

**CONSIDERATIONS IN THE USE OF SHALLOW WATER  
COVERS FOR DECOMMISSIONING REACTIVE TAILINGS**

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## CONSIDERATIONS IN THE USE OF SHALLOW WATER COVERS FOR DECOMMISSIONING REACTIVE TAILINGS

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### ABSTRACT

Shallow water covers in engineered containment structures are becoming increasingly accepted as state-of-the-art for the decommissioning of mine waste disposal sites. However, the benefits of water covers are site-specific. The shallow water cover system is a complex combination of physical and chemical processes which take place simultaneously and interdependently. To predict the long-term performance of shallow water covers, these processes must be considered and the key processes modelled. This paper examines the processes and factors influencing underwater sulphide oxidation and ultimately the water cover quality. Mathematical modelling using the Louvicourt site as a test case shows that contributions of water cover aeration, downward infiltration, and tailings resuspension to total subaqueous sulphide oxidation are in the same order of magnitude. Each of these three oxygen transport mechanisms is able to increase subaqueous oxidation by an order of magnitude when compared with a stagnant water cover, where molecular diffusion is the only oxygen transport mechanism. A simulation based on conservative assumptions shows that the discharge water quality after mine closure could meet current federal discharge limits and that the shallow water cover could provide an acceptable long-term solution for reactive tailings disposal at this site.

**Key Words:** water cover, reactive tailings, AMD prevention, sulphide oxidation, resuspension, metal release, water quality, wind speed, wave action

### INTRODUCTION

Shallow water covers in engineered containment structures are considered state-of-the-art technology for acid mine drainage (AMD) prevention, and are seen as a potential permanent solution for acid-generating wastes, especially tailings. However, there are still some uncertainties with regards to the long-term performance of such covers. The uncertainties relate to the quantification of various mechanisms transporting dissolved oxygen to sulphides contained in the submerged tailings: diffusion, convection, circulating current, tailings resuspension, and wave action due to wind effect. One concern is that, if sufficient dissolved oxygen is transported to oxidize sulphide particles, the resulting acid generation and metal mobilization could deteriorate the water cover quality. Over the long run, this could make the water discharge out of compliance. A recent column experiment at Noranda Technology Centre (NTC) found that enough Zn was released from reactive waste rock to produce concentrations of 5 to 10 mg/L in the overlying water (Aubé et al, 1995). However, this is not to suggest that subaqueous sulphide oxidation will cause water quality problems at the field scale. The situation is site specific, depending on the local climate, hydrology, hydrogeology, and tailings characteristics. We therefore need analytical tools to distinguish potentially problematic sites from problem-free sites. For the former, we need to identify additional cost-effective preventive measures. To do this, we must identify and quantify factors influencing subaqueous oxidation of sulphides and the resulting water quality.

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The basic questions to ask in evaluating and designing a water cover are the following: (1) What are the major factors and processes governing the effectiveness of a water cover? (2) What factors determine the water depth required for effective long-term performance, and how is it determined? (3) What alternatives exist for enhancing the performance of a water cover?

This paper attempts to answer these questions. It examines and compares, through mathematical modelling, the magnitudes of influence of various processes and factors controlling the subaqueous sulphide oxidation rate. The modelling was performed using the site conditions and tailings properties found at the Louvicourt Mine in northwestern Québec, but the methodology can be applied equally well at other sites.

## FACTORS AFFECTING SUBAQUEOUS OXIDATION AND WATER QUALITY

Figure 1 depicts the various processes affecting subaqueous oxidation of sulphides and water cover quality. A shallow water cover over tailings is a complex and dynamic system. All processes are interdependent and interactive; any one particular factor, such as wind, can influence several processes. To predict the long-term quality of the water cover, these processes and their interactions must be considered simultaneously.

