INFOMINE E-BOOK

Control of Air Flow in Waste Rock Dumps

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ABSTRACT

Air movement and associated oxygen transport through waste rock dumps has the potential to significantly enhance the rate of oxidation of pyrite-bearing material. While this is a desired outcome for most heap leach operations, airflow in waste rock storage facilities can result in significant increases in generation and acceleration of acid rock drainage. Hence, a good understanding of internal airflow through waste rock dumps is required to control ARD and minimize any associated liability.

The principal mechanisms contributing to airflow and oxygen transport in a waste rock pile include (i) diffusion, (ii) advection due to a thermal gradient (chimney effect) and/or wind pressure gradients and (iii) advection due to barometric pumping. While diffusion is typically limited to a near-surface zone of a few meters depth, advection and barometric pumping have the potential to move air (and oxygen) to much greater depths into the pile. In general, the more permeable the waste rock material, and the greater the height-to-depth ratio of the waste rock pile, the greater is the potential for advective air movement. The reactivity of the waste rock material as well as the coarseness (hence air permeability), and the spatial variability of these properties within a pile, have a strong influence on the magnitude of thermally induced advection. In contrast, air movement due to barometric pumping is controlled by the waste rock porosity, changes in ambient air pressure and the heterogeneity of air permeability of the waste rock dump. Results of field monitoring and numerical modeling using TOUGH AMD are presented to illustrate the concepts on air movement in waste rock piles discussed in this paper.

During the design and construction phase, airflow can be controlled by judicious placement of reactive waste rock and use of selective placement techniques to control the internal structure of the waste rock facility (e.g. introduction of horizontal layering, prevention of inclined, high-permeability, channels ("chimneys")). Several closure measures are available to minimize airflow including (i) placement of a low-permeability cover to reduce air entry, (ii) placement of a non-reactive cover material to isolate reactive material from the zone of active airflow and/or regrading of the waste rock pile to obtain a geometry and internal structure less susceptible to advective airflow.

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INTRODUCTION

A complex interaction of physical, hydrological, geochemical and microbiological processes contribute to acid rock drainage (ARD). The oxidation of pyrite-bearing rocks can be summarized by the following exothermic reaction (Nordstrom, 1977):

$$FeS_2 + H_2O + 3.5\ O_2 \rightarrow 2\ H+ + 2\ SO_4^{2-} + Fe^{2+}$$

In addition to pyrite, the presence of both water and oxygen is required to sustain pyrite oxidation and thus ARD. While most mine rock piles contain sufficient pore water to sustain this reaction, in many cases air movement within the pile is sufficiently slow, thus controlling oxidation by limiting the oxygen supply. Therefore, it is important to understand, and attempt to control, the mechanisms that contribute to air movement in waste rock piles as a means of mitigating ARD production.

Oxygen transport, also referred to simply as airflow, occurs in waste rock piles by advection and diffusion in response to concentration, pressure and thermal gradients. The magnitude of oxygen transport is controlled by a complex interaction of various physical and chemical properties of the waste rock. Characterization of these properties along with field monitoring needs to be completed in order to adequately assess and predict ARD. The results of characterization and monitoring work can then be used to calibrate an air transport and ARD production model of the mine rock piles.

This paper provides an overview of the theoretical and practical aspects of airflow in waste rock dumps. First, we provide a brief review of the key mechanisms of airflow (convection, diffusion, barometric pumping) and their fundamental controls. Second, we discuss the tools available for assessment and prediction of airflow, including material characterization, field monitoring, and numerical modeling. Examples of field monitoring and numerical modeling from well-studied waste rock piles at three different mine sites are presented to illustrate the concepts on air movement in waste rock piles discussed in this paper. Finally, airflow control options applicable both during and after pile construction are discussed.

MECHANISM OF AIR FLOW

Diffusion

Waste rock piles from hard rock mines are large accumulations of generally coarse-grained material containing sulphides (mostly pyrite) that remain only partially water saturated, i.e. gaseous and liquid phases are simultaneously present in the pore space between the solid grains. Initially, following the oxidation of the sulphides, a partial depletion of the oxygen present in waste rock piles occurs. Oxygen concentration gradients are thus created between the gas phase within the wastes and the atmospheric air surrounding the pile. This oxygen concentration gradient drives gaseous oxygen diffusion from the surface to the interior of the waste rock pile. Gaseous diffusion is the main process providing oxygen within waste rock accumulations after their initial placement and diffusion remains active thereafter as long as the oxidation process contributes to the depletion of oxygen concentration Co (mol/m3) in the gas phase within the waste rock pile.

In partially water saturated porous media, the following form of Fick's Law describes the molar diffusive flux Jo (mol/m2′) of oxygen from the atmosphere to the interior of waste rock piles:

$$J_o = -n \cdot S_g \cdot \tau' \cdot D_o \cdot \frac{\mathrm{d}\,C_o}{\mathrm{d}\,l} \qquad 1$$

Fick's Law states that the mass flux of oxygen is proportional to the oxygen concentration gradient and the effective diffusivity De (m2/s). The magnitude of the effective diffusivity is lower than the diffusion coefficient Do (m2/s) in a free fluid because of the presence of solids hindering diffusion by increasing the tortuosity of the transport pathways. In equation 1, a linear relationship is assumed between the effective diffusivity De and Do, tortuosity t' (dim.), porosity n, and gas saturation Sg. Other commonly used effective diffusivity models are discussed in the review by Aachib (1997).

A simple analytical solution allows the prediction of one-dimensional oxygen concentration profiles in materials where it is consumed by a first-order reaction, which is often applied to pyrite oxidation. In such systems, the oxygen mass loss Ro (mol/m3′) directly depends on its concentration Co (mol/m3) and the kinetic constant Ko (s-1):

$$R_o = -K_o \ C_o \qquad 2$$

A fixed concentration C_o^* is imposed on the surface and the oxygen concentration Co is obtained as a function of the distance z (m) from the surface:

$$C_o = C_o^* \cdot e^{-z\sqrt{K_o/D_e}} \qquad 3$$

The oxygen molar flux from the surface Jo must be equal to the total oxygen consumption in the system and it is obtained from the following relationship:

$$J_o = C_o^* \cdot \sqrt{K_o \cdot D_e} \qquad 4$$

These relationships strictly apply to systems in which diffusion is homogeneous with constant values of De and Ki. Even though such conditions seldom apply, it is still possible to use the relationships to obtain representative oxidation constants.

As an example of the application of the previous relationships, we can use the oxygen profile measured by Yanful (1991) in a test column of partially saturated mine tailings with a porosity n of 0.32 and a gas saturation Sg of 0.50. The oxygen diffusion coefficient Do and its concentration in air Co are known to be 2.0x10-5 m/s2 and 0.2095, respectively. Under such conditions, the effective diffusivity of oxygen De would be 2.24x10-6 m/s2 according to equation 1, assuming a tortuosity t' of 0.7. The De of mine tailings is typically in the order of 10-6 m/s2.

Figure 1 shows equation 3 fitted to the relative concentration of oxygen Co/C_o^* measured in the column. In a semi-log plot, the slope of the line fitted through the relative concentration data allows the estimation of the oxygen oxidation kinetic constant Ko as 2.6x10-4 s-1. Note that the estimated value of the kinetics constant depends a lot on the calculated value of effective diffusivity De. It is thus preferable to independently measure De in the lab or field (Aachib, 1997). The molar mass flux of oxygen corresponding to these conditions can be estimated from equation 4. If we choose to determine the mass flux of oxygen Fo (kg/m3′) we substitute the partial density of oxygen in air ρ_{air}^o (0.279 kg/m3) for C_o^* in equation 4. We thus obtain 82.4 kg/m2/year of oxygen consumption, which is equivalent to the oxidation of 88.1 kg of pyrite per unit area of tailings each year, based on the stoichiometry of the pyrite oxidation reaction.

