste facility engineering design, and not just on material properties such as geochemical characteristics in isolation. It also allows assessment of the benefit of progressive management measures as compared to deferring to final closure solutions such as covers.

Key words: Toe seepage, gas flux, sulfide oxidation rate

Introduction

The characterisation and assessment of waste rock forms the initial stage of waste management strategy planning. Prior to decision making, waste management strategies should evaluate both costs of waste management and risks associated with the exposure, stockpiling and placement of waste materials, such as spontaneous combustion, toxic gas production, and acid and metalliferous drainage (AMD). These risks are complex, are all interrelated, and are associated with air and water entry into the waste material where subsequent oxidation reactions occur (Lottermoser, 2010).

It has become common practice in the industry as part of waste characterisation to classify material in a deterministic manner on the basis of primarily geochemical risk factors and to define material types, for example, as potential acid forming (PAF). Material that is determined to pose significant risks of AMD such as PAF is then prescribed a specific management method such as "encapsulation" as part of a placement strategy to reduce potential AMD risks. However this method of assessment is prescriptive and polarised as materials are categorised into a few catch all categories such as PAF, which in turn results in polarised decisions such as all PAF must be managed in a set manner.

In the field AMD risks are known to be complex and interrelated and are strongly related to the structure of the waste and how this influences oxygen ingress and water flow into the waste pile, where subsequent oxidation reactions can occur (Javadi et al, 2012, Lottermoser, 2010). The influence of airflow, water infiltration and flow, and the site specific diurnal or seasonal variations in these are likely to be key risk drivers.

General factors that are known to control AMD risks are detailed in Pearce et al (2015) and include:

- Geometry of waste dump including footprint, height, slope area
- Sulfide and carbon content of material;
- Physical properties of material (grain size and distribution, saturation, weathering rate);
- Geochemical properties of material (intrinsic oxidation rates, carbonate dissolution rates, kinetically controlled metal/non metal release rate)
- Timing of waste placement and any closure mitigation engineering solution (such as a cover)
- Structure of waste rock due to placement (pathways for air and water movement); and
- Climate (temperature and rainfall).

Geochemistry forms only one of these risk factors, however it is interesting to note that typical industry approach to AMD assessments is for the study to be based for the most part on laboratory testing related to geochemical properties only. While these geochemistry based assessments are robust, they are essentially just methods to classify and categorize materials based on the results of tests carried out in laboratory conditions. The use of laboratory kinetic leach column data for example, although considered to be the gold standard to estimate field estimates of sulfide oxidation rates and seepage quality, requires careful consideration when extrapolating to field conditions. This is because scaling factors will considerably impact the validity of the results (Pearce et al 2015).

A simple summary of these observations is to state that although the characterisation of materials is important, the method and timing of placement, and the site environment in which they are placed are perhaps more important variables, and are often disregarded.

In order to evaluate risk based on multifaceted variables requires application of semi quantitative analysis such as the operation of an analytical model. OKC has developed an assessment process based around a risk matrix that captures these multifaceted inputs and employs an analytical model to provide semi quantitative analysis and outputs. This method of assessment allows risk to be assessed on the basis of placement technique and not just on material geochemical properties in isolation. A full description of this method is outside the scope of this paper and is described in detail in Pearce et al (2015). In summary the assessment process based around a quantitative risk assessment tool that utilises a series of complex algorithms to "model" how waste materials will react to placement in a given scenario. Outputs from this model are then collated into a risk matrix that captures these multifaceted inputs. This method of assessment allows risk to be assessed on the basis of placement technique, and incorporation of closure mitigation solutions and not just on material properties in isolation.

The analytical model developed evaluates convective gas transport, intrinsic oxidation rate (pyrite and carbon) spontaneous combustion, seepage, carbonate dissolution rate and acidity generation. The analytical model is a one dimensional, quasi-steady state model

Method

Waste rock dump construction and link to AMD seepage risks

Construction of waste dumps is mainly based on one of the following methods; end-tipping, paddock dumping, push-dumping, or encapsulation. The specific method used on a given site to construct a landform is generally based on availability of equipment, cost and the scale of construction and so construction methods are far from uniform across all sites. Aspects of WRD construction that relate to AMD risk (that are commonly overlooked) are the internal structure created as a consequence of the prevalence of end tipping material, and the resulting hydro-geological characteristics which control air (oxygen) and water flux throughout the waste material (Wilson 2011). Given that oxygen and water flux are major controls in the production and release of AMD to the receiving environment, construction is clearly a very signicant variable to factor into AMD risk.