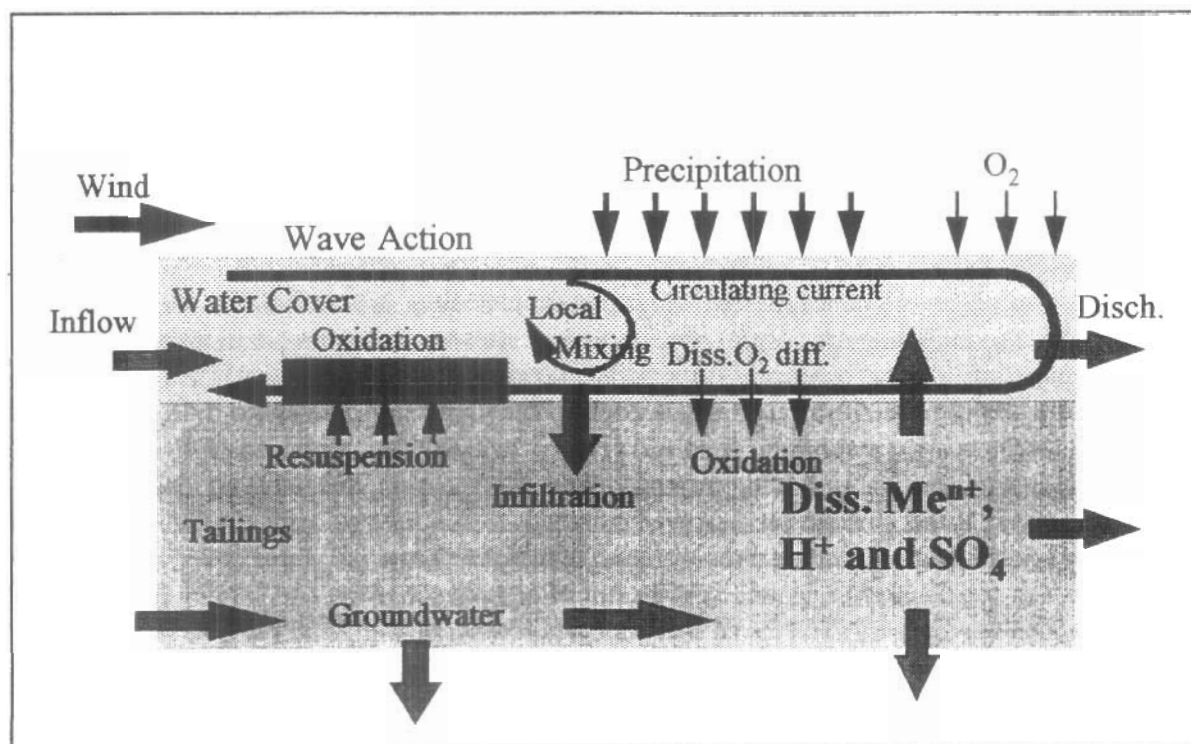


Figure 1. Processes Affecting Subaqueous Sulphide Oxidation and Water Quality.

### Water Movement

Water can enter the system as precipitation, surface inflow, and groundwater inflow. It leaves the system as evaporation, surface discharge, and groundwater outflow. A self-sustaining water cover is typically designed to receive a continuous inflow from a sufficiently-large catchment area to assure

a positive water balance under the evaporative conditions occurring in summer months. Internal water movements include currents caused by inflow and discharge, infiltration from the water column into the tailings, upwelling from tailings into the water column (when there is a upward gradient), and currents caused by wind. Wind causes two types of mixing: local mixing dominated by eddy currents manifested as waves at the surface and larger-scale mixing in the form of a circulating current. The circulating current flows in the direction of wind at the water surface and in the opposite direction near the water/tailings interface. Water currents are important in that they act as carriers of dissolved oxygen, tailings, and oxidation products. Unfavourable combinations of water movements could occur to accelerate sulphide oxidation and degrade water cover quality.

The most important water movements are eddy currents and infiltration as these can significantly affect oxidation rates and water quality. The recirculating current has a smaller velocity than the eddy currents, but it can cause a continuous turnover of the water in a shallow cover. In this paper, the currents caused by inflow and discharge will not be included in calculations of oxygen transport, as their effects are generally negligible compared to the others just mentioned.

### **Oxygen Transport Processes**

Oxygen transport processes ultimately deliver dissolved oxygen to reactive sulphide particles to cause oxidation. These include (1) oxygen input to the system through a) transfer across the air/water boundary, b) oxygen carried by water inflow and outflow; (2) vertical oxygen transport across the water column, and (3) oxygen transport across the water/tailings interface to the tailings pore water.

Oxygen input (1a) is controlled by two main factors: oxygen concentration in the top of the water column, and the air/water oxygen transfer coefficient. The latter is strongly dependent of the speed, duration, and frequency of wind. Rain also increases the oxygen transfer coefficient through surface disturbances in the forms of splashes and ripples, but the consistency of wind at studied sites makes the oxygen input due to rain effects on the diffusion coefficient less important. For (1b), oxygen inputs are from precipitation (oxygen-saturated droplets) and surface water inflow; oxygen outputs are carried by evaporative loss and water outflow. Inflows and outflows may affect the oxygen concentration of the water cover only if a difference exists in the dissolved oxygen concentrations of these two streams. Generally, the effects of (1b) on water cover oxygen concentration are small.

Vertical oxygen transport (2) depends on the oxygen concentration gradient from the top to the bottom of the water column, and on the degree of mixing primarily caused by wind. Under average field conditions, the contribution of oxygen molecular diffusion to (2) is insignificant as wind-induced and thermal currents dominate the oxygen transport within the water cover.

Oxygen transport to tailings (3) is determined by the oxygen concentration gradient across the water/tailings interface and within the tailings, the oxidation rate of sulphides, porosity, and tortuosity of the tailings. The existence of an oxidized layer of tailings, or inert, or organic deposits at this interface could significantly cut down the oxygen flux to the reactive tailings.

### **Tailings Transport Processes**

Resuspension of tailings is principally caused by wave action due to wind. Resuspension exposes sulphide particles to dissolved oxygen, causing accelerated oxidation relative to settled tailings, where molecular diffusion limits the oxygen availability immediately below the water/tailings interface. Once tailings are resuspended, relocation of these partially-oxidized particles can expose fresh tailings, also

promoting accelerated oxidation. Relocation could be caused by wind-induced recirculating currents, or less importantly, currents generated by water inflow and discharge. The major controlling factor for tailings transport is therefore the speed, duration and frequency of wind.

