Gas Flux Rates and the Linkage with Predicting AMD Loads in Waste Rock Dumps, and Designing Practical Engineering Solutions – Field Based Case Studies in Three Distinct Climates

Steven Pearce[1], Mitchell Barteaux[2]

[1]*Sr. Geo-Environmental Scientist, O'Kane Consultants, Unit 14, St Asaph Business Park, St Asaph, Wales, UK LL17 0LJ spearce@okc-sk.com*
[2]*Geoscientist, O'Kane Consultants, Fredericton, NB, Canada mbarteaux@okc-sk.com*

Abstract Oxygen flux into waste rock dumps (WRD), as well as the role oxygen plays in the development of acid and metalliferous drainage (AMD) is a critical area of research with respect to management of reactive waste at mining sits. The ability to practically manage gas flux (if at all) is however highly site-specific. O'Kane Consultants (OKC) has completed detailed assessments of gas flux rates as part of WRD investigations and AMD management engineering projects, at sites in three different climatic regions. The extensive data set collected has allowed the improvement of oxygen flux conceptual models to calculate oxygen ingress rates.

Key words Gas flux, Load predictions, cover design, AMD management, WRD instrumentation

Introduction – Gas Flux in WRD

The minimisation of oxygen ingress is widely acknowledged as a key waste management strategy employed at mine sites around the world to address the process of oxidation of reactive materials that may produce negative outcomes. These strategies are adopted to mitigate risks such as spontaneous combustion, toxic gas production, and acid and metalliferous drainage (AMD). In general the movement of air (and thus oxygen) within, and into WRDs occurs by:

- Diffusion through the near surface WRD material, or through engineered cover systems employed as a remediation measure;
- Advection due to density gradients as developed by temperature differences between atmosphere and internal WRD conditions commonly as a result of pyrite oxidation (Lu 2011);
- Dissolved oxygen contained in infiltrating water such as rainfall or snowmelt; and
- Convection cells within WRDs developed due to vertical temperature gradients, which transport air throughout the WRD pore-space due to differences in density (hot air is less dense than old air).

Given the primary role that oxygen plays in the oxidation of reactive minerals like sulfides, reducing their interaction would be an obvious advantage in the successful operation and closure of a WRD in terms of limiting risks such as AMD. It is somewhat surprising then to note in this regard that commonly the focus of AMD management, assessment and management studies are focused primarily on the liquid phase geochemical aspects. For example a number of key issues can be identified with using industry standard static and kinetic testing procedures for predictions of geochemical evolution of waste materials containing sulfides in the field. In the main there is significant uncertainty with how to apply scale up factors for the extrapolation of laboratory data to the field because the test methods are not linked in any way to the dynamic process of oxygen and water flux in the field.

In this regard it is therefore important to recognise that independent of any geochemical assessment that may be carried out, that site-specific factors that directly influence the dynamic process of gas/water flux are considered. These factors include material characteristics (geochemical and geotechnical), geometry and climate. These factors can be investigated early in mine development it is vital that a good understanding is gained of them to recognize what is achievable in WRD closure, specifically with regards to potential AMD controls and oxygen ingress management.

The following paper reviews three case studies located in three different climate zones, and provides monitoring data to support the conceptual model of oxygen flux in those regions. Specifically, the climate zones include (Peel 2007):

- tropical rainforest– Northern Sumatra, Indonesia;
- arid hot desert – Pilbara, Australia; and
- humid alpine – British Columbia, Canada.

Tropical Rainforest Climate

The Tropical Rainforest site reviewed in this paper is characterized by high rainfall with an annual average of approximately 4,426 mm based on a 35 year climate database. Daily rain events are common, usually occurring in the afternoon, and temperatures are hot and humid. As part of AMD mitigation the site mining teams have employed a progressive waste rock management strategy which aims to mitigate the AMD risks of a WRD by selectively placing finer-grained material at the outer edge of the waste facility as construction progresses. The encapsulation method is a viable option for AMD risk management at this site due to the presence of sufficient volumes of low risk (respect to AMD) material that has suitable texture (i.e. finer grain size fractions), and high rainfall. These contributing factors mean that there is greater probability for the material to remain tension-saturated, thereby reducing the airflow capacity into the waste mass. In addition because of the high rainfall volumes it was understood that net percolation was going to be challenging to manage in the long term, therefore an approach to manage oxygen ingress was determined to be the optimal strategy in AMD management.