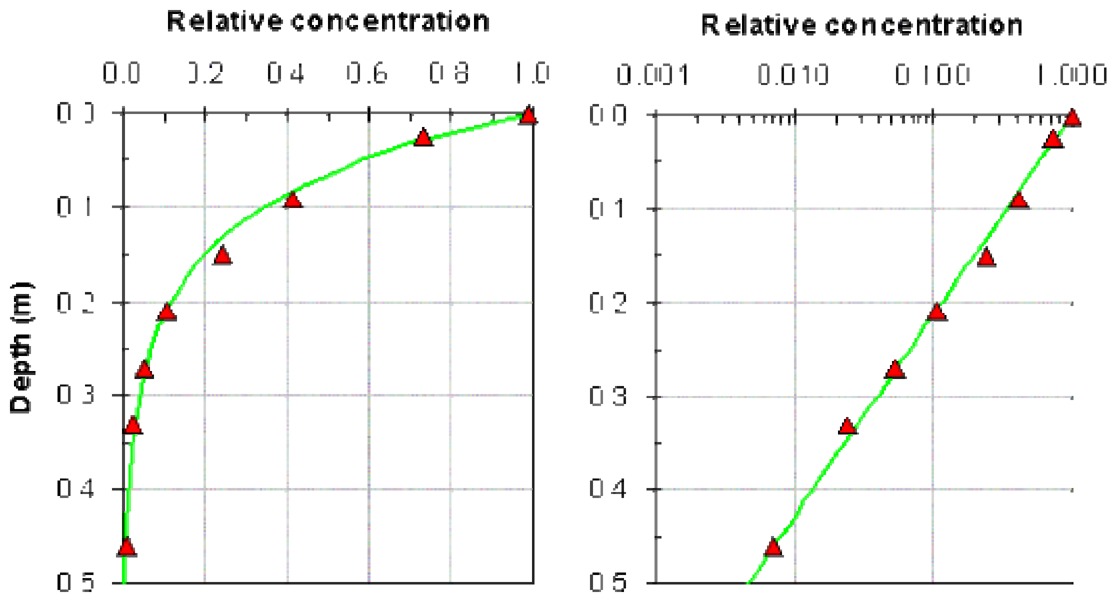


Figure 1. Relative oxygen concentration in a mine tailings column (after Yanful, 1991).

If the kinetics constant K (s-2) related to oxygen consumption in pyrite oxidation is lower, oxygen will penetrate deeper by diffusion within partially saturated material. Figure 2 (left) illustrates theoretical oxygen profiles calculated with equation 3 for different oxidation rates and a constant effective diffusivity De of 10-6 m/s2. For reaction rates typical of mine tailings (10-5 to 10-4 s-1), oxygen remains shallow within the material and penetrates typically less than 1 m before being totally consumed by pyrite oxidation. For oxidation rates typical of waste rock piles (10-7 to 10-8 s-1), oxygen can reach much greater depths by diffusion, even beyond 10 m. Figure 2 shows the "penetration depth" do (m) of oxygen, defined as the depth at which relative oxygen concentration reaches 0.05, for different values of K and the same De. For such conditions, the following empirical relationship allows the prediction of the oxygen penetration depth:

$$d_o = \frac{0.003}{\sqrt{K}} \tag{5}$$

Equation 4 can also be used to estimate the mass flux of oxygen related to the conditions illustrated in Figure 2. Such calculations show that the diffusive oxygen flux from the surface of a reactive material is reduced when the material is less reactive. Oxygen diffusion is thus a less efficient means of supplying oxygen into waste rock piles compared to tailings, because they are typically less reactive than mine tailings.

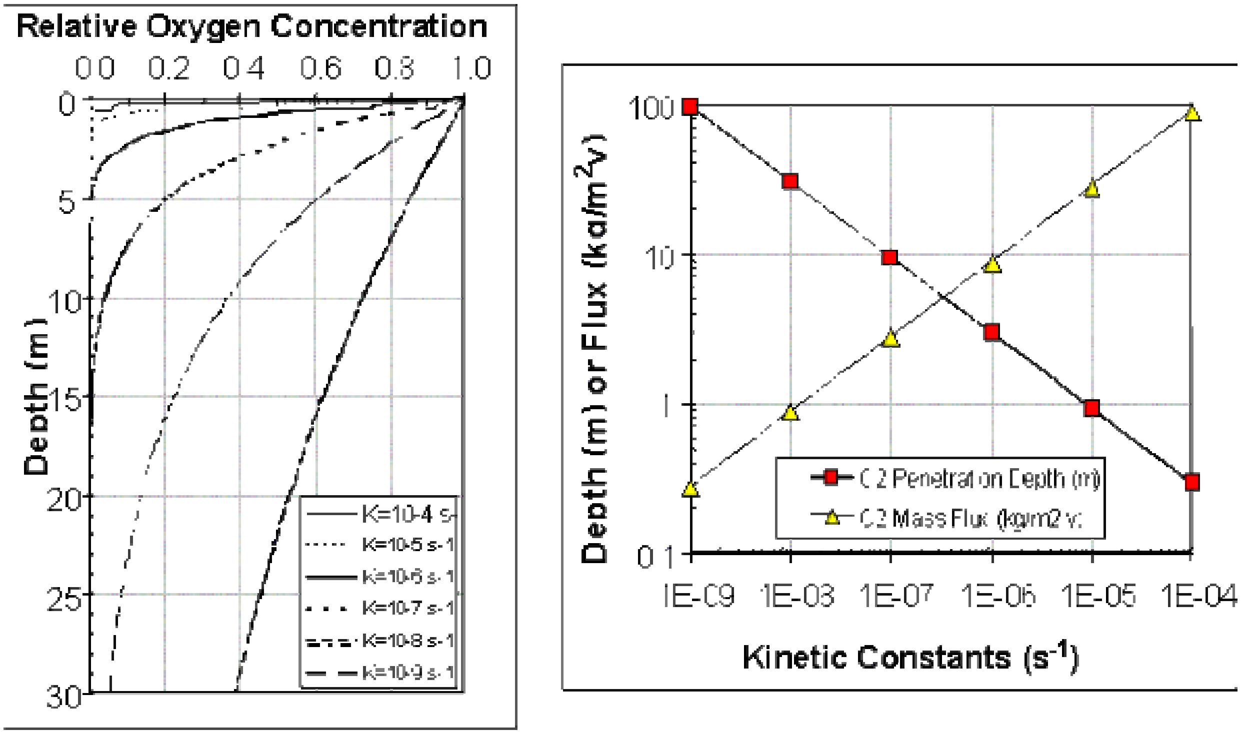


Figure 2. Oxygen diffusion as a function of the oxidation kinetics constant K (s-1). Left: oxygen profiles vs depth. Right: oxygen penetration depth at which the relative concentration is 0.05 and the related oxygen mass flux from the surface.

Convection

Pyrite oxidation is strongly exothermic producing 1409 kJ of heat per mole of pyrite oxidized. The release of heat from pyrite oxidation drives temperature up within waste rock piles, which has been reported as high as 70 ?C (Gelinas et al, 1994). This increase in temperature can completely modify the mechanism responsible for oxygen transfer in waste rock piles. Following an initial increase in temperature in waste rock piles of sufficiently high air permeability, temperature and density driven gas convection currents are initiated in waste rock piles. The resulting advective transport "draws" atmospheric air into the waste rock piles, which is a much more efficient oxygen transfer process than diffusion.