### **Dissolved Metal Releases**

Oxidation of resuspended sulphide particles releases dissolved metals directly to the water cover. The oxidation of settled tailings releases dissolved metals to pore water. To influence the quality of the water cover or groundwater, they have to be transported. The release of dissolved metals to the water cover can occur via three routes: molecular diffusion (a slow process), pore-water upwelling (if there is an upward gradient), and tailings resuspension (when the pore water is lifted along with the associated tailings into the water cover). Oxidation products which precipitate or are adsorbed soon after release will not affect the metal concentrations in the water cover.

The release of dissolved metals to groundwater is determined by similar transport processes with advection being the most dominant. Effects such as natural soil-water interactions (adsorption and carbonate buffering) can significantly reduce the negative effects on groundwater quality.

## **ANALYSIS OF TAILINGS OXIDATION UNDER WATER COVER**

### **Louvicourt Site Conditions and Tailings Characteristics**

The Louvicourt Mine, located in Canada about 20 km east of Val d'Or, Québec, is a copper-zinc-gold massive sulphide property co-owned by Novicourt (a subsidiary of Noranda Mining and Exploration), Aur Resources, and Teck and operated by Aur. Mine production commenced in mid-1994 and the current production is about 1200 t/day. The average air temperature at the site for the seven unfrozen months is 10 °C and the annual average wind speed is 3.6 m/s.

The tailings area is 9 km from the mine site and was designed from the outset for underwater disposal of tailings. The initial average water cover depth was 3.0 m, which is gradually decreasing as the basin is filled with tailings. Current closure plans specify a minimum water cover depth of 1 m, whereas a water depth of 0.3 m is being studied in two field test plots.

The tailings contain 30-50% pyrite, 5-24% carbonates, and 0.6% sphalerite, with the remainder being quartz and other silicate minerals (Li, 1997). The average effective grain size is 0.01 mm and most pyrite and carbonates exist as liberated grains. The specific pyrite surface area calculated from size distribution data is 29 m<sup>2</sup> per kg of tailings. The average oxidation rate in ample supply of oxygen, as measured by eight humidity cell tests and adjusted for the site conditions, is 0.065 nmol FeS<sub>2</sub> per m<sup>2</sup> pyrite surface per second.

### **Mathematical Models and Assumptions**

To examine key processes and parameters influencing the water cover quality, we compare the degree of oxidation under a water cover for four idealized cases: (1) a stagnant water cover, (2) a fully-oxygenated water cover without downward infiltration, (3) a fully-oxygenated water cover with downward infiltration, and (4) a fully-oxygenated water cover with downward infiltration and resuspension of tailings. The water cover depth is assumed to be 0.3 m for all cases. The conditions

used for the four cases are given in Table 1. Table 2 lists the mathematical models used, and a list of symbols is included at the end of this paper.

The modelling assumptions for Case 1 are that the water cover is saturated with oxygen at the air/water interface and dissolved oxygen diffuses downward entirely by molecular diffusion. The water cover is modelled and the limiting factor for sulphide oxidation in the settled tailings is the diffusion of oxygen across the water column. For Case 2, the entire water cover is assumed saturated with dissolved oxygen and the top layer of the settled tailings is modelled. The limiting factor for sulphide oxidation is the rate of oxidation and the diffusion of oxygen in the tailings pore water. For Case 3, advective oxygen transport by downward infiltration of water is added to Case 2; the top layer of tailings is modelled, and the linear water velocity is an additional rate-limiting factor. For Case 4, due to a lack of theory and field data for quantitatively predicting the amount of tailings resuspended, it is simply assumed that a 2 mm tailings layer is resuspended. Oxygen is considered to be in ample supply, oxidation is assumed to be controlled by sulphide oxidation rate, and rate-limiting factors are the quantity and duration of tailings resuspension.

Table 1 Idealized Cases for Calculation of Sulphide Oxidation under Water Cover

Case No.	Water Cover Description	O <sub>2</sub> Conc. (mg/L)		Downward Infiltration	Tailings Resuspension
		Surface	Interface		
1	Stagnant	11.3	0	No	No
2	Fully oxygenated	11.3	11.3	No	No
3	Case 2 plus downward infiltration	11.3	11.3	1 m/year	No
4	Case 3 plus tailings resuspension	11.3	11.3	N/A	Yes

### Case Comparisons

The dissolved oxygen consumption by sulphide oxidation for the four cases are compared in Figure 2. Comparison to the base case of stagnant water cover shows that cover aeration, downward infiltration, and tailings resuspension can each cause an approximate ten-fold increase in oxygen consumption. The cumulative effect of aeration, infiltration, and resuspension is a 24-fold increase in oxygen consumption by sulphide oxidation at the end of the first year after deposition. The actual magnitude of increase depends on the validity of the assumptions made for infiltration, and resuspension. The infiltration rate of 1 m per year and the resuspended tailings layer thickness of 2 mm thickness are both considered to be conservative assumptions which tend to overestimate oxidation. In reality, oxidation caused by tailings resuspension is affected by the following parameters: mass of tailings resuspended, duration of resuspension, intrinsic sulphide oxidation rate, and the specific surface area of sulphide in the tailings. The mass of tailings resuspended is, in turn, determined by density and particle size of tailings, tailings cohesive properties, and shear forces at the tailings/water interface. The assumption of full aeration of the water cover is further examined in the next section.

