

Evaluation of the Function of the Dry Cover System at WRD5 at the Boliden Aitik Copper Mine, Northern Sweden

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Abstract

The Boliden Aitik copper mine is located outside Gällivare, northern Sweden (67° N). Since mining started in 1968, more than 500 Mt of waste rock have been deposited in waste rock dumps (WRDs) surrounding the open pit mine. In the 1990's, a dry cover system was designed to reduce oxygen diffusion to the underlying waste rock and limit subsequent formation of acid rock drainage (ARD). The cover system consists of 1.0 m compacted glacial till placed in two lifts, which is covered by 0.3 m organic material. As part of ongoing reclamation activities at Aitik, this dry cover design has been applied to WRD5 and parts of WRD2. Due to the difficulty in evaluating the function of a dry cover system design based on oxygen measurements in a WRD that has not been completely covered, a new monitoring system was designed and commissioned in 2008, which focuses on temporal and moisture flow dynamics within the till cover system and underlying waste rock. To compare field data collected to design oxygen ingress rates, a numerical model was calibrated to represent the covered WRD5 field conditions, which predicted oxygen diffusion fluxes going through the cover system. To understand the relative influence advection has on WRD5 compared to diffusion, an analytical model was developed to estimate oxygen diffusion and advection fluxes through the cover. The results of the modelling program with conservative assumptions indicated that the current cover system in place on WRD5 is not performing according to the original design criteria with respect to oxygen ingress.

Key Words: field performance monitoring, numerical modelling, oxygen ingress

Introduction

The principle design objective of a cover system for reactive mine waste is to control acid rock drainage (ARD) by preventing moisture and oxygen movement into and through the waste material. To prevent oxygen ingress it is important to install a robust cover system that will maintain a tension-saturated layer within the cover system, which relies greatly on the climate conditions at the mine site (MEND 2004).

As part of closure activities, Boliden has designed and constructed a full-scale cover system on some of the waste rock dumps (WRDs) at the Aitik mine site in northern Sweden. This paper presents a review of the design and construction of the full-scale cover system on WRD5, and early studies and monitoring completed to date, with the primary focus on evaluation of performance of the cover system based on three years of field monitoring data.

Background

Boliden's Aitik (Aitik) mine, located 100 km north of the Arctic Circle and 15 km southeast of the town Gällivare, is the largest copper mine in Europe with an annual production exceeding 27 Mt of ore in 2010. The climate in the area is subarctic, characterized by long, cold winters and short mild summers. The site has an annual precipitation and potential evaporation of approximately 575 mm and 350 mm, respectively.

The current WRD5 footprint is approximately 49 ha with a dump height of approximately 60 m constructed in three lifts. The waste rock was separated into non-sulphidic and sulphidic waste rock to

allow for less extensive decommissioning procedures. Approximately 35% of the waste rock was found to be potentially ARD producing (Lindvall 2005).

When Aitik received its formal operating license in 1970 a closure plan was not discussed. Boliden was later required to develop a decommissioning plan for the entire site in 1989. Investigations were initiated to develop and evaluate various closure plans for the Aitik WRDs and tailings. A conceptual decommissioning plan was submitted in 1993 with modifications in 1994 and 1996 after laboratory, field, and modelling investigations were completed. In 1997, a permit for decommissioning the WRDs was issued after design of an acceptable dry cover system.

WRD5 Design and Construction

In 1993, studies were completed to evaluate the WRDs at Aitik. Studies included characterization of waste and potential cover materials as well as surface water investigations. Eleven (11) multi-level probes for gas sampling and temperature measurements were installed in drill holes up to 24 m deep in areas of the south-western WRD. Oxygen concentrations and diffusion coefficients were measured and used to estimate reaction rates within the south-western WRD. Most of the waste material was reported to be inert with highly reactive waste located in pods throughout the dumps (Gibson and Ritchie 1993).

In 1996, Australian Nuclear Science and Technology Organisation (ANSTO) completed a numerical modelling program to design a cover system for the WRDs at Aitik to limit the ingress of oxygen into the waste rock material and as such limit ARD (Ritchie 1996). The model HEAPCOV, a one-dimensional gas/water/heat transport program that quantifies sulfide oxidation rates in WRDs, was used to estimate the overall oxidation rate in covered and uncovered WRDs at Aitik.

Different combinations of moraine till and tailings sand were modelled with varying layer thickness and hydraulic properties as well as variable infiltration rates representative of both average and dry years. Properties such as dump height, bulk density, sulfur content and saturated hydraulic conductivity (k_{sat}) were estimated based on those expected at Aitik. The k_{sat} of the waste rock was estimated to be 1×10^{-4} m/s, while the moraine till k_{sat} was predicted to range from 1.5×10^{-7} m/s to 4.5×10^{-8} m/s. Models were run using both the maximum and minimum estimated k_{sat} values for the till.