Work by Wilson (2011) and Pearce (2014) shows that for end tipped waste oxygen ingress will primarily occur at the bottom of the pile with gas flux being into the toe and basal rubble zone of the waste pile moving upwards through the free draining course material layers by the process of thermal advection. Vapour flux also occurs along with gas flux and is an important aspect of the overall redistribution of water within the waste, and moisture loss from waste masses, the process is termed advective drying and is described by Pearce (2014). This conceptual internal structure of WRDs constructed by the common practice of end dumping is an ideal scenario for the production of AMD given the ample supply of atmospheric oxygen and water.

Figure 1 shows an example of waste being placed by paddock dumping, and end-tipping. Co-disposal of material is clearly visible from the rock types at this site, and material segregation through end-tipping is visible between the base and the top of the tip head. A cross section through an end tipped waste rock dump is shown in Figure 1 that depicts schematically the internal structure that results from the end tipping process as a result of particle segregation. The segregation of material as shown in Figure 1 has been confirmed by WRD excavations in the work of Wilson (2011), and drilling of multiple waste rock dumps Pearce et al (2014).

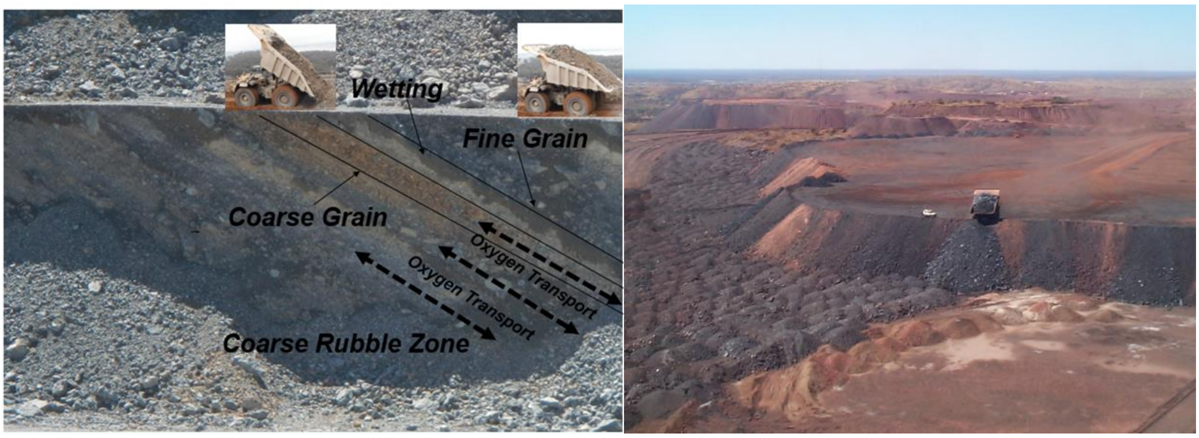

Figure 1 *Internal dump structure after Pearce et al (2016)*

The structure of the WRD will then dictate variables that directly control risks with respect to AMD due to the nature of material segregation. These features will have a direct influence on:

- Gas flux (oxygen ingress);
- Water flux (net percolation rates and vapour phase transport);
- Erosion and stability;

Conceptual model for seepage quality assessment from waste rock storage facilities

With respect to making quantitative predictions about future seepage quality that may discharge from a waste rock dump the key processes that will drive quality over time relate to the relative flux rates of gas, water and vapour through the waste as well as the properties of the waste itself. If the waste contains reactive material such as sulfides or organic carbon then the relative oxidation rate of these materials over time will be a key control on potential seepage loading. In conjunction with the oxidation rate, the relative rate of seepage through the waste over time will dictate seepage load and quality. These processes are interlinked to a high degree as shown by scenarios in Table 1. The scenarios shown are similar and involve the same material type in all cases, however one other key variable is changed in each scenario. Even though the material is the same in each scenario the seepage quality and load are significantly different in each scenario, thus the impact of changing variables other than material type is clearly significant.

It is clear from this scenario based conceptual level of analysis, that focusing on the waste classification in isolation is not a sufficient means to determine AMD risk and seepage quality (and to determine appropriate management strategies).