Mathematical modelling using the site conditions and tailings properties found at Louvicourt also allows the following additional observations to be made:



**Table 2 Mathematical Models**

**Static Water Cover**

Model  $D \frac{\partial^2 C}{\partial z^2} = \frac{\partial C}{\partial t}; \quad C(z, 0) = C_0, \quad C(0, t) = C_0, \quad C(h, t) = 0$

**Transient Solution (Crank, 1956)**

$$C(z, t) = C_0 \left(1 - \frac{z}{h}\right) + \frac{2}{\pi} \sum_{n=1}^{\infty} \frac{C_0}{n} \sin \frac{n\pi z}{h} \exp\left(-\frac{D n^2 \pi^2 t}{h^2}\right) + \frac{4C_0}{\pi} \sum_{m=0}^{\infty} \frac{1}{2m+1} \sin \frac{(2m+1)\pi z}{h} \exp\left[-\frac{D(2m+1)^2 \pi^2 t}{h^2}\right]$$

Steady-State Solution  $C(z, +\infty) = C_0 \left(1 - \frac{z}{h}\right)$

**Oxygen Flux into Tailings**

$$F(h, t) = -D \left[ \frac{-C_0}{h} + \sum_{n=1}^{\infty} -\frac{2C_0}{h} \cos(n\pi) \exp\left(-\frac{D n^2 \pi^2 t}{h^2}\right) + \sum_{m=0}^{\infty} \frac{4C_0}{h} \cos[(2m+1)\pi] \exp\left(-\frac{D(2m+1)^2 \pi^2 t}{h^2}\right) \right]; F(h, \infty) = D \frac{C_0}{h}$$

**Cumulative Oxygen Flux into Tailings**

$$M(h, t) = \frac{DC_0}{h} t + \sum_{n=1}^{\infty} \frac{2hC_0}{n\pi^2} \cos(n\pi) \left[ 1 - \exp\left(-\frac{D n^2 \pi^2 t}{h^2}\right) \right] - \sum_{m=0}^{\infty} \frac{4hC_0}{(2m+1)^2 \pi^2} \cos[(2m+1)\pi] \left\{ 1 - \exp\left[-\frac{D(2m+1)^2 \pi^2 t}{h^2}\right] \right\}$$

**Fully-Aerated Water Cover**

Model  $D_e \frac{\partial^2 C}{\partial z^2} - \frac{\partial C}{\partial t} - kC = 0; \quad C(z, 0) = 0, \quad C(0, t) = C_0$

Transient Solution (Crank, 1956)  $C(z, t) = C_0 \left[ \frac{1}{2} \exp(-z \sqrt{\frac{k}{D_e}}) \operatorname{erfc}\left(\frac{z}{2\sqrt{D_e t}} - \sqrt{kt}\right) + \frac{1}{2} \exp(-z \sqrt{\frac{k}{D_e}}) \operatorname{erfc}\left(\frac{z}{2\sqrt{D_e t}} + \sqrt{kt}\right) \right]$

Steady-State Solution  $C(z, +\infty) = C_0 \exp\left[-z \sqrt{\frac{k}{D_e}}\right]$

Oxygen Flux into Tailings  $F(0, t) = C_0 \sqrt{D_e k} \left[ \operatorname{erf}(\sqrt{kt}) + \frac{\exp(-kt)}{\sqrt{\pi kt}} \right]; \quad F(0, \infty) = C_0 \sqrt{D_e k}$

Cumulative Oxygen Flux into Tailings  $M(0, t) = C_0 \sqrt{\frac{D_e}{k}} \left[ \left(kt + \frac{1}{2}\right) \operatorname{erf}(\sqrt{kt}) + \sqrt{\frac{kt}{\pi}} \exp(-kt) \right]$

**Table 2 Mathematical Models (Continued)**

**Fully -Areated Water Cover With Downward Infiltration**

**Model**  $D_e \frac{\partial^2 C}{\partial z^2} - v_z \frac{\partial C}{\partial z} - \frac{\partial C}{\partial t} = kC = 0; \quad C(z, 0) = 0, \quad C(0, t) = C_0$

Transient Solution (Jost, 1960; Domenico et. al., 1990)

$C(z, t) = \frac{C_0}{2} \exp \left[ \frac{v_z}{2D_e} z \left( 1 - \sqrt{1 + \frac{4kD_e}{v_z^2}} \right) \right] \operatorname{erfc} \left[ \frac{z - v_z t \sqrt{1 + \frac{4kD_e}{v_z^2}}}{2\sqrt{D_e t}} \right]$