In partially saturated porous media, the general form of Darcy's Law can be used to describe gas flow. Instead of the hydraulic head, gas flow is driven by the pneumatic head h (m). In a one-dimensional system where flow occurs along direction l, Darcy's Law can be written as follows:

$$q = -Ki = -\frac{k\rho g}{\mu} \cdot \frac{dh}{dl} \qquad (6)$$

For a perfect gas, the pneumatic head hg (m) is expressed as follows (Massmann and Farier, 1992):

$$h_g = z + \frac{R \cdot T}{g \cdot m} \cdot \ln \frac{p}{p_o} \qquad (7)$$

Where z (m) is the elevation relative to a reference level, R is the gas constant (8.314 Pa?m3/mol?K), T is absolute temperature (K), g is the gravitational acceleration (9.81 m/s2), m is the molar mass of the gas phase (kg/mol), p is the gas pressure (Pa) and po is the reference gas pressure (Pa). According to the expression of the pneumatic head, gas flow can occur under gradients in (i) temperature T, (ii) composition (affecting the molar mass m) and/or (iii) pressure p. None of these processes can be neglected in waste rock systems.

Due to the generally high temperatures present in waste rock piles, temperature-driven convection of the gas phase is commonplace (Harries and Ritchie, 1987; Pantelis and Ritchie, 1991; Lefebvre, 1995). The magnitude of airflow into a waste rock pile by thermal convection depends on the difference in temperature within the pile relative to atmospheric air temperature. Figure 3 shows indications of increased thermal convection during the winter months (higher temperature gradients) as evidenced by higher oxygen concentrations within the Nordhalde, in Germany. At that site, during the late autumn and early winter, when temperatures in the upper portions of the pile fall below the pile's internal temperature, the oxygen profiles show an overall increase in concentrations within the lower ports, indicating the onset of thermal convection. This pattern is most marked in the boreholes closer to the edge of the pile, where oxygen concentrations at depth remain high throughout the winter months.

Kuo and Ritchie (1999) have recently proposed compositional changes in the gas phase as a significant contribution to gas convection. Two common processes that can lead to a change in the molar mass of the gas phase in waste rock piles include (i) oxygen consumption in the gas phase related to pyrite oxidation as well as (ii) the increase in water vapor in the gas phase caused by increased temperatures.

Finally, variations in barometric pressure at the surface of waste rock piles can also influence the pneumatic head and therefore induce gas flow. This process of "barometric pumping" is discussed in more detail in the next section.

As can be deduced from this brief review of the numerous processes affecting gas convection in waste rock piles, it is not a process easily described by analytical solutions, as is the case for oxygen diffusion. Instead, this process is highly non-linear because the three driving forces temperature, gas composition, and air pressure are interdependent. For example, an increase in air temperature (due to pyrite oxidation) produces changes in the gas composition and internal air pressure thus producing more advective airflow into the pile, which in turn produces more internal heating. This non-linear feedback mechanism leads to "self-acceleration" of pyrite oxidation and ARD often observed in advection-dominated waste rock piles. Another non-linear aspect of advective airflow is the strongly non-linear dependency of the relative air permeability on water saturation.

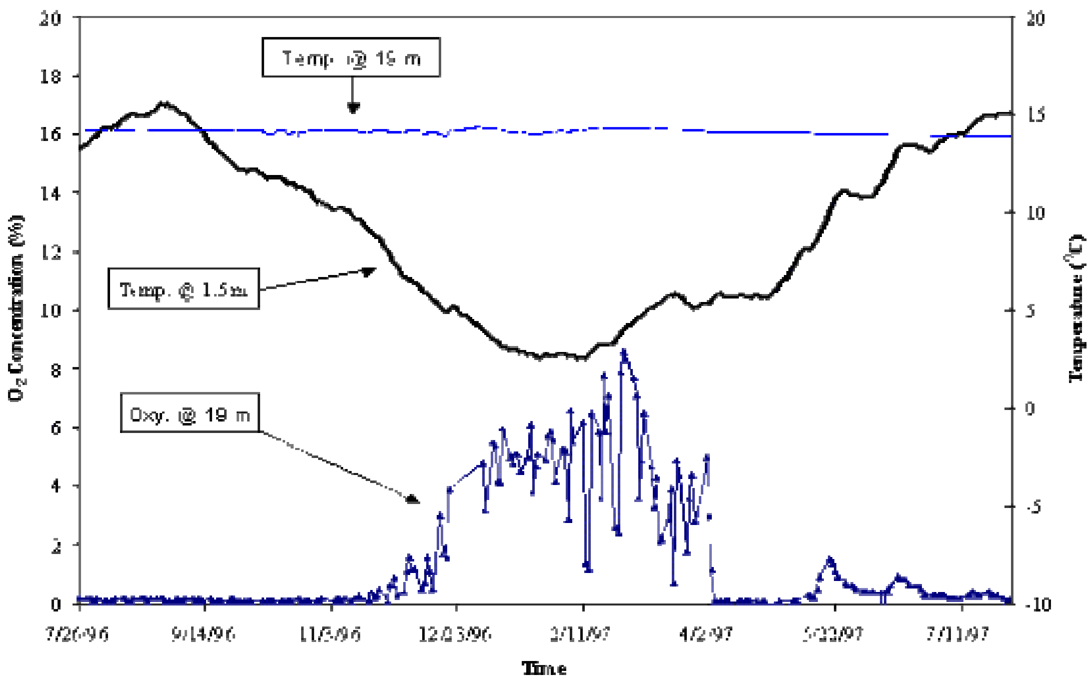


Figure 3. Relationship of oxygen concentrations in the 19 m port to temperatures in the 1.5 m and 19 m ports for Borehole 36, Nordhalde, Germany (From Smolensky et al, 1999).

Airflow is also highly affected by the internal structure and anisotropy of waste rock material making it difficult to estimate "effective" parameters for back-on-the-envelope calculations of oxygen mass flux or oxygen penetration. For example, Wilson, Newman and Ferguson (2000) have proposed a conceptual model of air and water flow in waste rock to describe the "chimney" effect of high permeability semi-vertical layers of coarse material created by free dumping of waste rock. Fala (2002) provides a thorough review of waste rock construction methods, of their effect on the internal structure and on its influence on water flow. Similar effects are likely to influence airflow.

Barometric Pumping

Massmann and Farier (1992) have described the effect of barometric pressure changes on gas transport whereas Lefebvre, Smolensky and Hockley (1998) made preliminary simulations of the effect of barometric pressure changes on ARD production in waste rocks. Figure 4 shows observed variations of in situ oxygen concentration in the well-instrumented Nordhalde pile in response to atmospheric pressure changes. The process involved is the compression of the gas phase within the waste rock pile, which then allows the entry of atmospheric oxygen into the pile. Such effects would be more important for thicker unsaturated waste rock piles as shown by Massmann and Farier (1992). However, anisotropy may be capable of enhancing the local entry of oxygen in zones where waste rock material would locally be more permeable. Much remains to be understood on the net effect of barometric pumping on oxygen supply and ARD production in waste rock piles. Even though increases in barometric pressure would enhance oxygen entry, decreases in pressure would tend to oppose gas flow within waste rock piles. No detailed study has yet been carried to precisely determine the net effect of this potentially important oxygen supply process.

