

## ACID MINE DRAINAGE FROM ABANDONED MINE SITES: PROBLEMATIC AND RECLAMATION APPROACHES

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**ABSTRACT:** One of the most serious environmental issues related to the mining industry in Canada and elsewhere, is the pollution from abandoned mine waste disposal sites. The wastes containing sulphide minerals can oxidize and generate contaminants in the water drainage, a phenomenon called acid mine drainage (AMD). Different techniques are available to control the production of AMD. However, these techniques were mainly developed for the closure of operating sites, and are not as efficient for abandoned mine sites that were left exposed to natural conditions for years. The main differences between an operating and abandoned mine waste disposal site are the quality of the interstitial water, the presence of well implemented acidophilic bacteria, and the quality of the retaining infrastructures. To avoid contamination of surrounding ecosystems, it is necessary to take into consideration these particularities at the reclamation stage. The experience at the Lorraine mine site shows a slight improvement of the water quality in the waste disposal site 10 years after reclamation even if the oxygen barrier is working as expected. The addition of a passive treatment system to treat the contaminated pore water that will eventually flow out of the site is then a critical component of the reclamation at any abandoned AMD mine waste disposal site.

**KEYWORDS:** Acid Mine Drainage (AMD), AMD control methods, abandoned mine sites, passive treatment, case studies

### INTRODUCTION

The mining industry is an important asset for the economy of many regions across Canada, particularly with respect to exports and employment, but also through numerous technological developments. Nevertheless, mining operations generate different types of wastes which are potentially environmentally harmful. Effective and efficient waste management programs are therefore required to ensure their long-term environmental stability.

Active mining operations must respect governmental environmental criteria and, by doing so, the production of contaminants in the environment is limited to a level considered acceptable by the overseeing governments. Nevertheless, some abandoned mine sites are not well controlled and have significant impacts on the environment. Two Canadian examples of sites affected by abandoned mine wastes are presented in Fig. 1a and b.

Before going any further, it is important to define what is an abandoned mine site. Several expressions (orphans, abandoned, retrocessed, inactive, closed, etc.) can be found in literature and currently there is no consensus on a unique definition. Identifying a clear definition is an important step since it will affect the

number of sites categorized as abandoned. In the following paper, a slightly modified version of the definition proposed by van Zyl et al. (2002) is used:

*A mine site is considered abandoned if there are no solvable identifiable owners or operators for the facilities, or if the facilities have reverted to governmental ownership.*

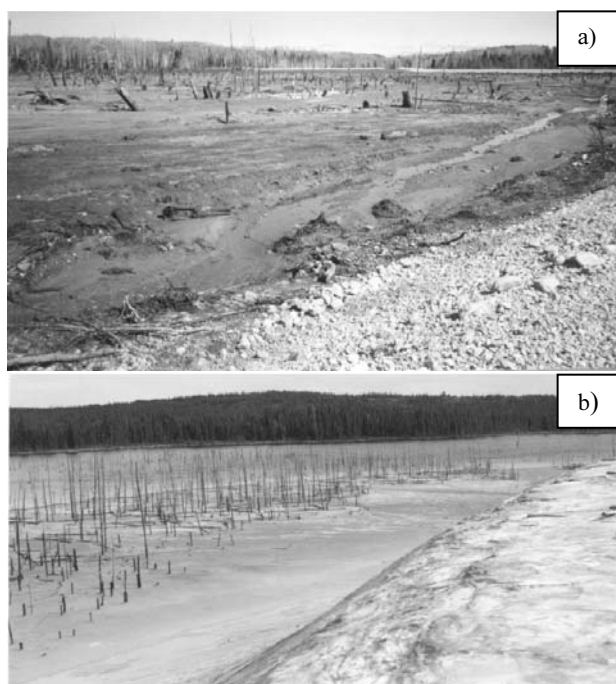
If we assume that having only one component of the mine is sufficient to categorize a site as an abandoned mine site (ex. a ramp, a shaft, an open cast, etc.), Canada has more than 10 000 abandoned sites (with more than 1,000 in the province of Quebec). In US, more than 550,000 sites are categorized as abandoned, while Sweden counts more than 1 000, 10,000 sites in Great-Britain and more than 5,500 in Japan (van Zyl et al. 2002).

It is well known that some components of the mine have a greater impact on the environment than others. Tailings impoundments and waste rock piles (called hereinafter mine waste disposal sites) are probably the most critical components; they can generate significant negative impacts on drainage water, on soils, and eventually on water drainage (e.g. Aguilar et al. 2004; Lee and Faure, 2007; Hakkou et al. 2008). To the knowledge of the author, no detailed and global statistics

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(or inventory) are available, at the planet scale, to quantify the volume and area of abandoned mine waste disposal sites.

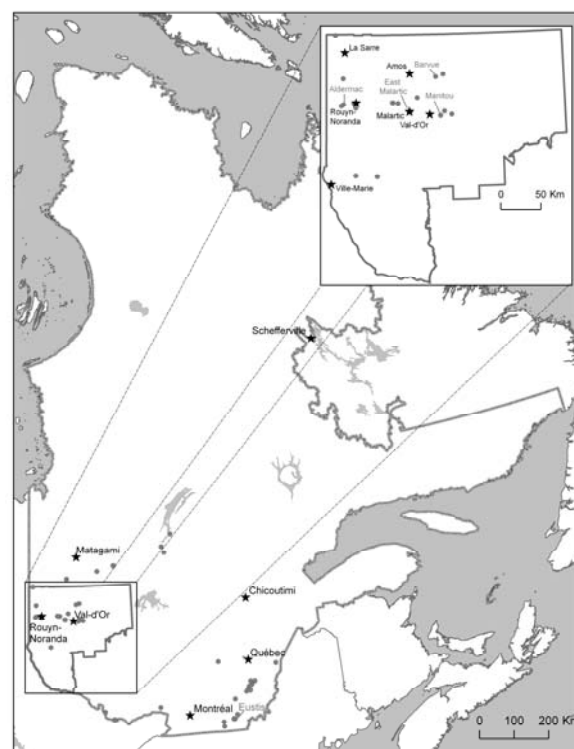


**Fig. 1** Photographs showing environmental impacts from two Canadian abandoned mine sites a) Aldermac site, Rouyn-Noranda, Quebec, Canada, b) Manitou site, Val-d'Or, Quebec, Canada

To have a better idea of the challenge facing governments and the mining industry with abandoned mine waste disposal sites, some statistics of the province of Quebec, Canada are presented. In the province of Quebec, 50 abandoned mine waste disposal sites (having an area greater than 1 ha) are inventoried (see Fig. 2), which collectively cover an area of approximately 2 000 ha. Each site has a different level of impact on the environment. It is estimated that approximately 1 000 ha are covered by mine wastes that can generate contaminated drainage water. The estimated reclamation costs for these sites, using typical unit costs, are \$150 million (CDN). The picture depicted above for the province of Quebec is similar for the other Canadian hard rock mining provinces such as Ontario, British Columbia, and Manitoba.