**Steady-State Solution**  $C(z, +\infty) = C_0 \exp \left[ \frac{v_z}{2D_e} z \left( 1 - \sqrt{1 + \frac{4kD_e}{v_z^2}} \right) \right]$

**Oxygen Flux into Tailings**

$F(0, t) = \frac{C_0 v_z}{2} \left[ 1 - \frac{1}{2} \left( 1 - \sqrt{1 + \frac{4kD_e}{v_z^2}} \right) \right] \left[ 1 + \operatorname{erf} \left( \frac{v_z}{2\sqrt{D_e}} \sqrt{1 + \frac{4kD_e}{v_z^2}} t \right) \right] + \frac{C_0}{2} \sqrt{\frac{D_e}{\pi t}} \exp \left[ -\frac{v_z^2}{4D_e} \left( 1 + \frac{4kD_e}{v_z^2} \right) t \right]$

$F(0, \infty) = C_0 v_z \left[ 1 - \frac{1}{2} \left( 1 - \sqrt{1 + \frac{4kD_e}{v_z^2}} \right) \right]$

**Cumulative Oxygen Flux into Tailings**

$M(0, t) = k_1 t + \left[ k_1 t - \frac{k_1}{2k_2^2 k_3} + \frac{k_4}{k_2} \sqrt{\frac{\pi}{k_3}} \right] \operatorname{erf} \left( k_2 \sqrt{k_3 t} \right) + \frac{k_1}{k_2} \sqrt{\frac{t}{\pi k_3}} \exp(-k_2^2 k_3 t)$

where  $k_1, k_2, k_3$  are predefined constants

**Tailings Resuspension**

**Model**  $M(L, T) = k_4 R_0 LT$ , where  $k_4$  is predefined constant

**Solution**  $M(L, T) = 0.933(1 - n) \rho_{tail} a_{py} R_0 LT$



- Under stagnant conditions, the effectiveness of a water cover would increase with depth; however, the incremental gain in the effectiveness would decrease quickly with water cover depth and, at a water depth greater than 1 m, the water cover effectiveness would not increase significantly with increasing cover depth.