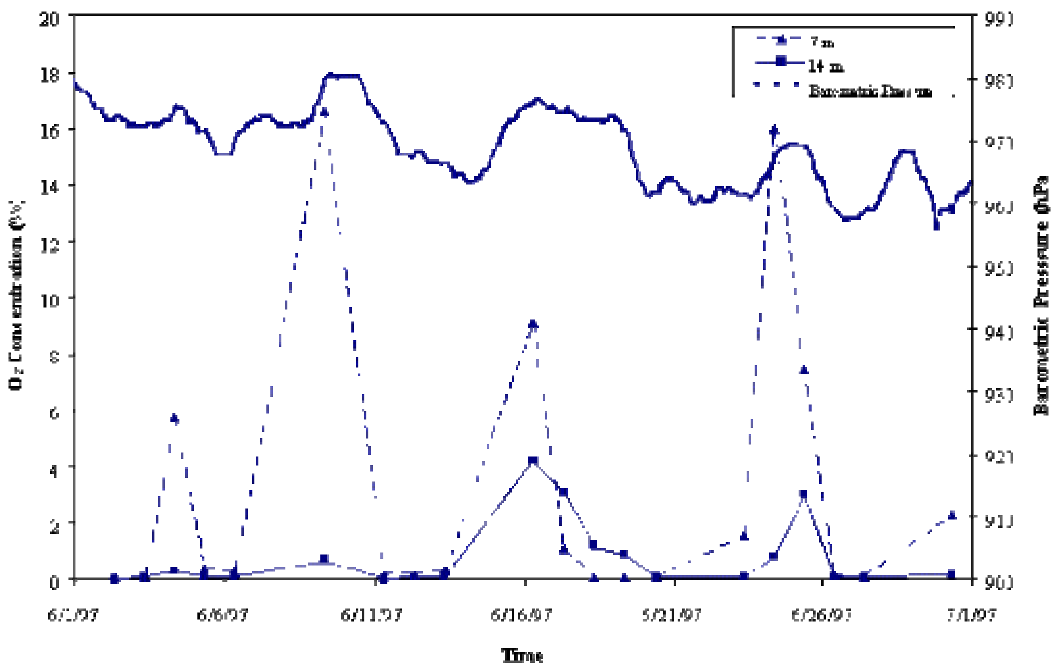


Figure 4. Fluctuations in oxygen concentrations and barometric pressure for Borehole 37, Nordhalde, Germany (from Smolensky et al, 1999).

ASSESSMENT AND PREDICTION OF AIRFLOW

A complex interaction of physical, hydrological, geochemical and microbiological processes contribute to ARD. To be able to assess and predict airflow in a system as large and complex as a waste rock pile, a three-pronged approach is used. The first step involves physical and geochemical characterization of the waste material in order to constrain some of the numerous properties controlling ARD. The second step involves field monitoring to understand the pile's current behavior. The data collected during field monitoring can be used to constrain properties that are difficult to determine in the lab. The results from the characterization and monitoring work are then used to calibrate a numerical model, which constitutes the third step in the approach. The model can be used to identify the main processes responsible for current conditions within a waste rock pile as well as predict future behavior.

In the following sections we provide an overview of the tools available for assessment and prediction of airflow in waste rock piles.

Material Characteristics

The first step in characterizing material from a waste rock dump involves collecting field samples from test pits and/or from drill cuttings (e.g. Swanson et al, 2000). Test pitting provides an excellent opportunity to observe large-scale structures (i.e. chimneys, rubble zones) whose properties cannot be captured with laboratory testing. In conjunction with test pitting, a drilling program may be implemented to collect samples from greater depth for physical/geochemical testing and to perform field measurements of moisture content, paste pH and conductivity. A dual-wall top-hammer percussion drill rig (also known as "Becker Hammer") should be ideally used for this purpose as it minimizes crushing of the sample during drilling and recovery (samples of up to 6" Ǿcan be recovered). In any event, drilling should be carried out with compressed air (not water!) as a drilling fluid to minimize the geochemical disturbance to the cuttings. All samples should be logged with respect to gradation, lithology, mineralisation (with emphasis on carbonate and sulphide content), and degree of alteration/oxidation.

Physical testing of mine rock samples typically includes grain size analysis, permeability tests, in situ water content and moisture retention. The particle size distribution (PSD) determined from the grain size analysis has important implications on various physical, hydrological and geochemical processes that contribute to ARD. The PSD determines the size and shape of pores, which governs permeability, the key property controlling fluid flow. In partially saturated media, such as waste rock piles, the effective permeability is, in part, a function of the capillary properties, which can be derived from the PSD curve. In addition, the PSD influences whether advection or diffusion is the dominant oxygen supply mechanism. The PSD also influences how the pyrite oxidation rate evolves through time, i.e., whether it is controlled by the diffusion of the oxygen through the rock fragments or by the chemical surface oxidation rate (Lefebvre et al, 2001a).

The degree of saturation is another important property affecting the various processes that contribute to ARD. Usually the degree of saturation is calculated from gravimetric water contents measured in situ or determined in the lab. In conjunction with capillary properties, water content is a key factor controlling the effective permeability of liquids and gases in unsaturated soils. The degree of saturation is also used in determining the global heat capacity of the pile and the gas diffusivity in air (Lefebvre et al, 2001a).

The degree of saturation is commonly determined by the lab for various values of matric suction to yield a soil water characteristic curve (SWCC). The position on this curve determines whether fluid flow in the pile is concentrated in the coarse or fine material. Therefore, in situ suction measurements (made with tensiometers) in combination with a PSD and/or SWCC can be used to constrain the effective permeability of the pile (Lefebvre et al, 2001a; Swanson et al, 1998). Permeability can be measured in situ in addition to being inferred from SWCC and PSD curves. Permeability of the liquid phase can be measured in observation boreholes if the base is saturated; otherwise, infiltration tests can be used (Swanson et al, 2000). Air permeability can be measured via gas pumping or injection tests. In some cases the air permeability of waste rock can also be determined by monitoring the response of internal air pressure in response to atmospheric pressure changes (Weeks, 1978).

In waste rock dumps where diffusion is the dominant mechanism, the O2 diffusion coefficient may also be determined in the field using gas pumping or injection tests (e.g. Garvie and Brodie, 1999).

Leachate flow data provide another means of constraining liquid flow and liquid mass transport properties in waste rock piles. Flow data can be analysed using hydrograph separation, infiltration modeling, saturated flow modeling and water balance calculations (e.g. Gelinas et al, 1994). The application of these methods, however, becomes more difficult when only part of the leachate flow is intercepted (Lefebvre et al, 2001a).

Geochemical screening tools include conductivity and paste pH in the field as well as static lab testing including rinse pH and conductivity tests, modified acid base accounting (ABA), and leach extraction tests (e.g. Shaw et al, 2002). Modified ABA is used to classify whether samples are acid generating or acid neutralizing and gives a qualitative indication of pyrite oxidation rate. The pyrite oxidation rate can also be indirectly supported by the leach extraction tests. Leach extraction tests indicate the amount (by weight) of soluble material in a sample. Using geochemical speciation modeling, concentrations in the leachate can be related to expected in situ concentrations, which can, in turn, be used to verify pyrite oxidation rates.

For a more accurate estimate of the oxidation rate of the waste rock material, kinetic tests are required. Hollings, Hendry and Kirkland (2000) determined oxidation rates for various size fractions of waste rock using three independent methods: sulphate measurement in effluent from kinetic cells, sulphate release rates from humidity cells and oxygen consumption rates in kinetic cells. Bennett, Comarmond and Jeffery (2000) found that oxidation rates measured by lab-scale tests (humidity cells and column tests) could be used in predicting short-term behavior of full-scale piles, irrespective of particle size distribution.

By analogy, effective oxidation rates can be estimated at the scale of an entire waste rock dump, if the flow rate and geochemistry of leachate reaching the base of the waste rock pile is known.

Field Monitoring

Field monitoring is essential for understanding the behavior of waste rock piles under current conditions as well as calibrating ARD production models to predict future behavior. To quantify the external processes acting upon the pile, it is necessary to collect location specific meteorological data including precipitation, temperature, air pressure and wind speed/direction. Infiltration and water flow as well as oxygen and heat transport within the waste rock pile are all strongly dependent on climate conditions (Lefebvre et al, 2001a). Hockley et al (2000) found that oxygen transport in the Nordhalde waste rock dump shows a strong seasonal effect, with convection dominating only in the winter months. The data collected from the meteorological stations form the basis of the boundary conditions imposed on the pile in numerical simulations.