These statistics show the importance of the problem. In the context of sustainable development, it is crucial for the mining industry to develop effective reclamation scenarios for existing and abandoned mine waste disposal sites, especially for those that generate acidic drainage (called acid mine drainage, AMD) in the environment. In the following, a description of the AMD problem will be given with some options available to rehabilitate waste disposal sites with AMD potential.

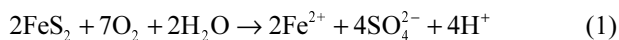
The main differences at the reclamation stage between abandoned and operating sites will be presented along with a case study of a rehabilitated abandoned acid generating mine waste disposal site. Finally, a short description of actions taken recently in Canada to reduce the environmental impacts of abandoned mine sites will be presented.



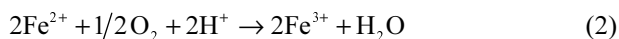
**Fig. 2** Location of the abandoned mine waste disposal sites in the province of Quebec, with a close up on the Abitibi region (the main mining region of the province), that covers an area greater than 1 ha

## AMD GENERATION

The AMD can be generated at or within a number of mine site components such as waste rock, tailings, open pit walls and underground workings (e.g. SRK, 1989; Morin and Hutt, 1997). The sulphide minerals such as pyrite and pyrrhotite oxidize in the presence of water and atmospheric oxygen producing AMD through a number of possible chemical and biochemical pathways. The oxidation of sulphide minerals (pyrite which is the more abundant sulphide mineral is taken here as reference) can be described by the following equations (e.g. Kleinmann et al. 1981; Ritcey, 1989; Blowes and Ptacek, 1994; Evangelou, 1995; Perkins et al. 1995; Morin and Hutt, 1997). The first step is the direct oxidation of pyrite ( $\text{FeS}_2$ ) by oxygen which produces sulphates ( $\text{SO}_4^{2-}$ ), ferrous iron ( $\text{Fe}^{2+}$ ) and acidity ( $\text{H}^+$ ):



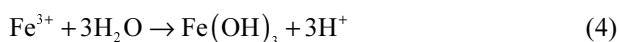
In the next step, the ferrous iron is further oxidized to ferric iron ( $\text{Fe}^{3+}$ ).



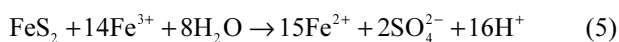
Ferrous iron can also be oxidized to produce iron hydroxide ( $\text{FeOOH}$ ) and acidity.



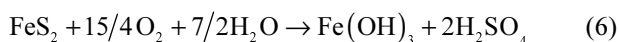
At a  $\text{pH} > 4$ ,  $\text{Fe}^{3+}$  is precipitated out as ferric hydroxide ( $\text{Fe}(\text{OH})_3$ ), which releases more acid in the environment.



At  $\text{pH} < 4$ , the ferric iron can remain soluble and can directly oxidize pyrite, liberating more acid into the surroundings.



The overall reaction for the complete oxidation of pyrite can be expressed as follows:



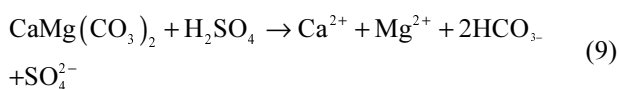
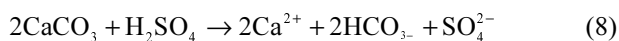
The oxidation of 1 mole of pyrite generates two moles of sulphuric acid. It is usually considered in the literature (e.g. Aubertin et al. 2002a) that direct oxidation by oxygen (Eq. 1) occurs at pH near neutrality ( $5 < \text{pH} < 7$ ) while the indirect oxidation (Eq. 5) is predominant at lower pH values ( $\text{pH} < 3$ ). The equations presented above are based on a stoichiometric equilibrium that does not take into account the kinetic of each reaction. The rate of oxidation is a function of additional factors (Morth and Smith, 1966 ; Lowson, 1982; Rogowski et Pionke, 1984 ; Nicholson et al. 1988 ; Frostad et al. 2000a,b ; Jerz and Rimstidt, 2004), including oxygen supply, temperature, pH, bacterial activity, mineral surface area, and crystallography.

It is usually considered that the rate of the reaction is controlled by Eq. 2. The reaction rate is slow at a low pH but increases rapidly as the pH drops due to the presence of bacteria. For example, *Acidithiobacillus ferrooxidans* bacteria have the capacity to catalyze the oxidation reaction of the ferrous iron into a ferric iron (Eq. 2); the rate of reaction can be increased by a factor up to 20 to 1,000 times (e.g. Berthelin, 1987). Some bacteria can also oxidize the sulfur produced during the sulphide oxidation:



The chemical quality of the drainage will also depend on the other minerals present in the mine waste. The acid can react by being neutralized by carbonates and (in a

lesser extent) silicate minerals, which are considered the main neutralizing minerals (e.g. Sverdrup, 1990; Kwong, 1993; Lawrence and Scheske, 1997). Eqs. 7 and 8 represent two possible reactions for the neutralization of sulphuric acid (at  $\text{pH} > 6.3$ ) by calcite ( $\text{CaCO}_3$ ) and dolomite ( $\text{CaMg}(\text{CO}_3)_2$ ) respectively, which are two abundant carbonate minerals (Lapakko, 1994).