The maximum intrinsic oxidation rate used for the dump material was 1×10^{-8} kg(O₂)/m³/s, which correlated to the highest rate calculated from the oxygen concentrations measured (Gibson and Ritchie 1993). The Millington and Shearer (1971) formulation of the oxygen diffusion coefficient was used. The study concluded that an effective dry cover, such as a 1.0 m compacted moraine till cover system, would reduce the oxygen flux due to diffusion into the waste rock material to below 1.2×10^{-9} kg(O₂)/m²/s (Ritchie 1996). This value represented an overall oxidation rate reduction of more than 100 times compared to an uncovered WRD simulation.

Based on these modelling results, Boliden constructed a nominal 1.0 m till cover system on WRD5 and part of WRD2. The cover design consisted of 1.0 m of till, distributed in two 0.5 m layers, which were compacted individually and overlain by 0.3 m of organic material. The latter material is currently comprised of municipal sludge from Stockholm, Sweden. Boliden commenced cover placement in 1997 with a 14 ha area of WRD5. The covered area was expanded in 2006 and cover construction continued on the dump until completion in 2011. The surface of the cover system was vegetated with grass after construction and surface water diverted to rip-rapped channels constructed along benches and down slopes (Lindvall and Eriksson 2005).

Monitoring Program Results

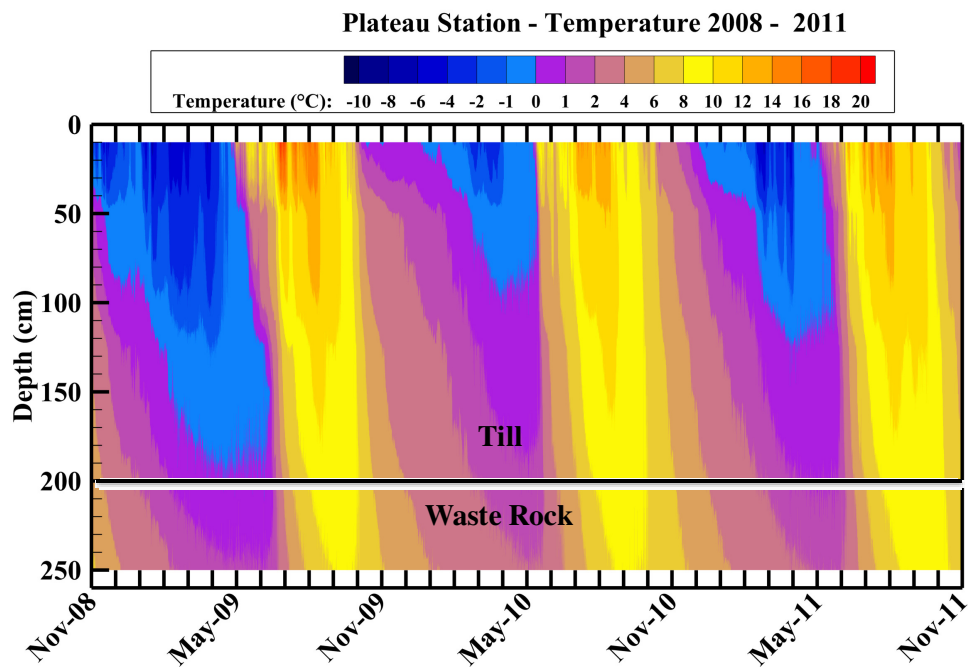
In 2000, a field installation was completed on WRD5 to measure water infiltration rates through the cover as well as waste surface oxygen concentrations, to evaluate effectiveness of the cover system in reducing overall oxidation rates. Three pairs of drainage lysimeters were installed, each comprising an open top 200 L plastic drum buried beneath the cover / waste rock interface. Eight (8) in-cover fluxmeters were installed in pairs at the cover / waste rock interface. Four (4) probe holes were installed throughout the cover to sample pore-gas (Timms 2001). The cover system on WRD5 was not completed at the time of monitoring and measurements were taken for a limited time after construction; therefore, it proved difficult to evaluate effectiveness of the full-scale cover system.

Additional performance monitoring systems were installed on WRD5 in July 2008. Three new monitoring sites were established: one on the upper, flat plateau area and one on each of the east- and west-facing slopes. Field data collected include *in situ* soil matric suction and temperature, *in situ* soil water content and changes in water storage, rainfall, air temperature, relative humidity, net radiation, wind speed and direction, and snowpack thickness. The monitoring system characterizes the range of *in situ* temperature and moisture flow dynamics within the till cover system and shallow underlying waste rock material.