***Table 1** Waste rock dump construction controls on seepage quality*

Scenario	Waste material type	Construction method	Climate	Gas flux	Seepage flux	Seepage quality and load predictions
Solubility control	Pyritic black shale S>1%	End tipping	Semi arid	Very high	Very low, L:S ratios <0.1 per year	Very high loads and high AMD concentrations for decades
Oxygen limited	Pyritic black shale S>1%	Paddock dumping	Semi arid	Low	Very low L:S ratio <0.1 per year	High concentrations and loads for short period of time, low total loads
Well flushed	Pyritic black shale S>1%	Paddock dumping	tropical	Low	High	Low concentrations and loads

Figure 2 shows schematically the interrelated physical processes related to water and gas flux that are required to be assessed quantitatively to determine seepage quality. As well as the variables shown the climate of the site will be an over-arching variable that will influence these physical processes.

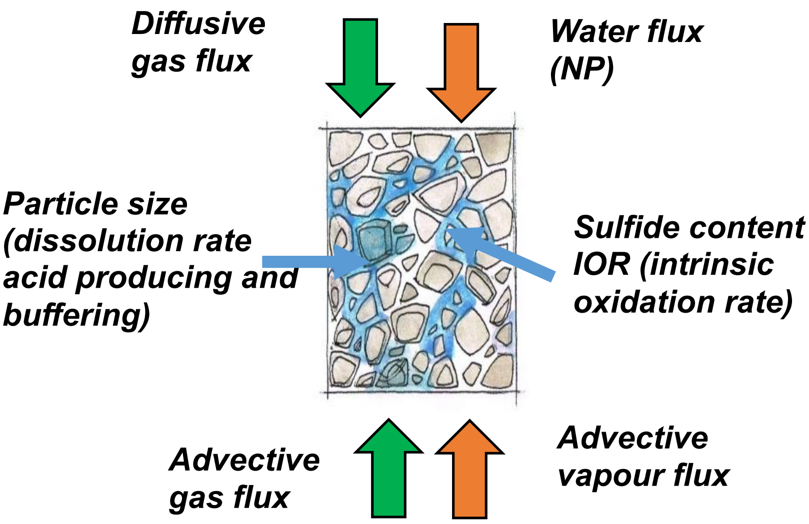

***Figure 2** Conceptual model showing controls on seepage quality*

The fluxes shown in Figure 2 are subject to significant temporal variability due to the nature of unsaturated zone hydrology. Material is generally placed in an unsaturated state and will over time move to an equilibrium state that is semi or fully saturated state. During this process the flux of water and gas through the pore spaces will occur at rates that vary on a relative basis over time. It is this relative nature of the flux rates that is the key concept that requires to be understood to explain the significant differences in seepage quality outcomes that can result from placement of the same material in a different manner (as shown in table 1).

It is beyond the scope of this paper to provide a detailed technical overview of all the contributing factors shown in Figure 1 and how they can be considered as part of the quantitative assessment method. Gas flux is considered in some detail herein however as an example of how these fluxes can be quantified and because this forms probably the most significant risk driving variable.

Gas flux

Convective transport of oxygen into waste rock is the dominant mechanism supplying oxygen to oxidation sites; and air convection driven by temperature gradients and partial pressure differentials are much more effective at transporting oxygen than diffusion processes in WRDs (Brown et al., 2014). To determine the effects of waste rock structure as a result of varying construction method has on gas flux potential in a qualitative manner, a waste rock management factor approach is described in Pearce (2015). A sliding scale was developed as part of this conceptual work to compare a well-constructed WRD, where oxygen is limited and the intrinsic oxidation rate (IOR) is decreased by another order of magnitude, and a poorly constructed WRD, where the IOR remains unchanged. A waste rock management factor (WRMF) was proposed ranging from 0.1 to 1.0.

- The WRMF is 0.1 for a well-constructed OSA that minimises tip height; uses paddock and push-dumping methods and has minimal fines segregation, preventing the formation of a basal rubble layer; and compacts lifts in 1 m to 2 m intervals.
- The WRMF is 1.0 for a poorly constructed waste rock dump that has a well-developed basal rubble zone and a strong segregation of coarse- and fine-textured materials.