Specialised instrumentation has been installed by OKC through 2014 and 2016 to monitor the performance of the WRD. Specifically, the performance of the fine-grained encapsulation layers has been assessed against engineering design objectives such as: decrease of oxygen ingress to acceptable levels and limiting AMD. Instrumentation utilised to date includes oxygen sensors, volumetric water content / electrical conductivity sensors, matric potential and pore-water pressure (Pearce 2014).

Figure 1 presents select temperature and near-surface oxygen data from the WRD at the study site. Internal WRD temperatures (i.e. below 10m depth) are noted very stable and comparable to, but slightly lower than ambient temperature, with lower temperatures being recorded with greater depth. Near-surface (0.5m depth) temperatures however show daily fluctuations, likely reflecting diurnal ambient air variations. The internal temperature profile results in a very low relative differential temperature values between internal and ambient conditions of up to approximately 2°C difference). These conditions result in low temperature gradients to promote advective airflow.

The near-surface oxygen monitoring data shows that concentrations of oxygen at 0.5 m depth are low, and are likely reflecting low oxygen diffusion coefficients through the near-surface layer. Based on the temperature data there is little to no evidence of exothermic activity within the waste which would be present if significant sulfide oxidation were occurring. This provides strong evidence (along with the oxygen data) that limited advective or convective air flow forcing air into or out of the landform. The low oxygen ingress conditions can be attributed to the high moisture retention characteristics of the encapsulation material which results in low air permeability functions for the waste material. The volumetric water content and suction state data collected from the site shows that the encapsulation layer has a high degree of saturation and very low suction, supporting this interpretation.

Drilling results through the main body of the landform showed near neutral pH conditions throughout the depth profile, supporting the interpretation that the encapsulation method is efficient in maintaining oxygen concentrations within the WRD low, and inhibiting the oxidation of PAF.

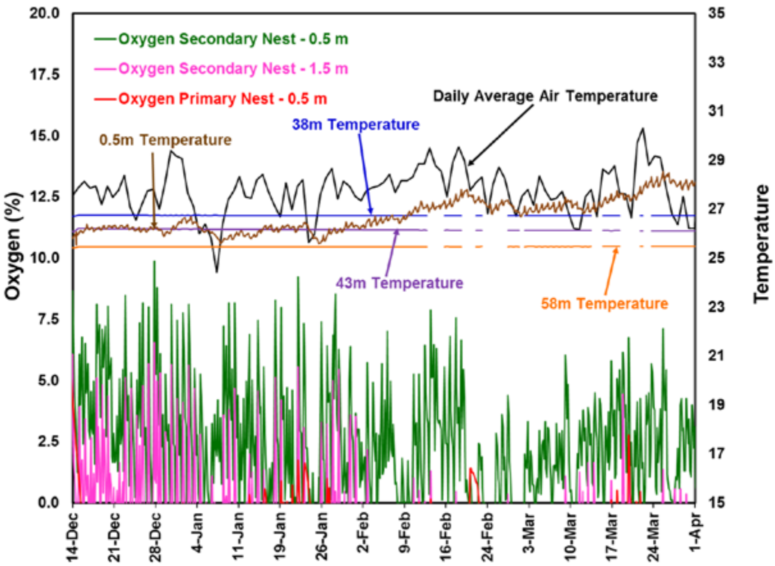

Figure 1 *Temperature and oxygen concentration at the tropical rainforest case study location.*

Arid Hot Desert Climate

Based on the Köppen-Geiger system (Peel 2007), this study site is classified as an arid hot desert (BWh), and is located in the Pilbara, Western Australia (WA). Almost 75% of the rainfall occurs during summer (October to March, inclusive) and the site experiences hot to very hot summers (with atmospheric temperatures up to 50°C) and warm to cool winters (near zero degrees). The long-term annual average rainfall for the area as quoted by the Australian Bureau of Meteorology is 320 mm. The WRD studied at the site is constructed with high tip heads (40 m), which has resulted in significant material segregation as a result of gravity sorting (Wilson 2011) with PAF material located throughout the WRD profile. As a result of the material sorting, the development of coarse rubble zones at the base of the tip heads have developed, acting as potential pathways for air entry into the landform (Pearce 2014). OKC had the opportunity to complete the installation of over 150 instruments in various waste rock dump landforms in the Pilbara, WA during 2013-2015. The instruments were installed to depths of up to 100 m as part of a long-term monitoring and assessment program. Instruments were installed using the sonic drilling technique and include galvanic oxygen probes, soil matric potential sensors, temperature sensors, and vibrating wire piezometers. The use of sonic drilling allowed the structure of the dumps to be assessed in detail during drilling and in turn the targeting of instrument placement in specific zones.