Figure 1 shows temperature profile contours from 2008-2011 at the Plateau station. It should be noted that the till cover at the Plateau station is 2.0 m thick due to this station being located at the overlap of the cover constructed in 1997 and the 2006 cover expansion. The cover is generally 1.0 m thick on the remaining area of the plateau. The temperature data show that freezing temperatures extended through the entire cover profile in 2009. The maximum depth of freezing was approximately 180 cm at the Plateau station, 90 cm at the East station, and 30 cm at the West station, which all occurred in the first year of monitoring. The maximum depth of freezing was shallower in the following two monitoring years. It is likely that the depth of freezing at the Plateau station in the first year of monitoring was due to lack of vegetation established on the plateau area at that time and late development of a snowpack. It was estimated that freezing would penetrate to a maximum depth of 70 cm (Lindvall 1996); therefore, it is a concern that freeze/thaw cycling deep into the till cover system could potentially alter the as-constructed structure of the compacted till layer and negatively affect performance of the cover system.

Figure 1. Plateau temperature profile contours for 2008-2011.

In situ soil matric suction and *in situ* soil water content measurements were used to look at the saturation profile of the cover system as shown for the Plateau station in Figure 2. The blank areas within Figure 2 represent periods of frozen or partially frozen material within the cover system. A cover system containing a layer maintained at a degree of saturation equal to or greater than 85% is generally required to efficiently limit oxygen ingress (McMullen et al. 1997, Bussière and Aubertin 1999, MEND 2004), but is not necessarily mandatory to decrease oxygen ingress to site-specific acceptable levels. Based on field measurements of saturation shown in Figure 2, the cover system does not maintain a layer of saturation greater than 85% all year round; suggesting that even till material at depth can reach a slightly drained condition. The cover system had a layer with a degree of saturation which remained above 65% for the three-year monitoring period.



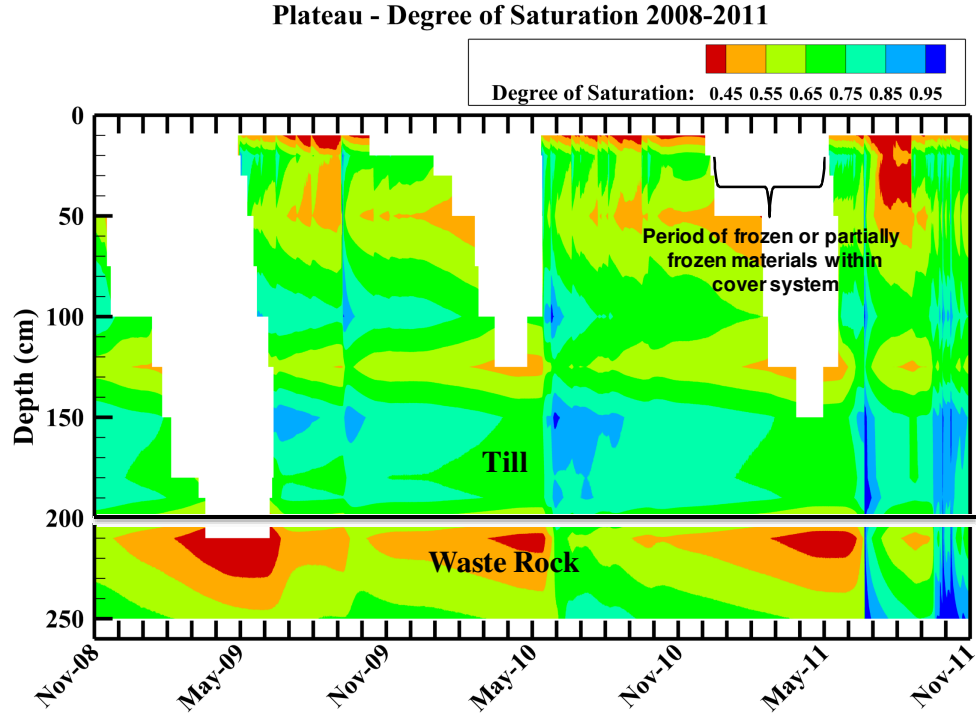


Figure 2. Plateau degree of saturation profile contours for 2008-2011.

Based on field data collected, a simple water balance was completed for the cover system to quantify the volume of water percolating through the cover system. The water balance for the Plateau site for 2009-2010 was completed based on field measurements and solving the water balance equation on a daily basis during the frost-free period (approximately April 20th to October 31st). The water balance for a sloping cover system consists of the following components expressed in mm:

$$\text{PPT} = \text{RO} + \text{AET} + \text{NP} + \Delta\text{S} + \text{ITF} \quad (\text{Equation 1})$$

where PPT = precipitation (rainfall plus snow water equivalent), RO = runoff, AET = actual evapotranspiration, NP = net percolation, ΔS = change in moisture storage, and ITF = interflow or lateral drainage within the cover profile.