A WRMF of 0.1 could also represent a WRD where diffusion is the dominant transport mechanism for oxygen into the WRD; a WRMF of 1.0 could represent a WRD where convection is the dominant. This simple sliding scale allows qualitative assessment of various waste placement techniques with respect to influence on gas flux and thus indicates an upper limit for oxidation rates (proxy for AMD risk).

Quantifying gas flux rates based on construction method

To take the assessment of gas flux further Pearce et al (2016) used extensive site monitoring data and detailed drill core analysis from a large scale waste rock dump drilling program to link temperature data and oxygen concentrations with gas fluxes, within actively monitored waste dumps. OKC have published the results of the large scale drilling and instrumentation project in Pearce & Barteaux (2014; 2015) that provide significant amounts of field data from internal waste rock dump investigations and monitoring programs. These projects included the completion of sonic drilling programs as part of the investigation of 12 WRDs in Australia. The mine sites are made up of multiple WRDs which have been constructed by various techniques including end dumping, and dumps incorporating encapsulation techniques.

Gas flux rates were calculated based on drill core data and data from instrumentation installed through dump profiles. Data from a 60 m high dump constructed with 8 m end tipped lifts and 2 m paddock dumped horizons indicated the weighted average air permeability through the waste was around $8.0\text{x}10^{-9}$ m^2. This is in line with other studies for example MEND (1997) where a mean value of 2.9 x 10-9 m2 (averaged over 24 measurements) was derived from waste rock dump air permeability investigation. The calculated gas flux based on these values was between ~$4.0\text{x}10^{-4}$ $m^3/m^2/s$ and ~-$1.0\text{x}10^{-4}$ $m^3/m^2/s$. After considering effects of material texture, saturation state and temperature on air permeability, it was estimated that the gas flux would be greatest at 15.5 m depth for both upward and downward flow, possibly achieving an upward gas flow rate between $1.0\text{x}10^{-4}$ $m^3/m^2/s$ and $1.0\text{x}10^{-3}$ $m^3/m^2/s$. Due to the spatial heterogeneity of the waste material properties flux rates will likely vary by order of magnitude in a temporal and spatial sense through the waste profile as gas flux rate is sensitive to material texture and temperature differential, but bulk averages are considered a suitable means of averaging out this variability.

The gas flux rate of $1.0\text{x}10^{-4}$ $m^3/m^2/s$ determined to be an appropriate weighted average for flux through the waste profile corresponds to an oxygen supply rate of $3E^{-5}$ $kg/m^3/s$. The importance of the flux rate is that this will act as the main limit to sulfide oxidation rates within the waste mass given that adequate moisture is present for reactions to occur (Pearce et al 2015). By comparing the expected oxygen demand (based on pyrite oxidation rates, from kinetic testing) to the modelled oxygen supply through the WRD (based on the gas flux rate) it is possible to determine if pyrite oxidation rates (POR) will be limited by oxygen supply. Testing on the fresh sulfidic materials within the dumps (prior to placement) indicated an average POR of 2.5 E^{-6} kg/m^3/s. The sulfidic material is present in a 20m thick zone therefore the potential supply of oxygen based on the calculated gas flux rate is about half of the demand load from oxidation at the rate determined by laboratory tests. The implication of this finding is that field oxidation rates relative to laboratory rates may only be limited by a factor of two by oxygen supply within a large proportion of the waste mass.

Geochemical analysis of drill core from the WRDs investigated supports the high gas flux rates indicated from monitoring, and the finding that oxidation rates may not be significantly (i.e. greater than an order of magnitude) limited by oxygen supply. Significant oxidation of sulfides has been recorded based on analysis of sulfide/sulfate ratios through the whole profile of the dumps. Core from WRDs up to and in excess of 30 yrs was assessed and approximately 1,500 samples were analysed from 49 boreholes. For the older samples (>30 years) the average and median oxidation rates 80% and 72% respectively. At higher grades of >1% sulfur the oxidation rate was lower around 60% average.

When oxidation rates in dumps constructed by different techniques are compared, the material in dumps constructed with 10m lifts with inter-bedded 2m compacted paddock dump layers was found to have oxidised significantly more slowly over time than that in 30 m end tipped lifts. This data supports the field monitoring data which indicates oxygen ingress rates should be lower in dumps using lower lift heads.