Figure 2 presents oxygen data and differential temperatures between various depths within one of the WRD profiles and ambient conditions (i.e. WRD temperature minus ambient temperature). Positive differential temperatures indicate when the internal temperature is higher than atmospheric, and negative temperatures demonstrate occurrences where internal temperatures are less than atmospheric. As illustrated, during summer months (September – March) there are instances where the entire WRD profile temperature is lower than ambient conditions, and during winter months (April – October) internal temperature becomes higher than ambient temperature. These variations in temperature differential on a seasonal basis result in dynamic oxygen flux conditions where gradients can change direction. During the winter when ambient temperatures fall below internal WRD temperatures, the result is a strong upwards gas flux forcing mechanism, where oxygen rich air enters the WRD through the basal rubble zones, and depleted less dense air moves towards the top of the WRD. In summer, when temperature gradients are low, or negative, there is potential for cooler oxygen depleted air to exit the toe of the landform, drawing in oxygen-rich air near the surface.

Sulfidic material along with organic carbon content is present within the profile which explains why oxygen concentrations are depleted at depth, however concentrations remain above 10% through the entire profile which is a strong indicator that significant oxygen flux is occurring to maintain oxygen supply through the waste profile. The data indicates that sulfide and carbon oxidation reactions are likely not limited by oxygen supply at this site.

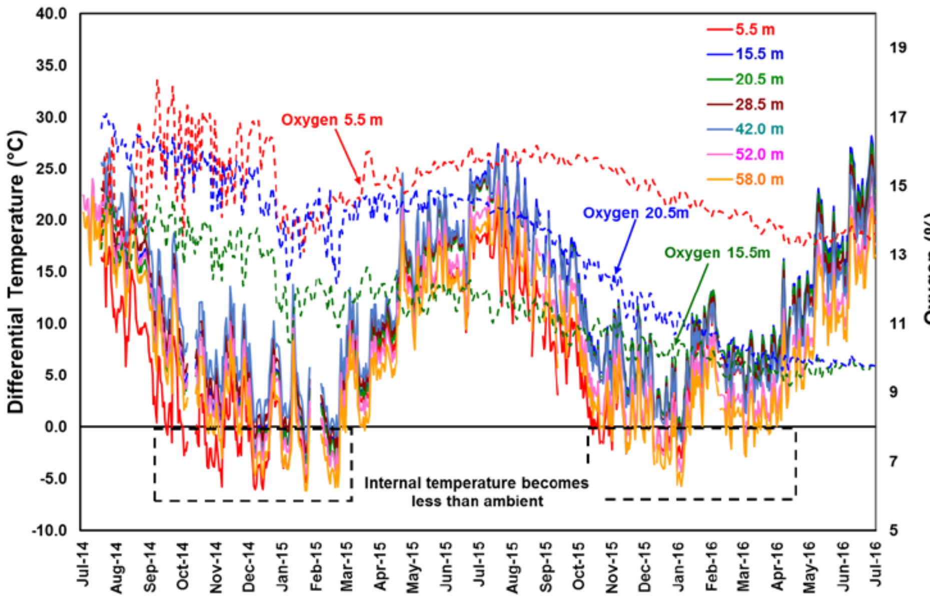

Figure 2 *Temperature and oxygen concentration at the arid hot desert case study location.*

Humid Alpine Climate

The Equity Silver mine is classified as humid alpine (Patterson 1987) and is used as the case study in this section. The study site is located near Houston, in the central interior of British Columbia, Canada. Information about the site was made available from publically accessible data, primarily as a result of the paper by Morin (2010). A significant amount of data has been collected from the site relating to AMD management, and is explored in said paper, where 23 years of WRD monitoring has taken place (1986-2009).

The Equity site receives approximately 660 mm of precipitation annually in the form of rainfall and snow. Daily average temperature remains below 12°C in summer, with winter daily average temperature falling to as low as -8.4°C for January (Environment Canada 2017).

The Equity WRD has a cover system, which was installed in 1991 and consists of compacted and non-compacted till, including a capillary break layer. The waste rock is relatively coarse in nature lacking appreciable clay or silt sized particles (O'Kane 1998). Based on the material type, it can be assumed that there is little water-holding capacity within the waste, and that airflow is not limited by internal saturated layers. Field data collected from cover system monitoring work (O'Kane 1998) shows that the cover system itself is maintaining low matric suction and a high degree of saturation, therefore minimizing the oxygen diffusion coefficient across the cover system and into the waste rock.