Precipitation is measured at site with a tipping bucket gauge and snow surveys; RO is not measured but was estimated using an assumed runoff coefficient dependent on the magnitude of the rainfall event or snowmelt. AET was estimated based on rates of potential evaporation and climate data from the station. NP is not measured directly, but was estimated based on water content and suction sensor data. Change in moisture storage was calculated using volumetric water content data recorded at each monitoring station, while ITF was assumed to be negligible because the plateau area is relatively flat.

A relatively good match between measured and calculated change in moisture storage was obtained for the Plateau station during the monitoring period (see Figure 3). The average AET/PE ratio for the monitoring location was 0.86 and the estimated net percolation for the 2009-10 period was approximately 119 mm, or 21% of the 562 mm total precipitation (rainfall + SWE). Total estimated runoff was 177 mm or 31% of total precipitation.

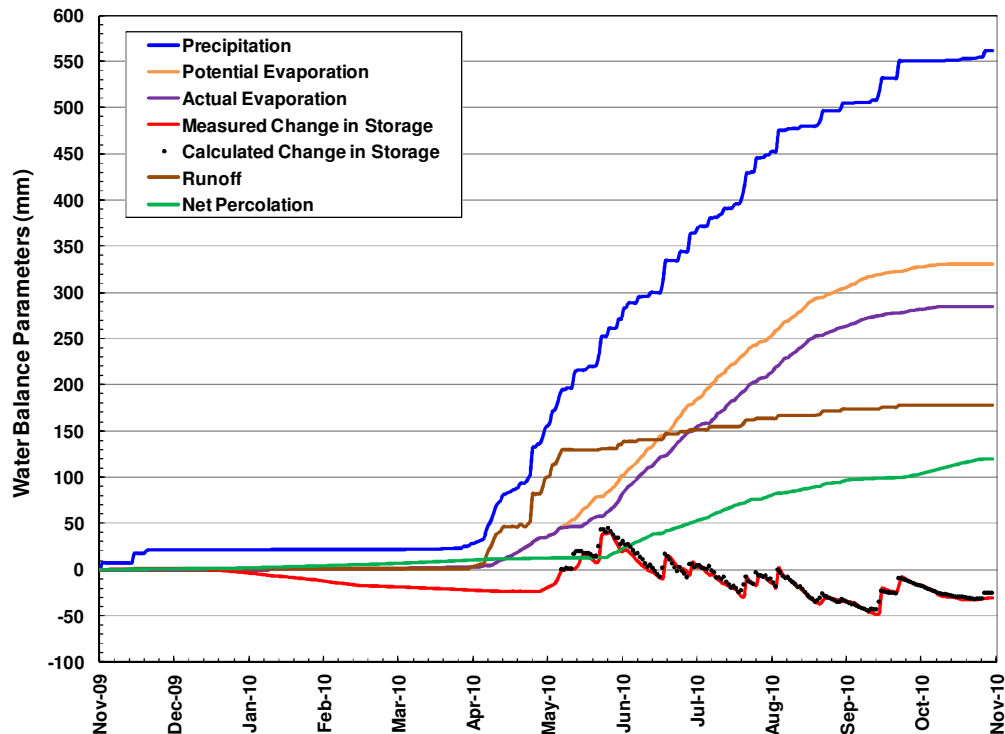


Figure 3. Cumulative water balance fluxes for Plateau station for the 2009-10 monitoring period.

Discrepancy Between Original Cover Design Objectives and Current Monitoring Program

The WRD5 cover system was designed to limit oxygen ingress but the gas flux monitoring system is currently not monitored. A gap exists between the approach taken to evaluate performance from the 2008 instrumentation program compared to characterization of oxygen ingress or flux into the waste rock materials. It was not possible to verify the oxygen limiting capabilities of the cover system from data being collected from the 2008 instrumentation program. A field program was completed in the fall of 2011 to enhance the existing monitoring program and better characterize performance of the cover system. These results were not available at the time of preparing this publication.

Numerical model calibration

The Geo-Slope software, VADOSE/W (Krahn 2007), was calibrated to field performance data collected from the monitoring stations established in 2008. VADOSE/W is a fully coupled heat and mass transfer model (through the vapour pressure term), which is capable of predicting water vapour movement, and actual evaporation and transpiration based on potential evaporation and predicted soil suction.

Calibration of a numerical model to measured *in situ* conditions allows for predicting performance of a full-scale cover system design in terms of both net percolation and oxygen ingress to underlying waste rock. Note that VADOSE/W only solves oxygen transfer as diffusion; advection was not numerically modelled.

Using the calibrated model to estimate oxygen diffusion rates provides a connection between data currently being collected at site and the 1996 cover design modelling results; namely, performance of the cover system in limiting oxygen ingress via diffusion. Field data collected at the Plateau station were used to calibrate the model. The three-year period used for model calibration was November 1, 2008 to October 31, 2011. The three-year average precipitation at the Plateau station was 536 mm, which included annual precipitation of 422 mm, 562 mm, and 625 mm for periods running November 1st to October 31st of 2008-2011.