As a part of the drilling program, the boreholes should be instrumented for pore gas and temperature monitoring. For example, thermistor wires (for temperature) and nylon pore gas sampling tubes (for O2 and CO2 measurements) can be fixed to the outside of the casing prior to insertion in the borehole (Shaw et al, 2002; Bennett and Timms, 1999). Helgen, Davis and Byrns (2000) used a drive point soil gas probe as well as a down hole inflatable packer fitted with temperature and O2 sampling probes to collect O2 and temperature profiles. Temperature and O2 are key parameters for model calibration as well as determining fluid flow, heat transfer and pyrite oxidation properties (see below). Near surface temperature data can also be used in determining heat transfer properties such as heat conductivity and diffusivity. Oxygen and temperature monitoring should be carried out for a minimum of one year to evaluate seasonal variations (Shaw et al, 2001) and to evaluate whether a pile is actively heating up, at pseudo steady-state, or cooling down (Bennett and Timms, 1999).

Other properties which may be monitored in the field include in-situ air pressure, water content and soil suction (e.g. Nichol, Smith and Beckie, 2000; Rowlett and Barbour, 2000). Coupled with a surface barometer, in-situ air pressure measurements indicate the magnitude by which the pile responds to outside changes in air pressure, which can be used to constrain the pile's effective air permeability (Weeks, 1978; Bennett, Garvie and Ritchie, 1993; Hockley et al, 2000). Water content can be used to calculate the degree of saturation, which directly relates to the effective permeability and global heat capacity of the pile and the gas diffusivity in air. In situ measurements of soil suction can indicate whether fluid flow is concentrated in the coarse or fine materials, which provides an additional constraint on permeability.

If budget allows, the construction of a trial dump is an excellent opportunity to test potential ARD control and mitigation options such as material placements, face treatments and capping treatments. Instrumentation should include lysimeters, a pore gas collection system, thermistors, pressure transducers and a weather station. A well-instrumented and well-characterized trial dump can be used to calibrated/validate a numerical airflow and ARD production model (see below).

Numerical Modeling

Airflow and ARD production in waste rock piles is a complex process involving multiphase flow (gas and water), chemical reactions, heat transfer, and mass transfer in the liquid phase (infiltration) and in the gas phase (advection, diffusion). Numerical simulation is needed to handle all these processes and understand their interactions. Only very few numerical models are currently available to represent the physical processes acting within waste rock piles. FIDHELM was developed by ANSTO and has been widely applied to theoretical as well as field problems (e.g. Pantelis and Ritchie, 1991; Pantelis, 1993; Kuo and Ritchie, 1999). The numerical simulations of waste rock piles described in this paper were carried out with TOUGH AMD developed by Lefebvre (1994 and 1995). TOUGH AMD is adapted to the modeling of acid rock drainage, especially in waste rocks, and allows the representation of the main physical processes involved (Table 1). For a detailed description of this numerical simulator, the reader is referred to Lefebvre et al (2001b).

The numerical simulation of acid rock drainage is very computer intensive because it involves the simultaneous solution of four unknowns (pressure, water saturation, oxygen mass fraction and temperature) at every numerical grid element. It is thus desirable to use relatively coarse grids that still capture the essential geometric features of the system and allow the representation of different material types. In our experience, the selection of an appropriate conceptual model is typically the most important, but also most difficult, step of airflow modeling.

Once a conceptual model has been formulated, the physicochemical properties of the waste rock material(s) need to be selected. Since many of the physical properties required for this model are interrelated, it is imperative that an internally consistent set of parameters is developed. Lefebvre et al (2001a) reviews the physicochemical properties required for model input and summarizes their mathematical relationships. In most applications, those parameters are initially developed from a combination of field and lab measurements, empirical formulae and/or the literature. The large spatial heterogeneity and structural controls on material properties (in particular air permeability) often require the development of "effective" properties that are representative of material properties at the scale of the model grid. Adjustments of those initial estimates are commonly required as part of model calibration.

The airflow model also requires the definition of boundary and initial conditions with respect to temperature, air pressure, water saturation and oxygen concentration. As outlined above, airflow and ARD production is a highly non-linear and dynamic process, which evolves over time. It is therefore essential, to simulate the progression of ARD from the start of pile construction to the time of interest. In many applications, dump construction is relatively short relative to the development of ARD. In those instances, the phase of dump construction can be ignored and initial conditions can be assumed to equal ambient atmospheric condition throughout the waste rock pile. However, if significant pyrite oxidation is known to have occurred already during dump construction, the process of dump construction may have to be simulated explicitly (e.g. using a series of model grids).

Once initial and boundary conditions are specified, the airflow model has to be calibrated. Because of the large number of unknowns a unique model calibration is rarely possible. Instead, parametric runs are typically undertaken, in which key parameters are systematically varied until a good match between observed and simulated system behaviour is achieved (as inferred from in situ measurements of temperature, oxygen, air pressure and/or seepage).

In many waste rock piles, the main properties influencing ARD production are material permeability and reactivity. Permeability controls the flow of fluids, especially gas, in the piles and thus the potential for the onset of thermal gas convection, which supplies the atmospheric oxygen required to sustain the pyrite oxidation process within the piles. Reactivity determines if the oxygen brought in the pile is consumed fast and thus close to the edges of the pile, or rather slowly so that it can penetrate deeper into the pile prior to being consumed. Contrary to intuition, greater reactivity does not necessarily lead to higher temperatures. On one hand, if the reactivity is very large, the oxygen is all consumed near the edge of a pile where heat loss to the atmosphere is strongest. When oxygen can penetrate deeper into a pile, the heat released by pyrite oxidation has a better chance to accumulate leading to higher temperatures. On the other hand, if the reactivity is too small, the heat released is not capable of increasing temperature in the pile significantly. These examples illustrate the need for a transient calibration using a range of observations including in situ air temperature and oxygen concentrations.

Table 1. Processes simulated by TOUGH AMD

System Phases and Components The system includes two fluid phases (liquid and gas) and four components (water, air, oxygen in air, and heat). All components are present in both phases. The state of the system is fixed by four primary variables: fluid pressure, water saturation, oxygen mass fraction in air and temperature. Six secondary variables for each fluid phase allow the calculation of fluxes (saturation, relative permeability, viscosity, density, specific enthalpy and capillary pressure).
Multiphase Fluid Flow

A multiphase formulation of Darcy's Law represents the simultaneous flow of gas and liquid phases under flow potentials including the effects of fluid pressure, temperature and density. Fluid pressures include capillary pressure, which is a function of water saturation. Relative permeability for each fluid phase is also related to water saturation.
Heat Transfer Conduction (Fourier's Law), fluid flow (gas and liquid), and gaseous diffusion of heat are simulated. Latent heat related to liquid vaporization and condensation is considered. The heat stored in solids is considered as well as the heat in fluids. A semi-analytical method is used to calculate conductive heat loss to impermeable confining units at boundaries.
Gaseous Diffusion Diffusion of all mass components in the gas phase is modeled using Fick's Law and an effective diffusion coefficient for a partially water-saturated porous media. A simple "linear" model is used to calculate the effective diffusion coefficient from the water saturation.
Pyrite Oxidation Kinetics A reaction core model is used to calculate the pyrite oxidation rate with first order kinetics relative to oxygen concentration. The reactions consume oxygen and produce heat according to pyrite oxidation thermodynamics. Pyrite remaining and sulphate production are tracked. There is no speciation of dissolved components and no calculation of the geochemical conditions of the solution, nor any consideration of secondary dissolution or precipitation.
Dissolved Mass Transport Dissolved mass transport of the sulphate produced by pyrite oxidation is considered by a simple mass balance after each time step. Other dissolved components such as metals can also be tracked.