Predicting gas flux and oxidation rate based on waste rock dump construction

Field data was used as part of analytical modelling as a validation/calibration exercise to determine if numerical modelling could be used to determine optimal waste placement techniques. Thermal and airflow modelling were completed to estimate the volume of air flowing through waste material due to density dependent convective airflow cycles. The impacts of total air flow rates through the WRD were assessed along with pyrite oxidation models to determine overall temperature increases as a result of convective airflow rates. Convective airflow modelling takes into consideration three key influencing processes within the WRD waste material: water seepage; thermal conductive heat transport; and airflow. Numerical modeling was completed in GeoStudio (Geo-Slope International, 2012a) software suite, SEEP/W, TEMP/W; and AIR/W. In addition, seepage rates were calculated using VADOSE/W. Two model scenarios are considered here as part of this paper:

Model 1: “Segregation” Scenario: simulates gravitational segregation of the waste material into texture layers due to end tipping from a high tip height of 30m (i.e. coarser waste material has a propensity to roll to the base of a slope while finer material stays near the top of the slope); and,

Model 2: “Compaction” Scenario: simulates an OSA built from the bottom up with alternating layers of 10 m of PAF/NAF topped with 2 m of NAF. The top 0.2 m of the PAF material at NAF/PAF interface is compacted due to haul truck traffic while placing the NAF layer (Figure 3).

The results of the convective airflow models show that airflow is predominantly in the coarser textured waste material as a result of the higher air permeability of this material. However, it was also noted that airflow did occur through the finer and intermediate sized waste material, despite the reduced air permeability of these materials; most likely due to lower in situ moisture conditions. The models also show that the configuration of the waste materials greatly affected airflow rates.

In the case of the segregation scenario development of a convective cycle was observed in the model in the coarser textured layer, which transported air through the coarser textured layer into the WRD. This convective cycle was identified by comparing equivalent airflow rates into and out of the WRD. The weighted average airflow rate was found to be 1.9×10^{-4} m^3/m^{2}s.

In the case of the compaction model in first year of the model simulation, airflow rates were relatively constant, and reached a peak of 3.0×10^{-6} m^3/m^{2}s during this time. The weighted average airflow rate was found to be 1.55×10^{-6} m^3/m^{2}s. This lower flux rates are due to the presence of compacted layers between each layer of deposited material limiting airflow from breaching into the overlying layer and continuing the convective cycle. In effect, the convective airflow is “shut down” by these compacted layers.

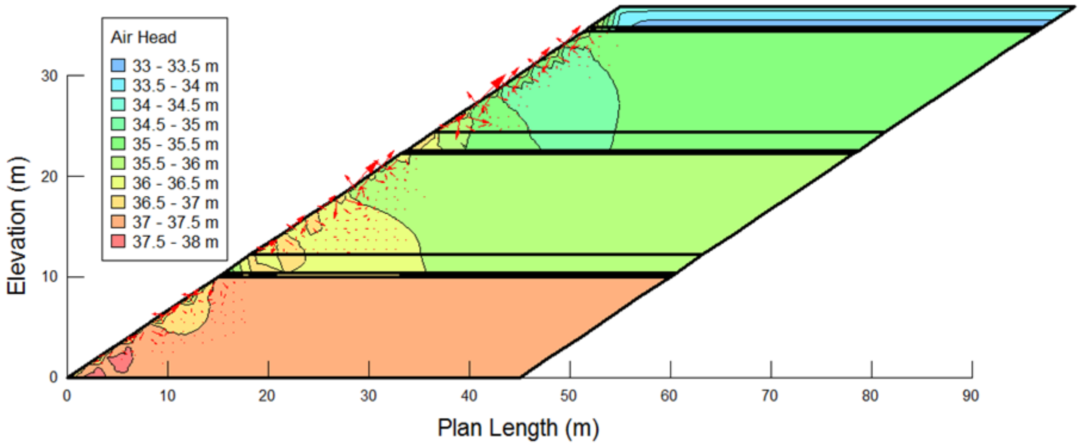

Figure 3 *Model 2 modelling results showing restricted air flux vectors*

The air flow rates calculated by numerical modelling are in very good agreement with site data and indicate that where coarse basal zones are present air flux rates through waste mass of around 1 x10^{-4} m^3/m^2s can be expected. This agreement between site data and model data supports the use of gas flux modelling to make predications of oxidation rate potential in waste rock dumps. The modelling of the compaction scenario indicates that the use of compacted finer textured layers and short lift heights significantly reduces the potential for air flux and therefore is a limiting factor for oxidation rates and thus AMD production.