The equations show that two moles of calcite and 1 mole of dolomite are necessary to neutralize 1 mole of sulphuric acid. The capacity of the neutralizing mineral to limit the production of AMD is also dependent on different factors affecting the reactivity of the minerals (ex. temperature, pH,  $\text{CO}_2$  pressure, mineral surface area and crystallography). The reactivity of carbonate minerals can be classified from the more reactive to the less: calcite > dolomite > Mg-ankerite > ankerite > siderite (Blowes et Ptacek, 1994). More details on the neutralization process in mine waste can be found in other publications (e.g. Sverdrup, 1990; Blowes and Ptacek, 1994; Lapakko, 1994; Sherlock et al. 1995; Aubertin et al. 2002a; Jambor et al. 2002; Bussière et al. 2005).

Finally, it is worth mentioning that other chemical reactions (other than oxidation and neutralization) can affect the rate at which AMD is generated. Precipitation of the secondary minerals can affect significantly the final water quality by reducing the concentration of certain elements at the effluent (elements are transferred from the liquid phase to the solid phase). For example, it is common to find secondary minerals that contain iron and sulfates in acid generating mine wastes (ex. goethite, jarosite, iron hydroxide; references). Precipitation of secondary minerals can also affect the reactivity of sulphides and carbonates (references) by forming a coating on the particles. It is also documented that the accumulation of secondary minerals in tailings (called hard pan) can locally create a zone where the hydraulic conductivity is lower which can reduce oxygen migration and, consequently, the production of AMD (see Blowes et al. 1991; Aubertin et al. 2002a). The comprehension of all of these mechanisms relating to the secondary mineral formation is necessary when one wants to predict the evolution of AMD in a given mine site.

## MAIN AMD CONTROL METHODS

When the neutralization potential of a given mine

waste is less than the acidification potential, AMD will occur and appropriate measures have to be taken at the mine waste storage site to mitigate it. Over the last few years, different techniques have been proposed to limit the environmental impacts of AMD. One approach is to control the production of AMD, from mine tailings or waste rocks, by eliminating one (or more) of the three main components of the oxidation reactions (see Eq. 1): oxygen, water and/or sulphide minerals.

### Sulphide Extraction

The presence of sulphide minerals is essential to generate AMD. AMD can be controlled by extracting a sufficient portion of these minerals thus limiting the quantity of AMD generated in the environment. The necessary recovery of sulphide minerals will depend on the amount of neutralizing minerals. Different techniques such as flotation and gravimetric separation can be used to separate the sulphides from the tailings (e.g. McLaughlin and Stuparyk, 1994; Humber, 1995; Bussière et al. 1995, 1998). This control method is mainly applicable for operating sites but the recycling (sulphide extraction combined with metal recovery) of old abandoned mine wastes could also be an option in some particular cases. More information on sulphide extraction for environmental purposes can be found in Bussière et al. (1995, 1998), Benzaazoua et al. (1998, 2000), Benzaazoua and Kongolo (2003), Bois et al. (2005), and Mermillod-Blondin et al. (2005).

### Oxygen Barriers

Oxygen is one of the key ingredients for the generation of AMD. Limiting oxygen availability for the reactive mine wastes is one of the most interesting approaches to control AMD, especially in humid climatic conditions (e.g. SRK 1989; MEND 2001). Different approaches can be used to create an oxygen barrier: placing a water cover or by elevating the water table, placing a cover with capillary barrier effects over the waste disposal site, or installing an oxygen consuming barrier (not discussed in this document).

#### *Water cover and elevated water table technique*

The water cover technique consists of completely covering the reactive mine wastes with water by submerging the mine waste in a lake or by building a dyke to hold both the mine waste and the water that submerges them. Because the oxygen diffusion coefficient is 10 000 times lower in water than in air, the flux of oxygen reaching the AMD mine wastes is usually sufficiently low and avoids AMD generation. However, a water cover is a complex, dynamic system subjected to

several factors such as tailings erosion and resuspension, oxygen migration, oxidation of sulphidic tailings by dissolved oxygen (DO), release of dissolved metals, water exchange with the surrounding environment, etc. Several studies on these aspects have been conducted to develop appropriate design tools for water covers (e.g. Adu-Wusu et al. 2001; Catalan and Yanful 2002; Yanful and Catalan 2002; Mian and Yanful 2004).

Water covers can raise serious stability concerns and can be difficult to maintain over the long term (Aubertin et al. 1997a). To reduce the geotechnical risks associated to a water cover, a new approach was proposed relatively recently for tailings: the Elevated Water Table (EWT) technique (MEND, 1996; Orava et al. 1997; Dagenais, 2005; Dagenais et al. 2006; Ouangrawa et al. 2006, 2009; Ouangrawa, 2007; Demers et al. 2008). The principle on which the EWT technique is based consists of maintaining a degree of saturation sufficiently high in the tailings above the water table in order to reduce the oxygen diffusion rate and prevent sulphide oxidation. A high degree of saturation is maintained by controlling seepage and capillary rise. Similar to water cover, the elevated water table technique is based on the fact that the effective diffusion coefficient of oxygen is very low in saturated (or nearly saturated) media (Mbonimpa et al. 2003, Achib et al. 2004).

#### *Cover with capillary barrier effects*

Multi-layered covers with capillary barrier effects (CCBEs) use unsaturated soil properties to create the capillary barrier effects that maintain one of the layers at a high degree of saturation at all times. The high degree of saturation makes the moisture-retaining layer an efficient barrier against oxygen flow, by impeding gas advection and diffusion. By limiting oxygen flux, the cover limits AMD generation since oxygen is one of the constitutive elements of the sulphide mineral oxidation reactions.