CASE STUDIES

In the following we present case studies from three well-characterized waste rock piles where a detailed characterization, monitoring and modeling program was carried out to assess airflow mechanisms and ARD control strategies: the Doyon Mine in Canada (Gelinas, Lefebvre and Choquette, 1992 and Gelinas et al 1994), the Nordhalde in Germany (Hockley et al, 1997; Smolensky et al, 1999), and the Questa Mine in the U.S.A. (Shaw et al, 2002; Lefebvre et al, 2002).

Site Description

The Doyon gold mine is located in Abitibi, Canada, and has been operating since 1978. The South Dump was constructed between 1983 and 1987 and contains approximately 11.5x106 m3 of waste rock. The South Dump is about 900 m long by 500 m wide and has a maximum height of about 35 m. The material consists predominantly of sericite schist with a pyrite content of 7%. The Dump first produced acidic seepage in 1985. The ARD produced is characterized by pH near 2.0 and total dissolved solids (mainly sulfates, iron, aluminum, and magnesium) reaching up to 200,000 mg/L. Acid effluents are collected by a ring of drainage ditches around the dump and pumped to a water treatment plant where acidity is neutralized and heavy metals are precipitated.

The Nordhalde is one of 14 waste rock piles located in the Ronneburg mining district located in former East Germany where extensive uranium mining was carried out between 1946 and 1990 (Hockley et al, 1997). Since 1992, Wismut GmbH has been carrying out extensive mine rehabilitation work in this area. A large portion of the rehabilitation effort has focused on the controlled relocation of mine waste rock to the Lichtenberg pit. The Nordhalde stands approximately 70 m above the original ground surface at its crest, and contains some 27x106 m3 of waste material. Two distinct materials form the pile. Acid generating material, referred to as Zone A, forms the largest portion of the dump volume and consists mainly of slates containing 1-2% pyrite. Typical seepage from this zone has a pH of about 2.7 and sulfate concentrations in excess of 10,000 mg/L. In some portions of the dump, the acid generating material is overlain by so-called Zone C material, which contains enough carbonate material to neutralize the acidity produced by oxidation of its suphides.

The Questa molybdenum mine, owned and operated by Molycorp Inc., is located in the Sangre de Cristo Mountains in Taos County, northern New Mexico. From 1965 to 1983 large-scale open pit mining at the Questa mine produced over 297 million tonnes of mine rock, which was end-dumped into various steep valleys adjacent to the open pit. As a result, the mine rock piles are typically at angle of repose and have long slope lengths (up to 600m), and comparatively shallow depths (~30-60m) (Shaw et al, 2002). The Sugar Shack South rock pile contains about 18x106 m3 of mine rock covering a surface area of approximately 1200 m by 450 m with a maximum thickness (in the valley center) of little over 100 m. The rocks are mixed volcanics with an average pyrite content of about 3.5%. The climate on the mine site is semi-arid with mild summers and cold winters. Mean annual precipitation at the mill site is about 400 mm. Average net infiltration into the mine rock piles is estimated to range from 30 to 90 mm/yr.

Interpretation of Monitoring Data

All three waste rock piles were instrumented to monitor in situ temperature and gas concentrations. Figure 5 shows oxygen and temperature profiles from these three piles over the period of one year. The physicochemical conditions measured in these waste rock piles are quite different. The processes leading to such conditions must then be distinct as well. The Doyon pile shows high temperatures, especially at the edge of the pile where the profiles shown were measured. These temperature and oxygen distributions are attributed to strong thermal gas convection in the pile (Lefebvre and Gelinas, 1995). This is inferred from the upward curvature of the temperature profiles and the decreasing upward oxygen concentrations. Lefebvre, Gelinas and Isabel (1992) have also shown that seasonal changes in the near-surface temperature profiles at this site would indicate strong upward gas flow.

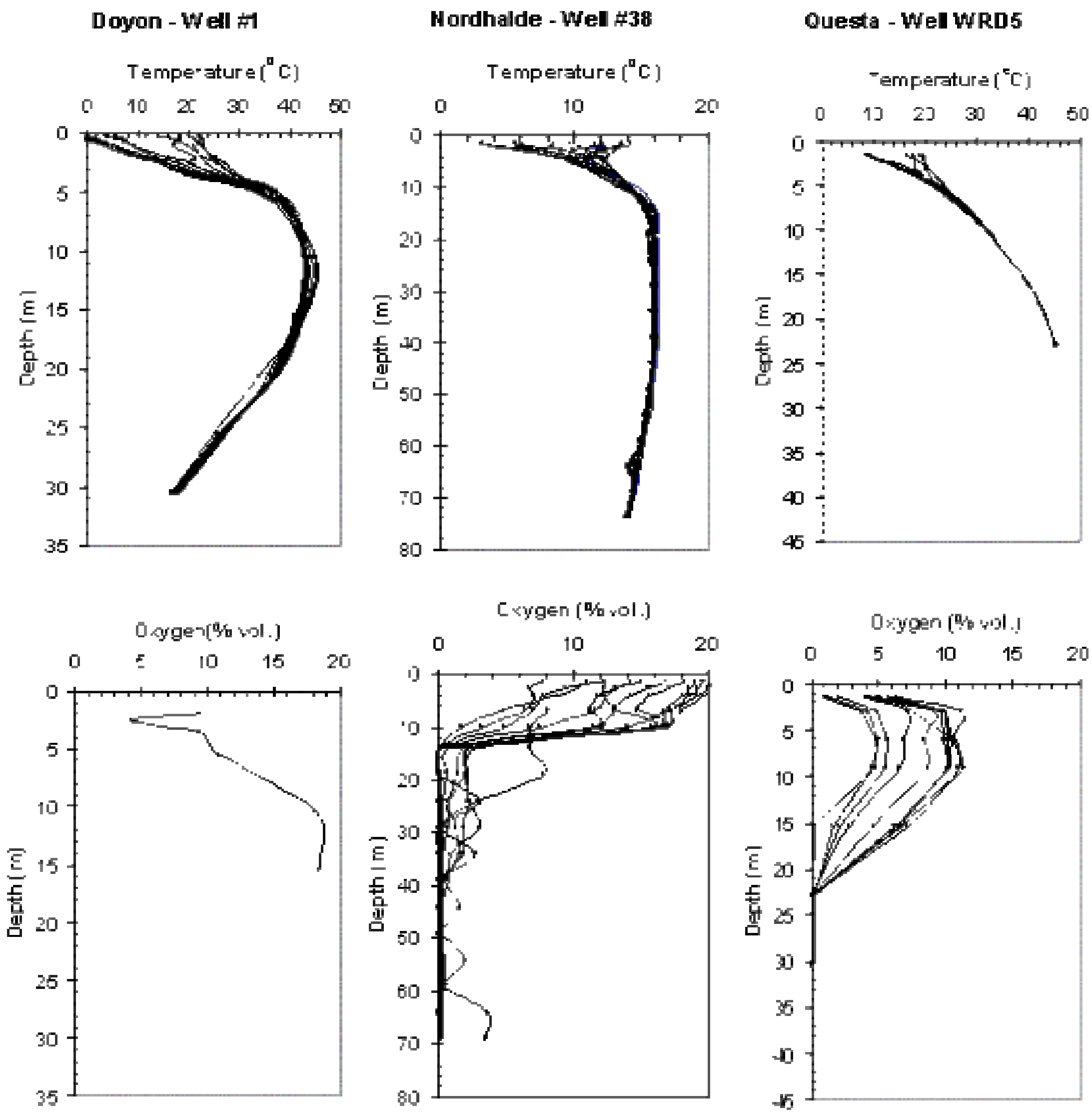


Figure 5. Temperature and oxygen profiles in three waste rock piles: Doyon Mine in Canada, Nordhalde in Germany and Questa in the U.S.A.