The Plateau model was calibrated to measured *in situ* moisture conditions, suction and temperature over the three-year period. Performance of the cover system over the three-year monitoring period was evaluated based on net percolation and oxygen flux to underlying waste rock predicted by the calibrated model. The average net percolation value estimated by the Plateau model was approximately 19% of recorded precipitation.

Oxygen ingress investigation

Oxygen movement in porous media can move by diffusion through both the air and water phases of porous media. Oxygen can also move by advection due to barometric pumping, wind effects, thermal gradients, or volume displacement during infiltration (Wels et al. 2003).

Oxygen diffusion

Oxygen diffusion is dependent on the change in oxygen concentration and distance across the cover system, as well as a diffusion coefficient, which is dependent on the degree of saturation of the cover system. An analytical calculation of diffusion using Fick's First Law was conducted for the WRD5 cover system using field measurements of water content and porosity values based on field testing. As a worst case scenario the concentration at the base of the cover system was assumed to be 0%. Fick's First Law is given in Equation 2:

$$q = -D^* \frac{\partial C}{\partial x} \quad (\text{Equation 2})$$

where q = mass flux of oxygen ($\text{kg}/\text{m}^2/\text{s}$), D^* = diffusion coefficient (m^2/s), C = oxygen concentration (kg/m^3), and x = depth (m). For multi-layered systems, an equivalent porosity (n_{eq}) and the bulk diffusion coefficient (D^*) are often combined into the variable D_e , effective diffusion coefficient, as defined in Equation 3:

$$D_e = n_{eq} D^* \quad (\text{Equation 3})$$

Aachib et al. (2002, 2004) have developed the following equation for D_e based on the Collin and Rasumson (1988) formulation:

$$D_e = \frac{1}{n^2} \left[D_a^0 n_a^{3.4} + H D_w^0 n_w^{3.4} \right] \quad (\text{Equation 4})$$

where D_a^0 = diffusion coefficient of gas through air (m^2/s), D_w^0 = diffusion coefficient of gas through water (m^2/s), n = soil total porosity (m^3/m^3), n_a = volumetric air content (m^3/m^3), n_w = volumetric water content (m^3/m^3), and H = Henry's Law coefficient (approximated as 0.03 for O_2 in air and water at 25 °C). VADOSE/W also uses the previously described Collin and Rasumson (1988) method for obtaining the effective diffusion coefficient.

The estimated oxygen diffusion fluxes from both methods for the three-year monitoring period are shown in Figure 4. For comparison, the estimated maximum oxygen diffusion for the compacted till cover system from the 1996 design modelling program is also presented. The oxygen concentration assumed at

the base of the cover system for the 1996 modelling program is not known as the model used was not based on concentration, but rather an intrinsic oxidation rate.

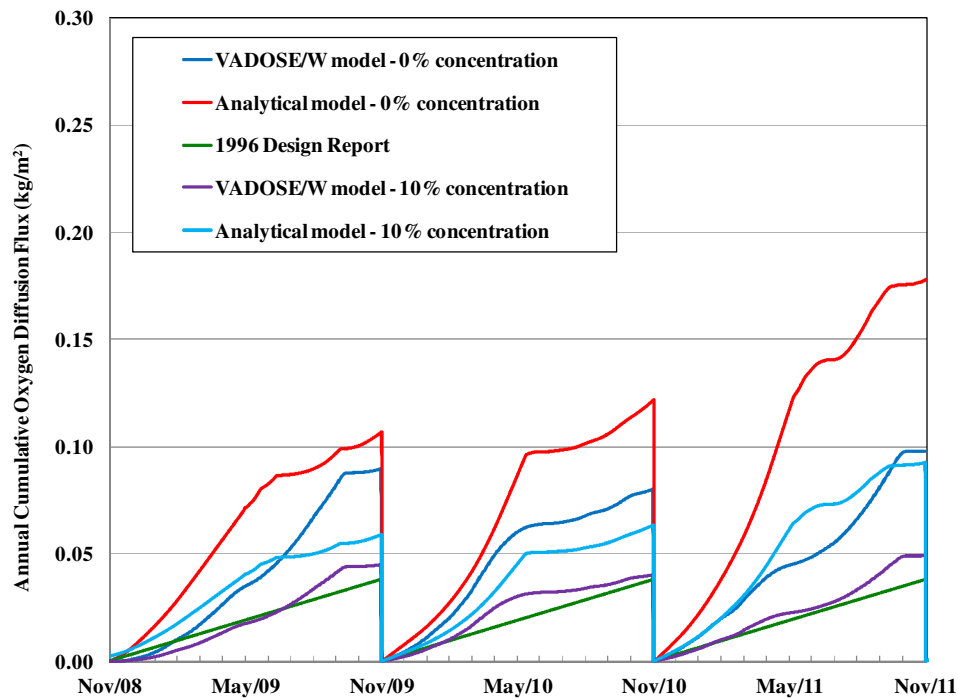


Figure 4. Cumulative oxygen diffusion flux for the three-year monitoring period.