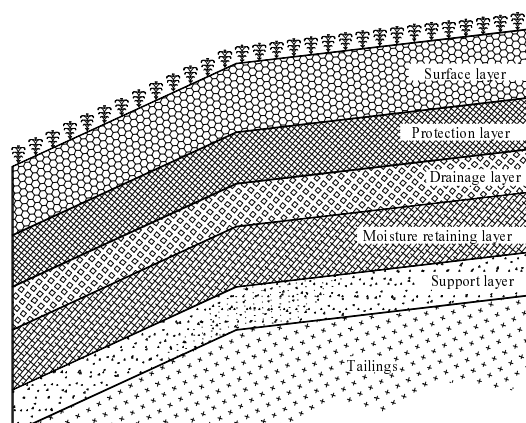
The effectiveness of this type of cover is dependant upon a phenomenon called the capillary barrier effect. This effect is present when a fine grained material is placed over a coarser one. The two materials have different hydrogeological properties because of their different textures. In the initial desaturation stage, the fine grained material layer retains water more easily than the coarse layer because it has smaller interstitial pores. As the coarse material drains, the presence of gas in its pore space reduces the interconnectivity of the voids which reduces its hydraulic conductivity ( $k$ ). This reduction of  $k$  in the coarse layer reduces the vertical water flow from the fine material and thus the latter layer can remain almost fully saturated at all times, creating the oxygen barrier. More details about capillary barrier effects and CCBE can be found in the literature (e.g. Nicholson et al. 1989; Akindunni et al. 1991; Aubertin et

al. 1995; Aachib 1997; Bussière 1999; Bussière et al. 2003).

Covers with capillary barrier effects usually contain three to five layers of different materials. Each layer has to play one (or more) specific role(s). Fig. 3 is a schematic illustration of a CCBE. The bottom layer is made of a fairly coarse material which functions as both a mechanical support and a capillary break. The fine grained material, utilized as the moisture retaining layer, is placed upon the first layer to create the capillary barrier effect. Another coarse material is placed upon the fine grained material layer to prevent water loss by evaporation and help lateral drainage. The other two layers (protection and surface layers) are protective layers against erosion and bio-intrusion for the CCBE; these are not discussed further in this paper.

### Water Infiltration Barriers

As seen in Eq. 1, water is one of the essential components of AMD generation. Hence, one can control the production of acid by limiting water flow through the reactive mine wastes. To do so a water infiltration barrier must be built on top of the mine waste disposal area. To limit the influx of water, covers made of low hydraulic conductivity soils or synthetic materials (such as geomembranes or bentonite geocomposites) can be used. The configuration of these covers is similar to designs developed for the isolation of domestic and hazardous wastes (e.g. Oakley, 1987; Aubertin and Chapuis, 1991; Daniel and Koerner, 1993; Koerner, 1993, 1994; Aubertin et al. 1995; Rowe et al. 2004).

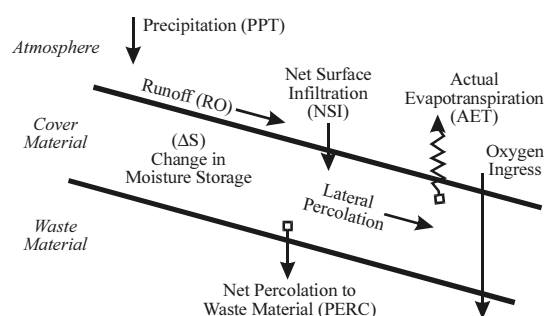


**Fig. 3** Typical configuration of a CCBE used to limit the production of AMD (Aubertin et al. 1995)

Another option to limit water infiltration in arid and semi-arid conditions is the use of “Store-and-Release” SR covers (also bearing various other names such as “alternative”, “water balance”, or “evapotranspirative” covers). Such engineered systems are attracting considerable interest as they may represent an advantageous alternative to more traditional covers that

rely on materials having a low saturated hydraulic conductivity (e.g. Morris and Stormont 1997; Ward and Gee 1997; Dwyer 1998; Zhan et al. 2001; Scanlon et al. 2005).

A typical SDR cover includes a fine-grained soil layer placed on top of a coarser material. The capillary barrier effect at the interface between the fine and coarse materials allows the finer soil layer to store incoming water, which can later be released by evaporation. In sloping areas, a capillary barrier cover also acts as a lateral water diversion system. Additional layers can also be added to help the cover play its role(s) efficiently. Fig. 4 shows a typical water balance of a SDR cover. The objective of the cover is to have sufficient runoff, evapotranspiration, storage, and lateral percolation (in the case of inclined covers) to avoid water infiltration into the mine waste. The main advantages of a SR cover lie in its relative simplicity, long-term stability, and potentially lower construction costs compared to more traditional covers that rely on materials (natural soils and/or geosynthetics) with a low saturated hydraulic conductivity (e.g. Morris and Stormont 1997). More information on SR or SDR covers can be found in Williams et al. (2003), Benson et al. (2001), Fourrie and Moonsammy (2002); Bussière et al. (2007) and Aubertin et al. (2009).



**Fig. 4** Schematic representation of an SDR cover water budget (MEND 2001)

### DIFFERENCES BETWEEN OPERATING AND ABANDONED MINE SITES

There are important differences between an operating mine and abandoned mine site (left exposed to natural conditions for years) and these differences influence the selection of the most appropriate reclamation scenario. These main differences are summarized in Table 1.

One of the main differences between abandoned and operating AMD mine waste disposal is the quality of the pore water. Sulphide oxidation in the mine wastes after the mine closure can significantly contaminate the pore water; typically, the pH of the water can be lower than 4, with high concentrations of sulphates and metals (in the order of thousands of ppm) such as iron, zinc, arsenic, etc. (see Aubertin et al. 2002a for examples). Moreover, a high concentration in iron can lead to indirect

oxidation of sulphide minerals (see for example Eq. 5) which would generate more acid even after the placement of an oxygen barrier. The addition of a neutralizing agent before the placement of the oxygen barrier could be a solution to reduce indirect oxidation (see Catalan et al. 2002). The objective is to precipitate iron ions and to reduce the concentration in ferric iron ( $\text{Fe}^{3+}$ ) responsible of the indirect oxidation.