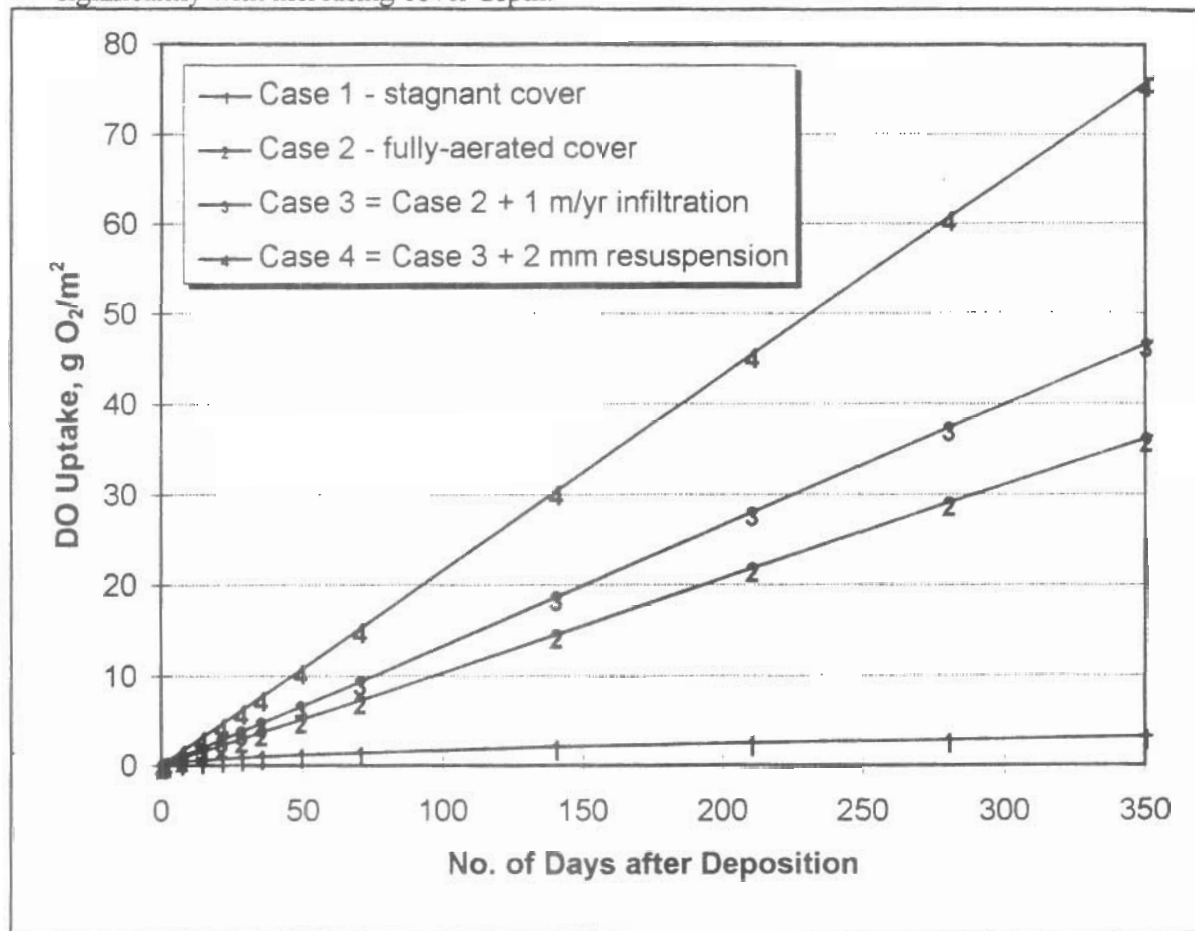


Figure 2. Comparison of Oxygen Uptake by Sulphide Oxidation for Four Cases Modelled.

- If the cover is fully-oxygenated, the cover depth does not affect the rate of sulphide oxidation.
- Steady state oxidation is reached very quickly, in about 0.5 days. At steady state, the dissolved oxygen penetration into the settled tailings is about 5 mm.
- When 1 m/year infiltration is added, the oxygen penetration is increased to about 8 mm. The total oxygen flux in this case is controlled by the infiltration rate in addition to the sulphide oxidation rate and the effective diffusion coefficient of oxygen in tailings pore water.

### Effect of Wind and Waves on Oxygen Transfer

To estimate the effect of wind on water covers, particularly the effect of wind on oxygen diffusion to the tailings, the transfer of oxygen to tailings was divided into three consecutive, discrete processes: (1) dissolution of oxygen into the water, (2) diffusion of oxygen from the surface to the

bottom of the water cover, and (3) the combined diffusion of oxygen into the pores of the tailings and subsequent depletion through oxidation of pyrite. To solve the problem, relationships for each of the transfer processes were obtained, and steady state was assumed. As we are concerned with the steady-state flux of oxygen from the air to the tailings, the flux of oxygen remains the same for each of the three processes. Empirical relationships were used for the dissolution of oxygen from air and for the turbulent diffusion of oxygen across the water depth. Banks (1975) provided equations relating both the oxygen transfer coefficient and the vertical diffusion coefficient in a shallow lake to wind speed. The transfer of oxygen to water (i.e. dissolution from air) can be calculated using the following equation:

$$F = K_L \cdot (C_s - C_o) \quad (1)$$

A relationship for  $K_L$  was published by Banks and Herrera (1977) to describe oxygen transfer due to wind:

$$K_L = 10^{-6}(8.43 U^{1/2} - 3.67 U + 0.43 U^2) \quad (2)$$

Equation (2) does not take into account oxygen transferred by rain. For the diffusion of dissolved oxygen from the surface of the water cover to the bottom, a "turbulent diffusion coefficient" was defined by Banks (1975) to describe the vertical diffusion. Equation (3) represents the vertical diffusion of oxygen and (4) is an empirical relationship developed for shallow lakes:

$$F = \frac{D_t}{h} (C_s - C_b) \quad (3)$$

$$D_t = \frac{h}{0.053} K_L \quad (4)$$

Notice that when (4) is substituted in (3), the depth of the water cover,  $h$ , cancels out. This means that the turbulent diffusion rate of oxygen from the top to the bottom of the water cover is independent of the cover thickness. For the diffusion of oxygen into the tailings and the subsequent reaction with pyrite, previously published relationships assembled by Aubé et al. (1995) were used. These relationships were developed using pyrite oxidation rates from literature and are essentially a simplified version of the corresponding equations in Table 2.

To solve this set of equations under steady state, the fluxes from all three processes were defined equal and the oxygen concentrations at the water surface and the water/tailings interface were determined. A wind speed of 2 m/s was used for the calculations. The results obtained are presented in Table 3.

Recent field observations in tailings ponds (for example, a sudden decrease in dissolved oxygen concentration immediately above the tailings) suggest the possible existence of a thin laminar layer

at the water/tailings interface. Such a layer, even as thin as 2 mm, could significantly affect the flux of oxygen to the tailings. In Table 3, the theoretical results show a 28% reduction in oxygen flux when a 2 mm laminar layer is incorporated into the calculations. If the laminar layer is 10 cm thick, the oxygen flux is then decreased by more than two orders of magnitude. A laminar layer of such thickness could be induced by the presence of inert granular material at the bottom of the water cover.

Table 3 Theoretical Results of Oxygen Transport under Water Covers

	Standard water cover	2 mm-thick laminar layer	10 cm-thick laminar layer
DO at surface ( $\text{g}/\text{m}^3$ )	10.57	10.70	11.00
DO at bottom ( $\text{g}/\text{m}^3$ )	10.55	10.68	11.00
DO at tailings interface ( $\text{g}/\text{m}^3$ )		7.70	0.05
Oxygen Flux ( $\text{g m}^{-2} \text{yr}^{-1}$ )	85	61	0.4

The calculations for the laminar layer were done using Fick's Law and were included in the steady-state flux equilibration. For the laminar layer, the dissolved oxygen diffusion coefficient of water was used, and for the inert barrier, a porosity of 0.4 and a tortuosity of 5 were incorporated into the effective diffusion coefficient.