Based on the modelling results shown, it appears that predicted oxygen ingress is greater than that estimated from the 1996 design modelling program. The VADOSE/W predicted diffusion, based on a 0% oxygen concentration at the base of the cover system, was two times that of the 1996 design modelling value, averaging 0.08 kg/m^2 per year, while the analytical solution provided the largest estimate of diffusion, averaging 0.13 kg/m^2 per year, three times the 1996 design modelling value. These differences could be due to a number of factors such as different assumed k_{sat} values, net infiltration rates, and initial oxygen concentrations applied to the models.

In the absence of field measured values with a fully established cover system, a conservative boundary condition was used in the oxygen ingress modelling. In practice, the 0% concentration gradient at the top of the waste rock profile directly below the till cover system produces instantaneous consumption of oxygen upon contact. As soon as oxygen reaches the waste rock it is consumed and factors such as oxygen consumption in the overlying till or organic topsoil layers, or the intrinsic oxidation rate of the waste rock itself (based on the geochemical properties of the waste rock) do not influence the oxygen ingress rate. Assumptions including moving the concentration boundary deeper into the waste rock profile, decreasing the oxygen concentration boundary, and introducing oxygen consumption within the cover profile due to the presence of the till and organic topsoil layers would decrease the predicted diffusion.

A sensitivity study was completed both with the numerical and analytical models to show the influence of oxygen concentration at the base of the cover system on the estimated diffusion fluxes. The diffusion rate for an oxygen concentration of approximately 10% at the base of the cover system is shown in Figure 4 for both the analytical and numerical model. The VADOSE/W model with the less conservative assumption of 10% oxygen concentration at the base of the cover predicted diffusion values that are relatively similar to the 1996 design report diffusion estimates.

Table 1 compares the estimated diffusion fluxes through the Plateau till cover system with a range of assumed oxygen concentration boundaries and depth of concentration boundary. The values highlighted in light grey represent results below the 1996 cover design predicted flux. Similar to previous simulations, the changes in degree of saturation of the cover system were considered over the three-year period. The predicted oxygen diffusion flux was influenced by the depth of the boundary condition beneath the base of the cover system. Increasing the depth of the concentration boundary condition produced estimated oxygen diffusion fluxes below the 1996 design flux even maintaining a conservative 0% oxygen concentration boundary. Note that moving the oxygen concentration boundary condition deeper into the waste rock represents a layer of non-acid generating waste above the concentration boundary condition. The sensitivity analysis highlighted the importance of properly characterizing the *in situ* oxygen condition within WRD5.

Table 1. Average annual diffusion flux for varying boundary condition depth and concentration.

Simulation	Depth of Boundary ¹	Boundary Concentration	VADOSE/W Model	% Decrease of Oxygen Diffusion	Analytical Model	% Decrease of Oxygen Diffusion
1 Conservative Base Case	0 m	0%	0.080 kg/m²/yr	-	0.130 kg/m²/yr	-
2	0 m	5%			0.104 kg/m ² /yr	20%
3	0 m	10%	0.046 kg/m ² /yr	42%	0.071 kg/m ² /yr	53%
4	5 m	0%	0.050 kg/m ² /yr	38%	0.026 kg/m ² /yr	80%
5	5 m	5%			0.020 kg/m ² /yr	85%
6	5 m	10%	0.029 kg/m ² /yr	64%	0.014 kg/m ² /yr	89%
7	10 m	0%			0.015 kg/m ² /yr	88%
8	10 m	5%			0.011 kg/m ² /yr	92%
9	10 m	10%			0.008 kg/m ² /yr	94%

¹ Depth measured from the base of the cover system.

Finally, it should be noted that the 1996 WRD5 cover system design was predicted to reduce annual diffusion flux by approximately 100 times compared to an uncovered waste rock condition. Based on conservative assumptions, the current oxygen diffusion flux exceeds the 1996 cover system design value.

Relative influence of advection

Although gas transport through diffusion is generally considered the dominant mechanism (Mendoza and Frind 1990), advective transport can also be important if pressure gradients caused by spatial variations in temperature, gas consumption, or changes in atmospheric and wind pressures exist (Birkham et al. 2010). Gas advection as a result of barometric pumping, convective gradients and dissolved oxygen in pore-water is addressed below.

It was common practice in the 1990's to assume diffusion as the dominant oxygen ingress mechanism; however, subsequent study of WRDs has determined that oxygen transport by advection can also produce substantial oxygen ingress (Phillip et al. 2009). Gas advection can occur due to barometric pumping, wind effects, thermal gradients, or volume displacement during infiltration. A series of papers presented at ICARD 2009 examined air movement within a WRD at a Canadian site with a cover system similar to WRD5; specifically, a 1.0 m till layer compacted in place with the upper 0.5 m scarified to reduce density

and allow vegetation growth. Air was found to move into and out of the WRD in response to temperature differentials (and therefore density differences) between the atmosphere and WRD interior (Phillip et al. 2009). However, the movement of air due to pressure differences between the dump interior and atmosphere was not substantial compared to temperature differentials.