**Table 1** Main differences between operating and abandoned AMD mine waste disposal sites (modified from Bussière et al. 2005)

Characteristics	Operating sites	Abandoned sites
Pore water contamination	Low risk	High risk
Presence of AMD bacteria	Low activity	Highly active
Modern storage infrastructures	yes, in general	No, in most cases
Presence of water treatment system	yes	No

The main objective of AMD mine waste disposal sites is to limit the environmental impacts to an acceptable level. For abandoned mine sites, in addition to the future contamination, the reclamation must take care of the previous contamination. Hence, it is usually necessary to integrate into the reclamation scenario the treatment of the pore water that will flow out of the site. In the context of sustainable development, traditional chemical treatment of AMD is not considered a viable long term solution. The other option available is the use of passive treatment systems such as bioreactors with sulphate-reducing bacteria (e.g. Zaluski et al. 2003; Johnson and Hallberg, 2005; Neculita et al. 2007), wetlands (see Kalin, 1993 ; Gazea et al. 1996 ; Goulet and Pick, 2001), and oxic and anoxic limestone drains (e.g., Ziemkiewicz et al. 1997; Bernier et al. 2002; Cravotta, 2003). Because of metal concentrations and the volume of water that have to be treated during the wet season in humid climates, these approaches cannot usually reach (alone) the environmental regulation criteria for effluents coming from AMD abandoned mine waste disposal sites. However, these approaches could be an interesting option for sites where an oxygen or water infiltration barrier is placed as a primary AMD control method.

Other aspects also have to be taken into account for an effective abandoned AMD mine waste disposal site. Acidophilic bacteria are well implemented in mine wastes. As mentioned earlier, the presence of these bacteria can accelerate the production of AMD by a significant factor. Limiting their development can help to

reduce the environmental contamination, but cannot completely eliminate the problem (e.g. Kleinmann and Erickson, 1981; Watzlaf, 1986; Rastogi, 1996). The old infrastructures used to contain mine tailings are usually made of the tailings themselves and were built by experienced people that were taught empirically how to construct dykes, without necessarily taking into account state-of-the-art (at the time relatively poorly developed) geotechnical considerations. Moreover, hydraulic deposition produces a non-homogenous tailings mass, with unsaturated portions and low strength characteristics that induce difficulties with respect to final closure of the impoundment, especially when the tailings have the potential to generate AMD (Vick, 1990; Strachan, 2002; Aubertin et al. 2002b; Bussière, 2007).

## THE LORRAINE CASE STUDY

Different abandoned mine waste disposal sites were reclaimed worldwide in the last two decades or so. One of these sites (Lorraine site, Quebec, Canada) is described in more details. This case study allows for a better understanding of the technical challenges associated to the reclamation of an abandoned AMD tailings impoundment.

### The Lorraine Mine Site

The Lorraine mine site, located in the Témiscamingue region, Québec, Canada (see Fig. 5), was operated from 1964 to 1968. It generated approximately 600,000 tons of acid generating tailings disposed in a pond area covering approximately 15.5 hectares. The tailings thickness ranges from a few centimeters in the pond area up to 6 m (Aubertin, 1996). There was little mitigation work done at the end of the operation and the abandoned tailings were left exposed for 30 years. Chemical analysis of the seepage was characteristic of AMD with elevated concentrations of sulphates and metals, and by a pH ranging from 2.2 to 2.6.



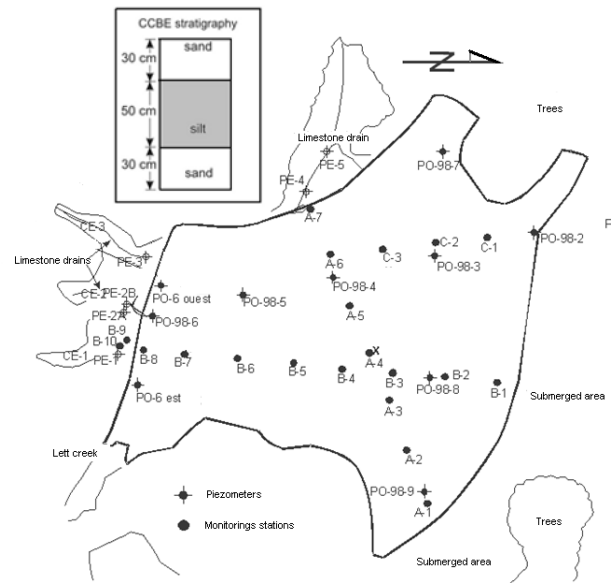
**Fig. 5** Lorraine mine site location



**Fig. 6** Photographs of the site before and after reclamation work

#### Lorraine CCBE and Dolomitic Drains

The design of the CCBE was made using basic hydrogeotechnical properties of the soils located near the site and numerical modeling tools (see Nastev and Aubertin, 2000; Dagenais, 2005; Dagenais et al. 2005). The CCBE is composed of three layers: a base layer consisting of 30 cm of sand used as capillary break layer; a moisture-retaining layer made of silty material with a thickness of 50 cm that limits gas diffusion and water infiltration; and a 30 cm top layer consisting of sand and gravel to protect the silt layer from evaporation. Saturated hydraulic conductivity ( $k_{sat}$ ) varies from  $2 \times 10^{-6}$  to  $1 \times 10^{-5}$  cm/s for the silt material and is about  $7 \times 10^{-3}$  cm/s for the sand. Suction tests done on the silt material gave an air entry value ( $\psi_a$ ; pressure at which a material starts to drain) ranging from 2.9 to 5 m of water for a void ratio between 0.85 and 0.62. The measured  $\psi_a$  for the sand is around 0.25 m of water. The contrast between the hydraulic properties makes possible the development of capillary barrier effects in the CCBE. More information on the construction, design and material properties can be found in Nastev and Aubertin (2000), Dagenais (2005), Dagenais et al. (2005), and Bussière et al. (2009).



**Fig. 7** Plan view after reclamation of the Lorraine Site showing the location of the instruments and the configuration of the CCBE

Even if the CCBE works as an oxygen barrier, the AMD presents in the pore water will have to be treated before discharging the water in the environment. At the Lorraine mine site, three dolomitic drains (Dol-1, 2, and 3) were built to treat the contaminated exfiltration from the south dykes. A fourth calcareous drain was installed near the west dykes but since the construction of the CCBE, the feed water draining to the drain was not contaminated by AMD, therefore this drain will not be discussed further.

The Lorraine dolomitic drains (see Fig. 7 for location) are trenches filled with coarse dolomitic stones (size of particles between 10 and 100 mm), with sides made of a silty material with a low saturated hydraulic conductivity (compared to the coarse dolomitic stones). The trench is isolated on top by a GCL liner. AMD flows by gravity into the drains that have a section of approximately  $1.5 \text{ m}^2$  and a length of 65, 69, 55 m for Dol-1, 2, and 3 respectively. The hydraulic residence time was estimated using tracer tests at values between 700 and 2 000 minutes depending on the influx of water (the targeted value was 900 minutes). More information on the dolomitic drains can be found in Maqsoud et al. (2007) and Bussière et al. (2009).