The results in Table 3 suggest that the assumptions of full aeration and oxygen saturation in the water cover (Cases 2, 3, and 4 in Table 1) are well-founded. A minimum wind speed of 2 m/s was used for the calculations while the average at Louvicourt is around 3.6 m/s (13 km/h). Furthermore, the assumption that wind is constant need not be made as the stored oxygen in only 0.3 m of water would take over 19 days to deplete, assuming the water cover remained well mixed and the oxidation rate remained the same as for the scenario with a 2-mm laminar layer. Field measurements (St-Germain et al., 1997) seem to confirm that dissolved oxygen concentrations in a water cover remain near saturation and that no gradient is formed.

## PREDICTION OF METAL RELEASE AND WATER QUALITY AT LOUVICOURT

To predict metal releases and long-term surface water quality at Louvicourt, the following assumptions were made:

- (1) The water cover is fully mixed and saturated with oxygen for the seven unfrozen months of the year.
- (2) For the frozen season (November to March), precipitation is accumulated on the ice and on land; it enters the water cover as snow melt in April. Tailings oxidation in the winter is assumed negligible.
- (3) The tailings resuspension is 2 mm over the entire pond surface during the seven unfrozen months (This is perhaps unrealistically high; but in the absence of field measurement and literature values, this assumption is in line with our conservative approach).

- (4) Zinc release from sphalerite oxidation is calculated from total oxygen consumption according to the sphalerite/pyrite molar ratio in the tailings and the oxidation rate at neutral pH, as observed in humidity cell tests (Li, 1997).
- (5) Sulphate and zinc released from sulphide oxidation do not precipitate and are completely flushed from pore water into the water cover (corresponding, for example, to a case where the tailings become resuspended, or a case where temporary groundwater upwelling occurs).
- (6) The water cover is completely mixed with respect to dissolved sulphate and zinc, discharging water at the same sulphate and zinc concentrations as the water cover.
- (7) The input water to the water cover contains no dissolved sulphate or zinc.
- (8) The 0.3 m water cover is maintained for all seven unfrozen months, which means water input as precipitation and runoff is instantly mixed with the water cover and discharged.
- (9) The downward water infiltration in the tailings is 1 m/year (a typical value for tailings).

Many of the above assumptions are conservative, resulting in an over-estimation of metal releases to the water cover. For (3), the tailings resuspension that may occur would not continue for the entire unfrozen season and may not be as much as 2 mm. For (5), particularly since there is downward infiltration, most of the oxidation products are more likely to seep through the tailings if not immobilised. Hence the prediction is for a worst case scenario, defining the upper limits for dissolved sulphate and zinc in the water cover. In reality, the concentrations are likely to be much lower than predicted. The water balance data used are from a recent hydrology study carried out at the site. The predicted water cover quality, represented by the dissolved concentrations of zinc and sulphate, is depicted in Figure 4. The simulation is shown for 10 years after the closure of the mine operation although the pattern would persist for a much longer time.

Both sulphate and zinc concentrations show a great deal of variation, mainly due the seasonal dilution effects and the assumed virtual cessation of oxidation in the winter. The maximum predicted concentrations, about 75 mg/L sulphate and 0.45 mg/L zinc, occur in early summer (about June).

The worst case simulation shows that, even with all the conservative assumptions, the predicted discharge water after closure would still meet the current provincial and federal discharge limits for zinc. Since zinc is the most problematic metal in application of the water cover at this site, it seems safe to conclude that the water cover provides a good long-term strategy for tailings disposal at the Louvicourt Mine.

## CONCLUSIONS

This paper shows through mathematical modelling that, for the Louvicourt site conditions and tailings properties, contributions of water cover aeration, downward infiltration, and tailings resuspension to subaqueous sulphide oxidation are in the same order of magnitude, and all of which are approximately one order of magnitude higher than the oxidation under a hypothetical stagnant water cover where molecular diffusion is the only oxygen transport mechanism. A worst-case simulation shows that the discharge water quality after mine closure would meet current provincial and federal discharge limits. A shallow water cover therefore provides a good long-term solution for tailings disposal at the Louvicourt Mine.