Modelled AMD production rates based on waste rock dump construction

Based on the field data and modelling data generated and interpreted, a clear quantitative link between waste rock dump construction method and AMD production can be established. Given a field validated modelling approach has been developed, then this supports a quantitative method for assessing how waste placement and construction method can be optimized to reduce AMD risk for future waste rock dump construction.

Figure 4 shows the results of additional proprietary modelling completed by OKC based on the field validated approach where by AMD production was quantitatively assessed against tipping height for a proposed waste rock facility.

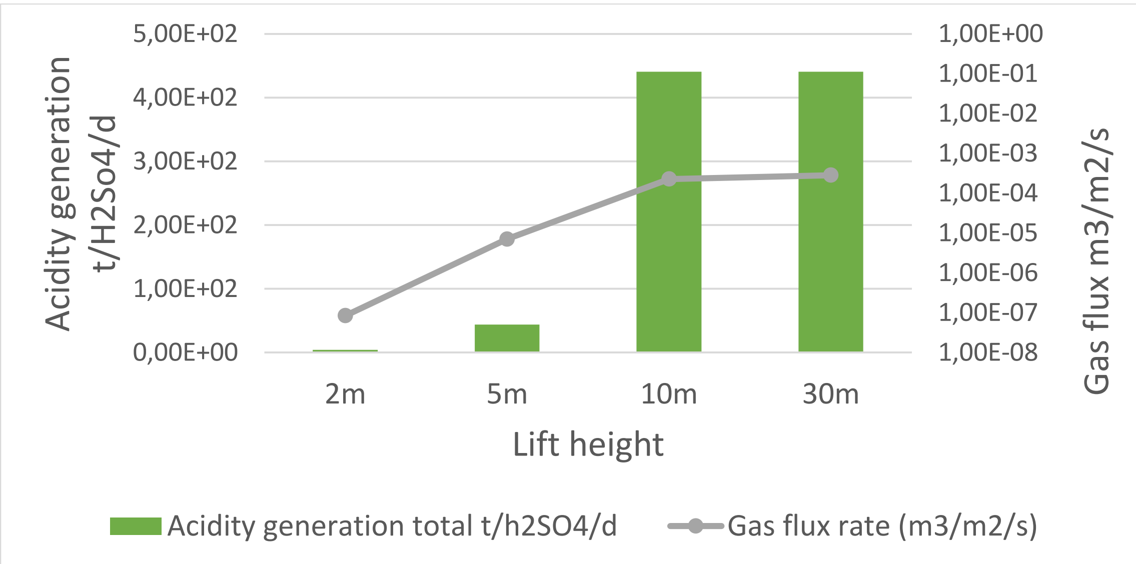

Figure 4 *Analytical model outputs for acidity generation as a function of lift height*

The results of this assessment show the clear benefits of using a quantitative approach to assessing waste rock dump construction method as part of mine planning and mine closure risk assessment. The clear benefits of using low tip heads (paddock dumping) as an alternative to large height end tipping is obvious. Although it is an accepted fact that paddock dumping is lower risk than end tipping, the fact that the relative difference can be quantified means that the risk/cost tradeoff can be completed at the mine planning stage and mine closure risk and cost estimation can be improved significantly.

It is interesting to note that gas flux is not directly related to AMD production, this is because at some point gas flux rates are higher than required to support oxidation demand from reactions and therefore more gas flux does not increase AMD production. This is seen in the move from 10m to 30m tip heights where gas flux increases but AMD production does not.

Conclusions

The significant finding of the study is not that the method of waste placement has a significant control on AMD risk, this is known and accepted in the industry but rather that this risk can be assessed on a quantitative basis. The fact that the relative difference can be quantified is important as this means that the risk/cost tradeoff assessment of how waste rock dumps are constructed can be completed at the mine planning stage, and mine closure risk and cost estimation can be improved significantly.

The secondary implications of this finding is that the management of reactive waste during construction as a result of placement technique is likely a key risk driver for future AMD release, due to challenges with controlling gas flux in periods where waste dumps are “open”. This conclusion is perhaps contrary to widely held views that AMD risks can be largely managed at closure. It is clear that an assessment of waste rock dump construction requires consideration when final closure solutions such as covers are being selected and relied on as the main closure mitigation solution for AMD management.

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