A monitoring strategy was developed to follow the performance of the CCBE and the dolomitic drains. TDR probes and Watermark sensors monitored volumetric water content and suction, respectively, in the different layers of the cover; the location of the 20 monitoring stations is presented in Fig. 7. Each station included four TDR probes (SoilMoisture) and four Watermark ceramic probes (Irrometer). A set of each was placed horizontally in both the sand layers and two sets were placed in the

silt layer of the CCBE. These instruments have been used previously by the authors to monitor the hydraulic behaviour of a CCBE during laboratory and test plot studies (Aubertin et al. 1995, 1997b, 1999; Bussière et al. 2003). The measurement of these characteristics gives insight into the hydrogeological behaviour of the CCBE and the development of capillary barrier effects. They also allow evaluation of the oxygen flux through the CCBE. Finally effluent flow and quality were also monitored. The frequency of the readings was similar for the CCBE and dolomitic drains monitoring: between 4 to 8 series of measurements per year. More information on the monitoring can be found in Dagenais et al. (2005) and Dagenais (2005).

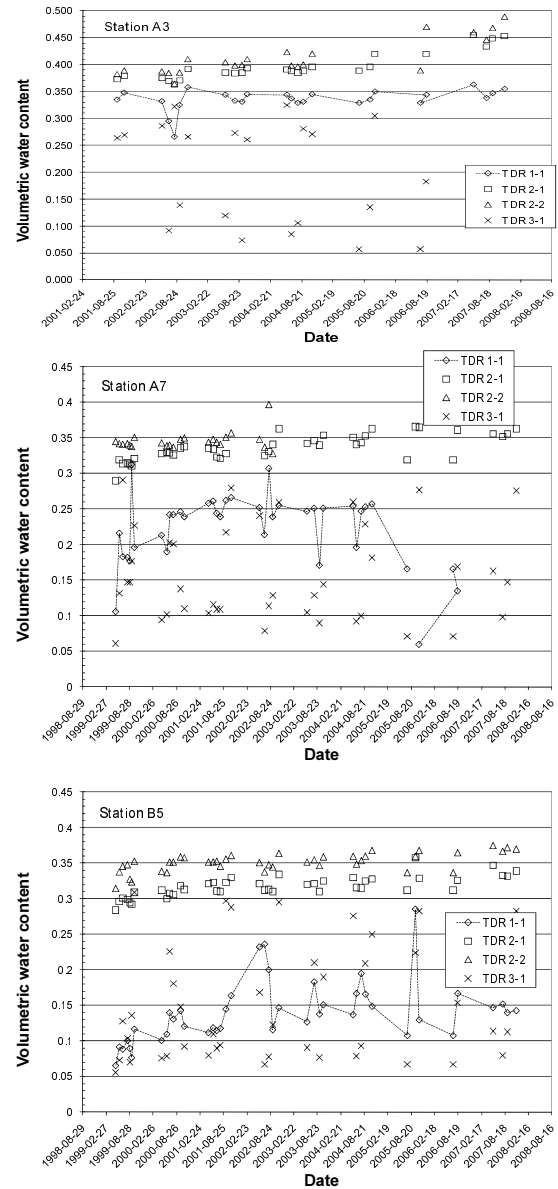
### Main Monitoring Results

To give a perspective on the performance of the CCBE to limit oxygen migrations, volumetric water content ( $\theta$ ) measurements from three representative monitoring stations (A3, A7 and B5) are presented with their corresponding oxygen flux calculated using the first Fick's law. The water quality evolution will be presented using key physico-chemical parameters: pH, iron and nickel (the most problematic metals at the Lorraine mine site).

#### *Volumetric water content and oxygen flux*

Results presented in Fig. 8 show that the moisture-retaining layer usually had volumetric water content between 0.32 and 0.35, except for station A3 where values were usually between 0.35 and 0.4. Considering the porosity ( $n$ ) of the layer estimated at 0.37 for stations A7 and B5, and at 0.4 for station A7, the degree of saturation ( $S_r = \theta/n$ ) usually met the design criteria of 85%. It is also interesting to note in Fig. 7 that the bottom sand layers are desaturated at station B5 ( $\theta$  usually between 0.10 and 0.20 for a porosity of 0.35), is closer to saturation at station A7 ( $\theta$  usually between 0.15 and 0.25 for a porosity of 0.35) and is saturated at station A3 ( $\theta$  values close to porosity at 0.35). This means that capillary barrier effects were present at station B5 and A7, and helped to maintain a high degree of saturation in the moisture-retaining layer while the phreatic surface at station A3 is close or in the CCBE.

The previous results showed that the CCBE hydrological behavior was working as planned and that the water retention layer maintained a high degree of saturation throughout the years of monitoring. To better assess the CCBE's performance, the oxygen flux that was diffusing into the reactive tailings was calculated. Since the transient state is expected to be fairly short (approximately 10 days, e.g. Mbonimpa et al. 2003), Fick's first law is used, for steady-state conditions, to



**Fig. 8** Evolution of volumetric water content at monitoring stations A3, A7, and B5; TDR 1-1 is located in the bottom capillary break layer at 15 cm of the interface with the moisture-retaining layer, TDR 2-1 is located in the moisture retaining layer at 15 cm from the interface with the capillary break layer, TDR 2-2 is located in the moisture retaining layer at 15 cm from the interface with the top sand layer, and the TDR 3-1 is located in the top sand layer at 5 cm from the interface with the moisture-retaining layer (modified from Bussière et al. 2009).

calculate the oxygen flux to the tailings. The solution is expressed as:

$$F = D_e \frac{(C_0 - C_l)}{h} \quad (10)$$

where  $F$  is the gas flux,  $C_0$  is 285 g/m<sup>3</sup> (atmospheric oxygen concentration at the top of the cover),  $C_l$  is