In contrast, the Nordhalde temperature profiles show moderate values although the shape of the profiles are similar to Doyon. Lefebvre and Gelinas (1995) have shown that such temperatures could not be reached if diffusion were the sole oxygen supply mechanism in the Nordhalde. Also, as illustrated by Figure 3, seasonal changes in the oxygen profiles imply that upward gas convection controls oxygen supply at this site.

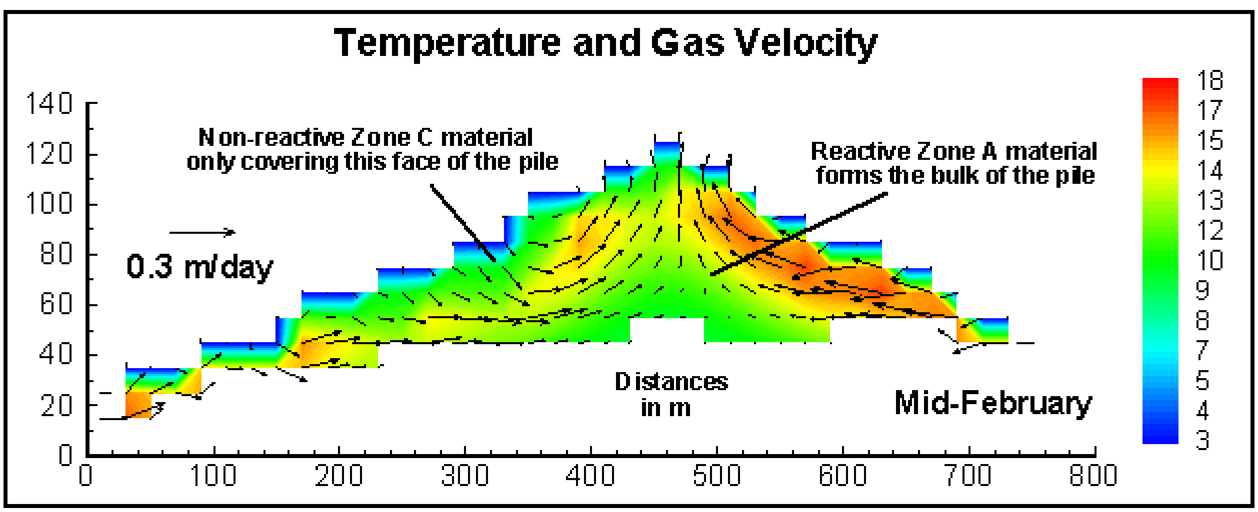
At the Questa site, temperature profiles also reach high values but they have steadily increasing values and regular curvature. The high temperature values imply strong pyrite oxidation that must occur over the entire thickness of the pile according to the steady temperature increase with depth. The high oxygen concentrations indicate that strong lateral gas flow must be responsible for a large supply of oxygen required to maintain such conditions. Table 2 summarizes the different mechanisms acting in these three sites (Lefebvre et al, 2000).

Table 2. Physicochemical processes in the Doyon, Nordhalde and Questa waste rock piles

Processes	Nordhalde	Doyon	Questa
Oxygen Supply	Diffusion and convection	Vertical convection	Lateral convection
Heat Transfer	Conduction	Conduction	Conduction and latent heat effects
Water Transfer	Liquid infiltration	Liquid infiltration	Infiltration and vaporization

Modeling Results

Numerical modeling was carried out at all three sites using TOUGH AMD to confirm the initial interpretation of monitoring data. Figure 6 shows some of the numerical modeling results obtained for the Nordhalde (top) (Lefebvre, Smolensky and Hockley, 1998; Smolensky et al, 1999), Doyon (center) (Lefebvre, 1994 and 1995), and Questa (lower) (Lefebvre, Lamontagne and Wels, 2001c and Lefebvre et al 2002) waste rock piles. In all three cases, temperature is shown as color shades whereas arrows indicate the gas velocity. In all three cases, the calibrated model reproduced the general physical conditions measured in these piles fairly well (compare Figures 5 and 6).



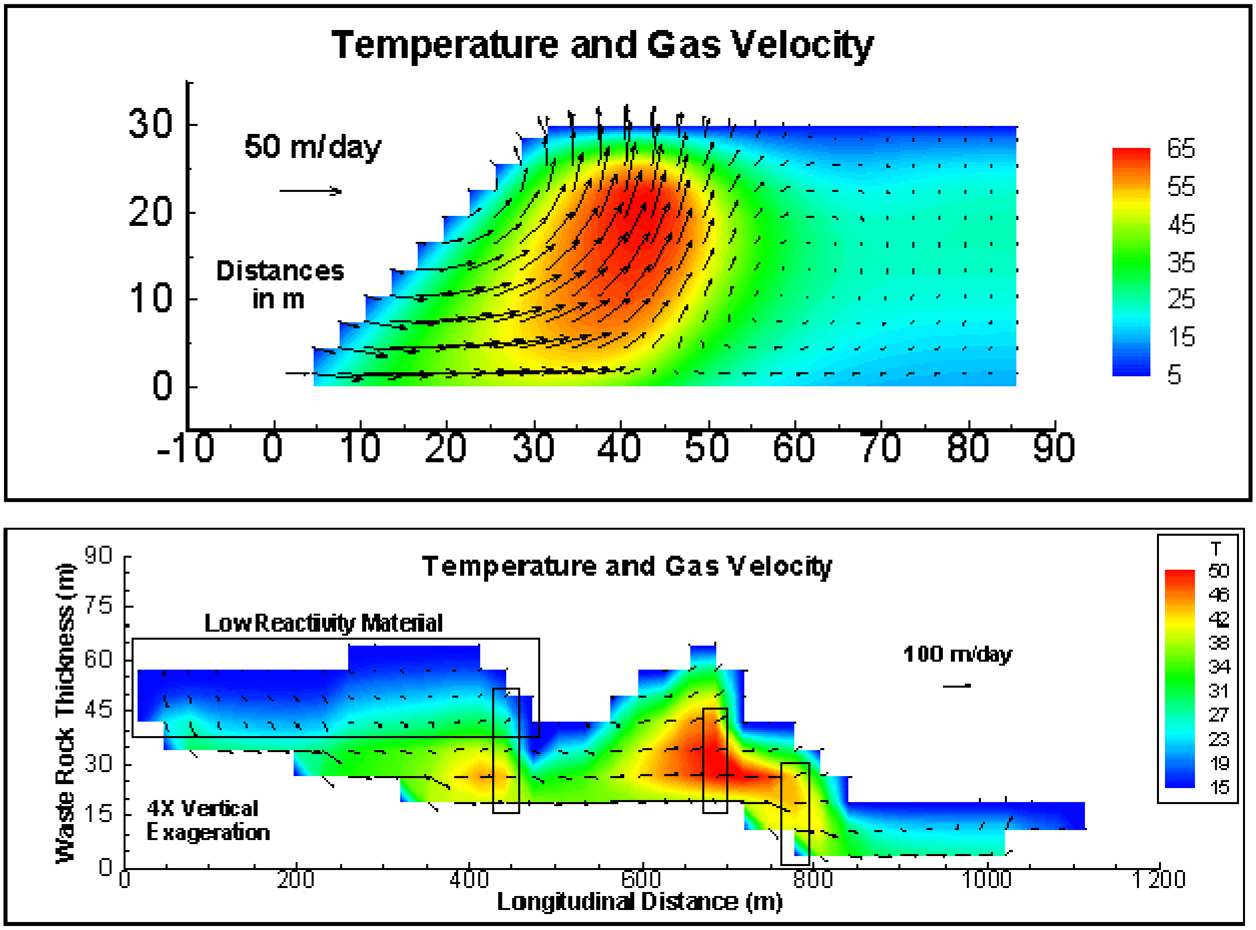


Figure 6. Simulated temperature and gas velocity for the Nordhalde (top, Lefebvre, Smolensky and Hockley, 1998), Doyon (center, Lefebvre, 1994) and Questa (bottom, Lefebvre et al, 2002) waste rock piles.