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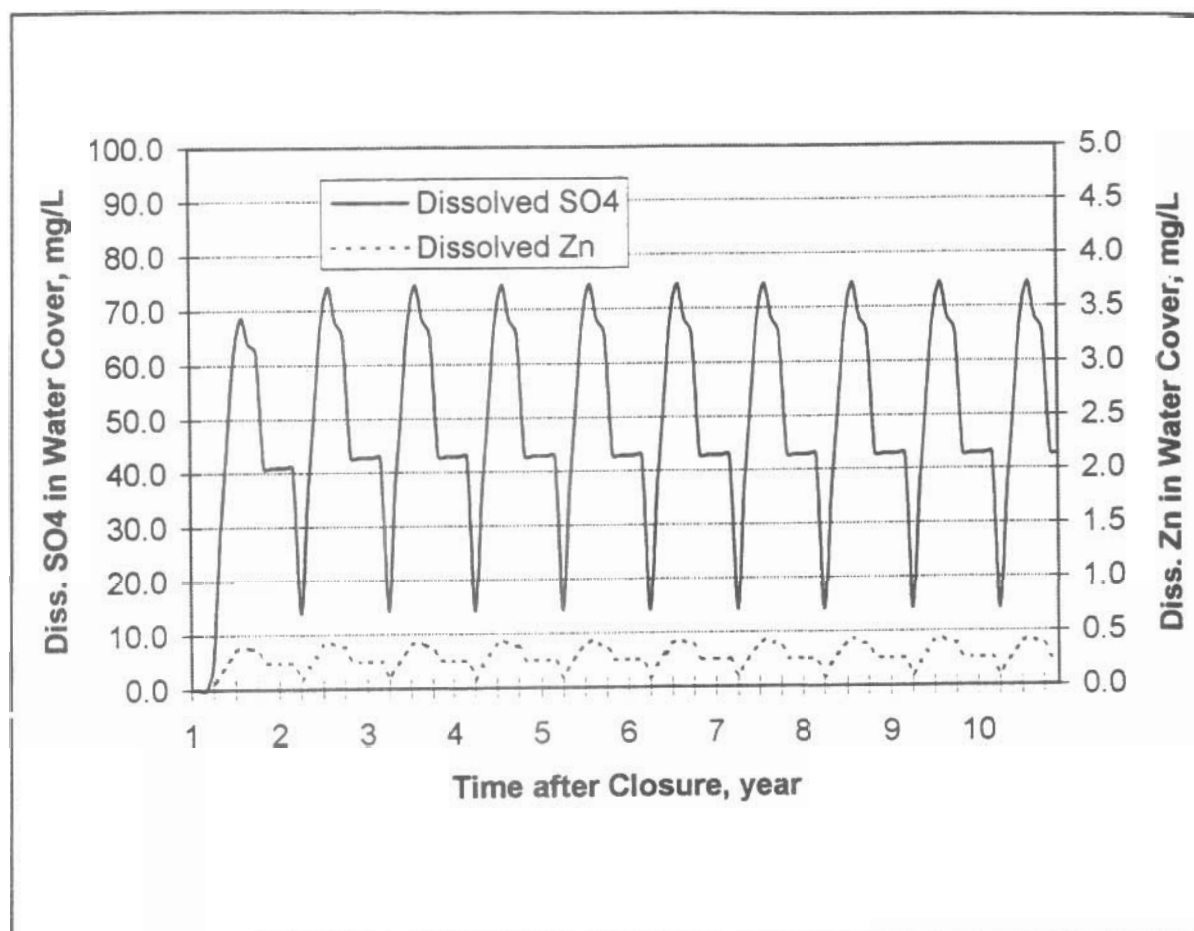


Figure 3. Long-Term Water Quality Prediction for 0.3 m Water Cover

## LIST OF SYMBOLS

$a_{py}$	= specific pyrite surface, $m^2 kg^{-1}$ tailings.
$C, C(z,t)$	= dissolved $O_2$ concentration, $g/m^3$ .
$C_o$	= saturated dissolved $O_2$ concentration in water, $11.3 g/m^3$ at $10^\circ C$ .
$C_s, C_h$	= dissolved $O_2$ concentration at water surface, and bottom $g/m^3$ .
$D$	= diffusion coefficient of $O_2$ in water, $1.3 \times 10^{-9} m^2 s^{-1}$ at $10^\circ C$ .
$D_t$	= turbulent vertical diffusion coefficient of $O_2$ in water, $m^2 s^{-1}$ .
$D_e$	= effective diffusion coefficient of $O_2$ in tailings pore water, $m^2 s^{-1}$ , calculated by $D \cdot n / \tau$ .
$F$	= oxygen flux, $g m^{-2} s^{-1}$ .
$h$	= depth of water cover, 0.3 m in this paper.
$k$	= first-order rate constant of pyrite oxidation with respect to diss. $O_2$ concentration, $s^{-1}$ .
$k_1, k_2, k_3, k_4$	= predefined constants.
$K_L$	= oxygen air-water transfer coefficient, $m s^{-1}$ .
$L$	= thickness of tailings resuspended, m.
$M$	= cumulative oxygen flux, $g m^{-2}$ .

$n$	= porosity of settled tailings, $0.4 \text{ m}^3 \text{ m}^{-3}$ in this paper
$R_0$	= rate of pyrite oxidation at saturated dissolved $\text{O}_2$ concentration, $\text{mol m}^{-2} \text{ s}^{-1}$
$t$	= time after deposition, s.
$T$	= duration of tailings resuspension, s
$U$	= wind speed 10 m above the water, m/s.
$v_z$	= downward linear velocity of pore water infiltrating the tailings, $\text{m s}^{-1}$ .
$z$	= depth below water surface or tailings/water interface, m.
$\rho_{\text{tail}}$	= average density of tailings, $3800 \text{ kg m}^{-3}$ in this paper.
$\tau$	= tortuosity, unitless (use 5 for tailings or soil)

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