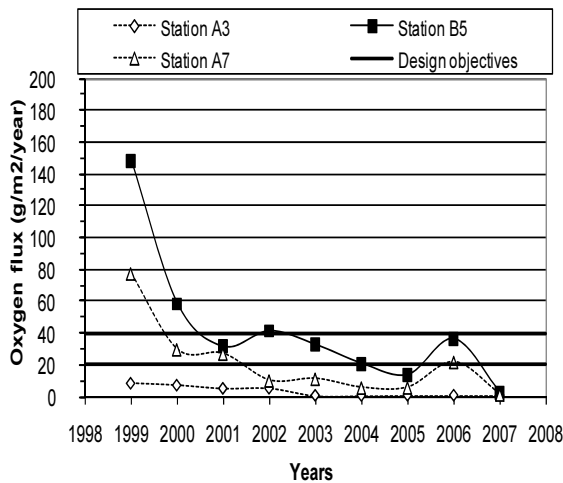
0 g/m<sup>3</sup> (oxygen consumed by sulfide tailings at the bottom of the cover),  $D_e$  is the effective diffusion coefficient and  $h$  is 0.5 m (silt layer thickness).

To estimate the parameter  $D_e$  in Eq. 10, the equation proposed by Aachib et al. (2002; 2004) was used:

$$D_e = \frac{1}{n^2} [D_a^0 \theta_a^{3.5} + HD_w^0 \theta^{3.5}] \quad (11)$$

where  $D_a^0$  is the diffusion coefficient in air ( $\approx 1.8 \times 10^{-5}$  m<sup>2</sup>/s) and  $D_w^0$  is the diffusion coefficient in water ( $\approx 2.5 \times 10^{-9}$  m<sup>2</sup>/s),  $n$  is the porosity,  $H$  is the Henry equilibrium constant (0.03 for oxygen at 20°C),  $\theta_a$  represents the volumetric air content of the material and  $\theta$  the volumetric water content of the material.

The estimated annual oxygen fluxes through the Lorraine CCBE (based on average annual volumetric water content in the moisture-retaining layer) are presented in Fig. 9. Results show that there is a transient period for the first two years after the CCBE construction. The higher oxygen flux for these first two years can be explained by a gradual saturation of the moisture-retaining layer. Since 2002, oxygen flux values were relatively stable at less than 5 g of O<sub>2</sub>/m<sup>2</sup>/year for station A3, less than 12 g of O<sub>2</sub>/m<sup>2</sup>/year for station A7 (except for 2006 where the flux was at 22 g of O<sub>2</sub>/m<sup>2</sup>/year), and between 20 and 40 g of O<sub>2</sub>/m<sup>2</sup>/year for station B5.

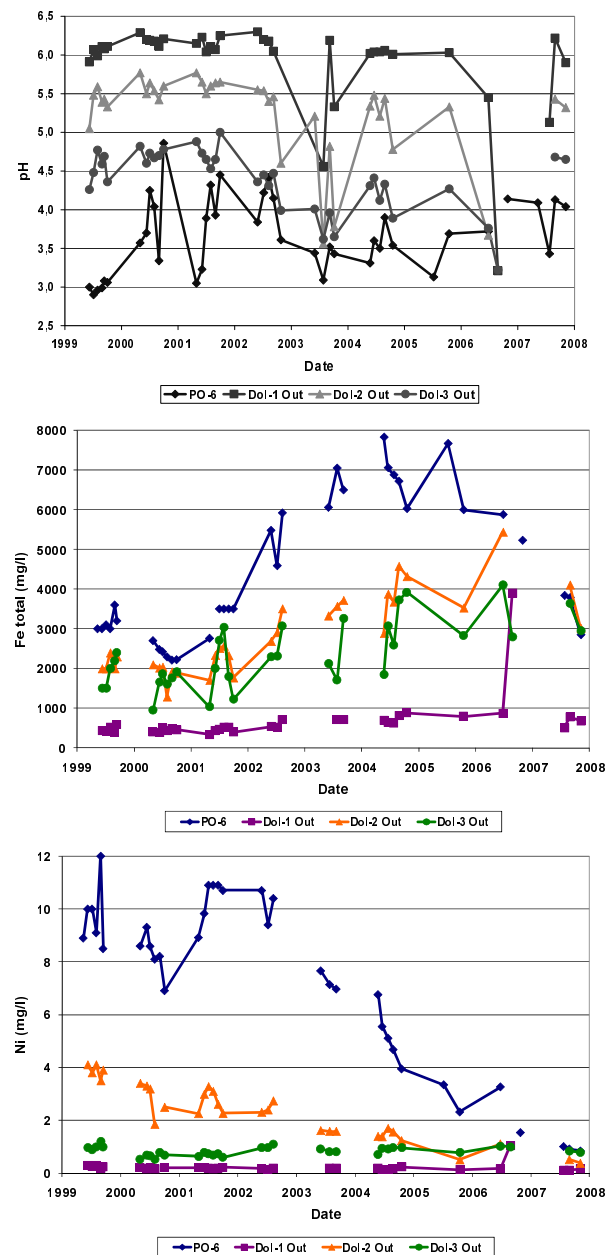


**Fig. 9** Oxygen flux calculated using average values of volumetric water content in the moisture-retaining layer at monitoring stations A3, A7, and B5 (modified from Bussière et al. 2009)

Considering the design objectives of having a flux between 20 and 40 g of O<sub>2</sub>/m<sup>2</sup>/year (Nastev et Aubertin, 2000), the Lorraine CCBE is considered efficient to limit the diffusion of oxygen from the atmosphere to the reactive tailings.

### Water quality

Improvement of the water quality at the effluent was also one of the objectives of the reclamation work at the Lorraine site. Fig. 10 presents the evolution of three critical parameters at the Lorraine site effluents: pH, iron and nickel. The influent pH (PO-6) slightly increased (typically from 3 to 4) between 1999 and 2007, even as the CCBE was working well as an oxygen barrier. The pH measurements at the effluent of the dolomitic drains were close to 6, 5.5 and 4.5 for Dol-1 Out, Dol-2 Out and Dol-3 Out respectively. One can also observe that the pH of Dol-3 Out had a decreasing tendency.