The numerical simulations provide a quantitative representation of processes inferred from the field observations (Table 2). The Nordhalde is shown to have light upward gas advection leading to a moderate increase in temperature. The Doyon pile has a very strong thermal convection at the edge of the pile producing a very high increase in temperature. At Questa, the peculiar geometry of the Sugar Shack South waste rock pile at Questa (a thin veneer of waste rock end-dumped over a mountain side at an angle of about 30 degrees) leads to a very strong lateral thermal gas convection along the length of the pile and thus a strong increase in temperature. This convection allows oxygen concentrations to remain high over the entire pile (not shown).

The calibrated models provide quantitative estimates of several parameters critical for an assessment of ARD generated within each pile, including oxygen mass flux within the pile, the depth of oxygen penetration, and global oxidation rate. Table 3 summarizes those parameters for the three waste rock piles studied. The model simulations suggest that ARD production at Doyon is about 40 times greater than at the Nordhalde. Simulated ARD production for the Questa pile falls in between those two extremes.

Table 3. Simulated ARD conditions in three waste rock piles using TOUGH AMD.

Parameter	Nordhalde	Doyon	Questa
Air velocity (m/day)	0.2	50	100
Depth of Oxygen Penetration (m)	~50	~50	>30 (full width)
Oxidation Rate (kg O2 /m3/yr)	0.058	2.6	0.33

AIRFLOW CONTROL STRATEGIES

Waste rock dumps are almost always constructed in such a fashion that they remain unsaturated, consequently, both liquid and air flow must be considered when mitigating ARD production. In most cases, there is sufficient pore water to sustain oxidation, therefore, controlling airflow and hence O2 supply becomes the major practicable means of controlling ARD. Airflow can be minimized both during pile and after pile construction.

Options to minimize airflow during construction

Pile geometry is a key parameter controlling airflow patterns in waste rock piles. Numerical simulations demonstrate that pile geometry, namely sloping of the pile and the presence of benches, could initiate convection regardless of the specific distribution or permeability of the materials contained within the pile (Lefebvre, Lamontagne and Wels, 2001c). Benches provide preferential gas entry and exit pathways, even when they do not represent large irregularities on the scale of the waste rock pile, therefore their presence should be minimized.

The height and slope of the pile should also be taken into consideration when trying to curtail convection. Kuo and Ritchie (1999) developed a phase diagram to delineate when bulk convection (convection occurring in the center of the dump) will and will not occur, based on pile height and a term related to buoyancy-driven instabilities.

Choosing an appropriate method of pile construction provides another means of controlling airflow. Where permissible by mine design and budget, the use of face dumping should be avoided. In this method of pile construction, gravity sorting leads to the formation of basal rubble zones and inclined interbedded layers of coarse and fine material (Herasymuik, 1996; Wilson, Newman and Ferguson, 2000). The fine layers provide conduits for water flow into the pile, while the rubble zone at the base allows for influx of O2-rich air. The inclined coarse layers allow for venting of warm gases to the surface (chimney effect). In essence, the structured pile with high vertical permeability that results from face dumping promotes convection.

Instead, truck dumping should be used as an alternative means of pile construction. This method limits the formation of structures with high vertical permeability and allows for the introduction of horizontal compacted layers with a low permeability. These compacted layers provide vertical barriers to liquid and gas flow, thereby inhibiting convection. Using this method, special waste rock dumps for reactive wastes can be constructed in a way that layers of the reactive, potentially acid generating waste can be encapsulated by a low permeability, potentially acid neutralizing layer before acidic conditions have a chance to develop (Day, Flemming and Demchuck, 2000). In periods of reduced mining activity, hence reduced waste production, intermediate till layers can be placed to further isolate the wastes.

The co-disposal of tailings and waste rock is a developing technology for mine waste management. By incorporating tailings into the matrix of the waste rock during construction of the pile (bulk co-mingling), the void spaces that would normally be occupied by air are instead filled with a saturated, low permeability material that can maintain saturation under larger suctions than waste rock alone (Wilson, Newman and Ferguson, 2000). As a result, oxygen transport is limited to diffusion through water, effectively minimizing oxidation rates. Tailings can also be introduced as distinct layers within the waste rock. Numerical simulations on the Doyon waste rock pile show that in addition to being a capillary barrier, these layers also limit gas convection to the outer edge of the pile (Lefebvre et al, 2001b).

Options to control airflow after construction

While taking measures to control airflow during pile construction is ideal, it is not always a workable option. Even when these measures have been used during construction, the pile usually requires some form of post-construction modification for closure.

In many cases, waste rock dumps are face-dumped in benches with coarse rubble zones occurring along the base and slopes at the angle of repose (43o or 1.1:1 grade). Resloping of the pile can be carried out to minimize the benches and cover the rubble zone at the toe, which form principle pathways for airflow into the pile (Lefebvre, Lamontagne and Wels, 2001c). Typically, slopes are re-graded to 18o (3:1), which represents the maximum slope that dozers can safely traverse. Numerical simulations have suggested that while resloping does significantly change gas flow patterns and temperature distributions within the pile, it may not entirely stop convection and acid rock drainage without additional control strategies (Lefebvre, Lamontagne and Wels, 2001c).

In conjunction with resloping, low permeability covers may be placed to limit the influx of water and/or air into the waste rock dump. The requirements for the low permeability cover depend a lot on whether the cover is intended to prevent flow of water or air into the pile. Typically, the permeability required to control airflow is a lot less stringent than for controlling infiltration. For instance, low permeability covers typically require a hydraulic conductivity in the range of 1x10-9 to 1x10-10 m/s corresponding to an infiltration rate of 3 to 30 mm/yr. Airflow modeling of the Sugar Shack waste rock pile at the Questa mine site demonstrated that convection could essentially be shut down by a cover with a permeability of 3x10-13 m2, roughly equivalent to a hydraulic conductivity of 3x10-6 m/s or an infiltration rate of over 90,000 mm/yr (Lefebvre, Lamontagne and Wels, 2001c). Clearly, such a cover would not be adequate for controlling infiltration.

In simulations of the Doyon waste rock pile, it was shown that placement of a low permeability cover (10-14 m2) along the sides of pile and not on the top was sufficient to significantly change convection patterns and was predicted to decrease the global oxidation rate and curb ARD production (Lefebvre et al, 2001b).

CONCLUSIONS

The key mechanisms controlling oxygen transport into waste rock piles are diffusion, convection and barometric pumping. The processes of diffusion and advection are well understood and numerical models are available to estimate their relative importance and magnitude. However, the effects of barometric pumping on oxygen transport and ARD production are still poorly understood and require future research.

A detailed characterization program including material sampling/characterization, field monitoring and numerical modeling is required to allow a quantitative assessment of airflow and ARD production. Once a numerical model has been calibrated it can be used to predict the effect of various control strategies on future airflow and ARD production. Numerical modeling of airflow and ARD production is still under development. Our ability to simulate and predict airflow in waste rock piles is likely to improve with advances in numerical methods and computer capacity and better instrumentation of waste rock piles.

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