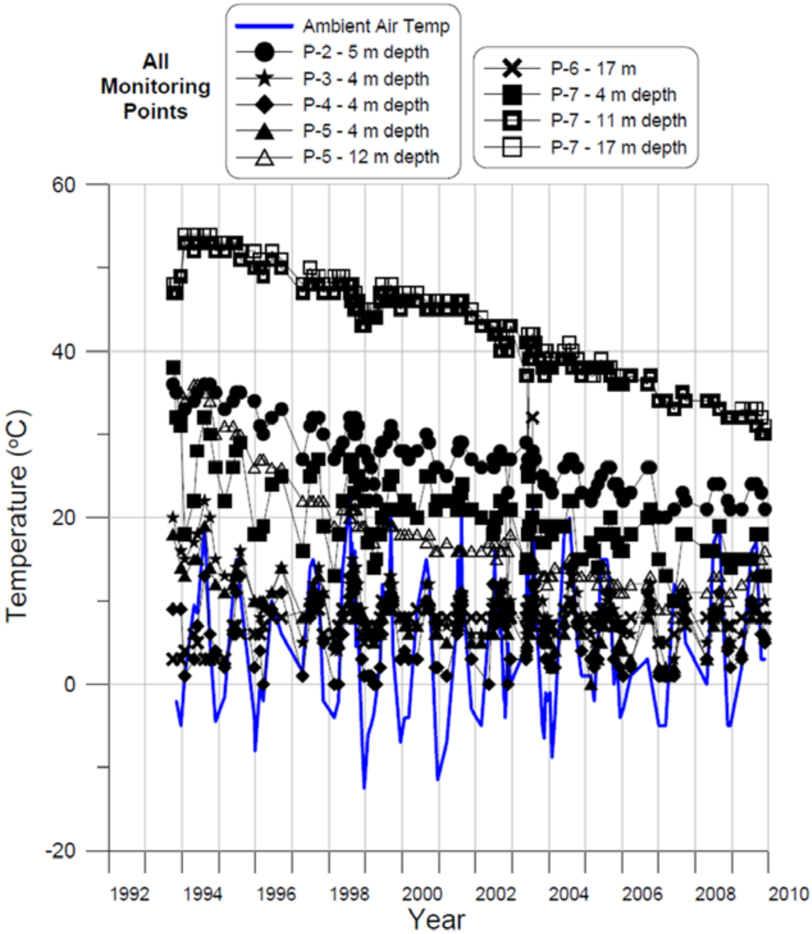

Figure 3 *Temperature data with depth at the Equity Silver site (from Morin 2010).*

Figure 3 shows the temperature data from the internal waste at the site which displays an overall cooling trend over time, however, it is clear that temperatures at a number of monitoring depths are well above the ambient air temperature. This data indicates significant oxygen ingress is/has occurring to support sulfide oxidation to maintain the elevated temperatures (as a result of exothermic reactions). The temperature differential remains constantly positive year round resulting in conditions that promote advective oxygen flux through the WRD. The data indicates that sulfide oxidation is occurring at an appreciable rate irrespective of the presen of the cover system. Temperature differentials between the WRD and the environment were similar at the humid alpine climate and arid hot desert climate, in that there is a seasonal aspect to the magnitude of the difference. A key difference however is that the humid alpine environment may have temperature gradients that remain positive (and high) throughout the entire year regardless of season, which is not seen at the other environment.

Discussion

Based on the data presented it is clear that although the key processes governing oxygen flux are remain constant across climatic zones, strategies to limit ingress must be tailored to meet site specific factors of which climate is a major factor. It has been demonstrated for example that strategies implemented in tropical climates which utilize highly engineered WRD's that employ fine grained material within cover layers to promote tension saturated conditions can be successful in limiting oxygen flux. However, for climates such as a hot arid dessert which lacks the sufficient rainfall to allow development of tension saturated layers, this would not be a viable option. For areas such as this, it is clear that the key focus would be on waste placement technique, such as limiting the amount of segregation during placement, or the use of advective barriers (such as toe bunds), which cut off the inflow of air through coarse rubble zones. These techniques can provide additional risk reduction by reducing the potential flux of air when high temperature gradients exist.

In climates such as the humid alpine environment WRDs that contain reactive suflides typically can attain very high internal/external temperature differentials. At these locations a combination of waste placement strategies and cover systems can be used to limit oxygen flux and ingress. Specifically, engineered cover systems, which utilize the enhanced store-and release-concept to maintain a layer at tension saturation as a result of a capillary break has been shown to significantly reduce the diffusion of air into the landform into the longterm (Ayres 2012). In these locations however cover systems may only be effective in limiting diffusive flux, or advective flux in certain times of the year, therefore waste placement techniques such as compacting waste in small lifts or the creation of advective barriers (such as toe bunds) may be employed to reduce bulk advective flux year round.

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