The 1996 design modelling program did not evaluate gas flux due to advection. In order to evaluate the relative importance of advection for the Aitik WRDs, an analytical solution was completed using Darcy's Law. Darcy's Law is an empirical expression and the general form as described in Soil Physics Companion (Warrick 2002) is:

$$J_G = -\frac{k_G}{\mu_G} (\Delta P + \rho_G g \Delta z) \quad (\text{Equation 5})$$

where J_G = the volumetric flux density (m/s), k_G = gas permeability (m^2), ρ_G = gas density (M/m^3), g = gravitation acceleration (m/s^2), μ_G = gas viscosity ($\text{M}/\text{m}/\text{s}$), P = pressure ($\text{M}/\text{m}/\text{s}^2$), and z = elevation (m). In a partially saturated porous media, Darcy's Law can be used to describe gas flow, but instead of a hydraulic head, gas flow is driven by a pneumatic head. The comparison can be simplified by ignoring the compositional effects of the gas.

Gas permeability describes the ability of the unsaturated zone to transmit gas. It is a function of the porous medium as well as the degree of saturation of the porous medium. The gas permeability decreases as water content of the soil increases. The Brooks and Corey (1964) relationship between saturation and relative permeability was used to relate saturation of both the waste rock and cover soil to gas transport through the cover profile.

Advection as a result of temperature gradients between the waste and atmosphere was estimated with an analytical solution using Darcy's Law. The temperature of the waste was assumed to be 5°C based on early temperature measurements, preliminary modelling, and seepage water temperatures. The initial assumption for degree of saturation of the waste rock was based on VADOSE/W modelling results. The advection calculations were done on a monthly basis, with atmospheric temperature and cover system water content averaged for each month of monitoring.

Figure 5 shows the advective gas flux over the monitoring period. When the atmospheric temperature was warmer than the assumed waste temperature, gas flow was into the top of the WRD; when atmospheric temperature was cooler, gas flow was into the toe of the dump (shown as negative in Figure 5). However, it should be noted that the direction of flow is inconsequential when considering cumulative advection because in both cases oxygen is being supplied to the waste and is available for production of ARD. The annual average advective gas flux into the waste is $2.6 \times 10^{-4} \text{ kg}/\text{m}^2$.

With the stated assumptions about the waste, the relative magnitude of advection compared to diffusion is insignificant (advection averaging approximately 0.3% of calculated diffusion). Oxygen ingress by advection would increase if the assumed temperature within the WRD was higher. If the WRD internal temperature was assumed to be 10°C , gas advection would be 20% greater. If the WRD internal temperature was assumed to be 20°C , gas advection would double. However, even these values are less than 1% of the calculated diffusion fluxes.

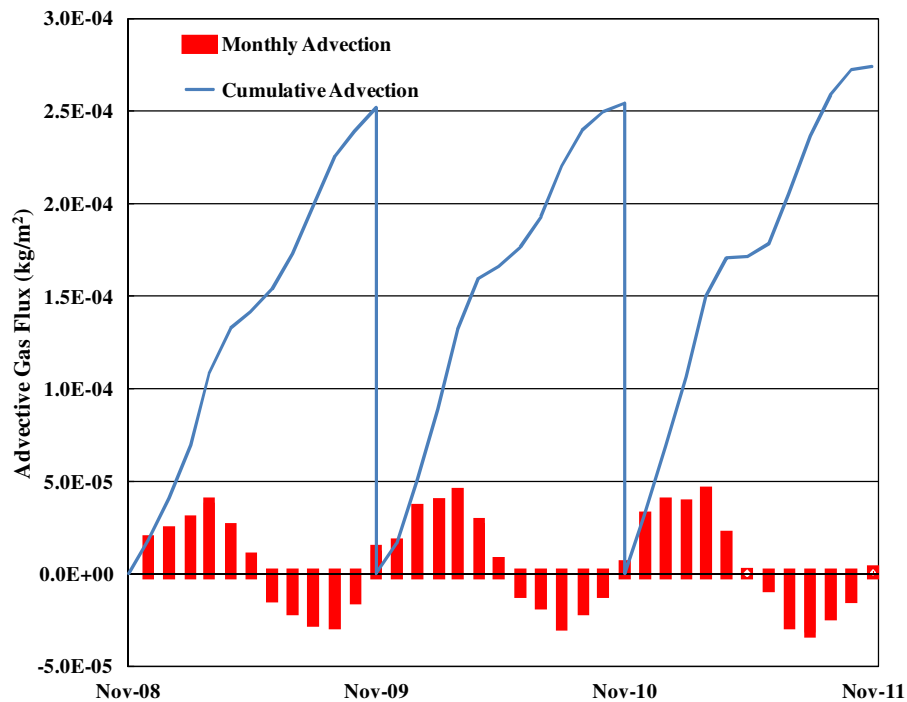


Figure 5. Predicted advective gas flux into WRD5 from 2008-2011.

Changing the assumed water content of the waste also affects the calculated advection. The model estimated the degree of saturation of the waste rock to average approximately 70%. If the waste was assumed drier more advection occurred. At 50% degree of waste rock saturation, advection was approximately 40% greater than the initial prediction, while at 30% degree of waste rock saturation, advection was nearly double that from the initial prediction, averaging $4.9 \times 10^{-4} \text{ kg/m}^2$, but still less than 1% of calculated diffusion. As the waste rock is much thicker than the cover, it dominates the calculation and changing the cover system degree of saturation resulted in no changes to the predictions.

Oxygen advection also occurs as a result of infiltration of oxygen-saturated water into the WRD. The calculated advective flux of dissolved oxygen was based on the predicted net percolation values from VADOSE/W modelling, assuming that water is oxygen-saturated at 10 mg/L. The dissolved oxygen advection presented is a high estimate as organic matter in the overlying soils would deplete some of the dissolved oxygen as it percolates down through the cover profile. Table 2 shows predicted oxygen flux as a result of dissolved oxygen advection.

Table 2. Predicted oxygen advection due to dissolved oxygen in infiltrating water.

	Dissolved Oxygen Advection (kg/m ² /year)
2008-2009	1.1×10^{-3}
2009-2010	9.8×10^{-4}
2010-2011	1.4×10^{-3}
Average	1.2×10^{-3}

The total calculated advection from dissolved oxygen and temperature driven advection is relatively insignificant compared to the calculated rate of diffusion, averaging less than 2% of calculated diffusion even for unfavourable assumptions of dump properties. It should be noted that advection can also occur

due to pressure gradients caused by spatial variations in gas consumption, or changes in atmospheric and wind pressures, which were not calculated in this program; however, they are likely to be insignificant compared to advection due to temperature differentials.

Summary

In 1996, ANSTO designed a 1.0 m compacted till cover system for the Aitik WRDs. Boliden commenced cover placement over WRD5 in 1997 and completed construction of the full-scale cover system in 2011. Monitoring stations were installed at three locations within the cover system in 2008, which have provided good measurements of moisture and thermal regimes; however, the 2008 instrumentation program has not provided data needed to compare to the estimated design oxygen ingress rates.

To compare field data collected and the 1996 design oxygen ingress rates, a numerical model was calibrated to represent field conditions of the WRD5 cover system. The numerical model predicted oxygen diffusive fluxes going through the cover system. An analytical model was also developed to estimate oxygen diffusion and advection through the cover system to develop an understanding of the relative influence advection has on the dump compared to diffusion.

Predicted diffusion flux through the Plateau cover system, based on a 0% oxygen concentration at the base of the cover system, averaged 0.08 kg/m^2 per year for the calibrated numerical model, while an analytical solution provided a higher estimate, averaging 0.13 kg/m^2 per year. Both values are greater than the 0.04 kg/m^2 per year design value. In practice, the 0% concentration gradient at the top of the waste rock profile produces instantaneous consumption of oxygen upon contact and results in a conservative estimation of oxygen ingress. A sensitivity study was completed to evaluate the influence of oxygen concentration at the base of the cover system on the estimated diffusion fluxes. Increasing the assumed oxygen concentration at the base of the till cover system decreased annual oxygen diffusion flux. The depth of the assumed oxygen concentration boundary also had a substantial influence; with greater decreases in estimated diffusion flux with placement of the oxygen concentration boundary a minimum of 5 m below the base of the till cover system.

Oxygen ingress due to advective transport mechanisms such as temperature driven gas flux and infiltration of oxygen-saturated water were found to be insubstantial compared to predicted diffusion fluxes, which indicates that the original 1996 design assumption that oxygen diffusion fluxes dominate total oxygen ingress was valid. The degree of saturation of the cover and waste material is also a major factor controlling the amount of oxygen ingress through both advection and diffusion. Degree of saturation within the cover system is 65% or greater year round. It is possible that diffusion was underestimated in the 1996 design modelling due to the model estimating that a 1.0 m compacted till cover would maintain a higher level of saturation within the cover system.

The 1996 cover system design was predicted to reduce the annual diffusion flux by approximately 100 times from an uncovered waste rock condition. Based on conservative assumptions, current oxygen diffusion flux exceeds the 1996 cover system design value. However, the conservative assumption could be refined with additional characterization of *in situ* WRD oxygen concentrations.

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