**Fig. 10** Evolution of pH, nickel and iron at the effluent of the three dolomitic drains (identified as Dol-1 Out, Dol-2 Out, and Dol-3 Out) in the incoming water (PO-6) (modified from Potvin, 2009)

Iron concentrations at the influent (PO-6) went from 3,000 to 7,000 mg/L between 1999 and 2004. In 2000, a slight reduction to under 2,500 mg/L was observed. Between 2002 and 2006, iron concentrations increased to values close to 8,000 mg/L and decreased in the year following to a value of 3,500 mg/L in 2007. This increase between 2002 and 2006 is attributed to secondary mineral dissolution that could have remobilized the iron. Iron concentration at the effluent of Dol-1 is significantly reduced to values usually less than 1 000 mg/L. The capacity to reduce iron concentration is less for the other two drains.

Nickel concentrations in the influent and effluents of the drains showed a progressive reduction since the reclamation of the site. In the influent, nickel concentrations started at values between 8 and 11 mg/L during the period of 1999–2002 and reached values less than 1 mg/L the following year. At the effluent of Dol-1, nickel concentrations were usually less than 0.3 mg/L. Values at the exit of Dol-2 and 3 were slightly higher than in Dol-1 (between 0.5 and 1 mg/L in 2007).

The dolomitic drains allowed for improving the water quality at the final effluent, but have not been able to reach the environmental criteria of the provincial government. The drains have also different efficiencies (Dol-1>Dol-2>Dol-3) even if they were built using the same approach and the same materials. More work is presently underway to better understand the treatment mechanisms of the Lorraine dolomitic drains (Maqsoud et al. 2007; Potvin, 2009).

#### *Lessons learned at the Lorraine mine site*

The work at the Lorraine mine site allowed researchers to improve their knowledge on the reclamation of already oxidized abandoned acid generating mine waste disposal site. The main lessons learned were:

- The improvement of water quality at the effluent is not instantaneous even if an efficient oxygen barrier is placed on top of the acid generating materials. This is due to the contaminated pore water that has to flow out. In the case of the Lorraine site, a slight improvement was observed after 10 years.
- The placement of a water treatment system is essential if one wants to limit the contamination of the environment from the exfiltration of the site.
- At the Lorraine site, the dolomitic drains have improved the quality of the final effluent. However, the concentrations are still higher than the regulation criteria. Other techniques could be used in conjunction with the dolomitic drains (ex. passive bio-reactors using sulfate-reducing bacteria; see Neculita et al. 2007 for details) to improve further the quality of the exiting water.
- More information on indirect oxidation (by bacteria

and/or iron) and other geochemical reactions (ex. precipitation/dissolution of secondary minerals) below the cover would be useful to better assess the Lorraine CCBE performance.

In summary, the reclamation of the Lorraine site showed the numerous scientific challenges related to the reclamation of abandoned acid generating mine waste disposal areas.

### **GOVERNMENTAL ACTIONS TO REHABILITATE CANADIAN ABANDONED MINE SITES**

Canada has made significant progress in the remediation of abandoned mine sites over the last 10 years. In the following, some of the recent initiatives are briefly described. The interested reader can consult the web site of the NAOMI (National Orphaned/Abandoned Mines Initiative) project for more information (<http://www.abandoned-mines.org/>).

In Ontario, the province created in 1999 a program to conduct reclamation work on Crown-held abandoned mine sites. The program will invest \$138 million (CDN) between 1999 and 2012. One of the prioritized sites is Kam Kotia located near the city of Timmins. The site (which contains three acid generating tailings impoundments) covers an area of approximately 500 ha. A five phase rehabilitation plan was proposed which integrated the construction of a chemical water treatment plant, relocation of tailings, the construction of engineered covers and the construction of a wetland. More information on Kam Kotia rehabilitation plan can be found in Hamblin and Kord (2003).

In Manitoba, the government has identified five high priority sites: Lynn Lake, Sherridon, Gods Lake, Snow Lake and Baker Patton. Environmental and risk assessments were completed in 2000 and at an additional 144 orphaned and abandoned sites (Tremblay and Hogan, 2009). 110 million dollars (CDN) has been committed to address the reclamation of Manitoban abandoned mines sites. More technical information on some of the abandoned mine sites of the province can be found in Moncur et al. (2005; Sheridan site) and Gunsinger et al. (2006a, b; Lynn Lake).

In British Columbia, the government has committed over \$190 million (CDN) for the management of the provinces contaminated sites and has spent \$35 million between 2002 and 2007; for the current year (2008–2009), the program has allocated \$27 million dollars

In Quebec, reclamation works are planned on different abandoned mine sites. The biggest site is Manitou, located near Val-d'Or. The 200 hectare acid generating mine waste disposal site will be rehabilitated using a non acid generating tailings coming from another mine (Goldex mine property of Agnico-Eagle). The non acid generating tailings (with a good neutralization

potential) will be used to cover the existing site and to create an oxygen barrier. Different cover scenarios are presently under investigation for the final reclamation. The overall costs related to the reclamation works at Manitou are estimated at \$40 to 50 million (CDN). Another acid generating site, Aldermac, will be rehabilitated in the next two years. The approximately 75 ha site is located near Rouyn-Noranda. The reclamation strategy selected at this site consists of isolating a portion of the site by a geomembrane and to use the elevated water table approach for the other portion. Other sites in the province of Quebec with different problematic occurrence have been rehabilitated in the last 15 years such as East Sullivan (Germain et al. 2003, 2004 ; Tassé and Germain, 2004), Lorraine (see the previous section), Canadian Malartic (Tassé et al. 1997), Candego (Aubertin et al. 2002a), Somex (Aubertin et al. 2002a), Wood Cadillac (Germain and Cyr, 2003 ; Tassé et al. 2003), Solbec-Cupra (Amyot et Vézina, 1997) and Poirier (Maurice, 2002).

## LAST REMARKS

The present paper showed that the reclamation of abandoned mine sites is a significant challenge for most Canadian provinces and Territories. The challenge is technical, as shown in this paper, but also political since the sites are owned by the government and the decision to rehabilitate a given site must consider the availability of governmental financial resources. However, the last few years are encouraging since several millions of Canadian dollars have been engaged to reduce the pollution of the most problematic abandoned mine waste disposal areas.

The environmental problems related to abandoned mine sites are not restricted to Canada. Many other countries face similar problems and some of them have decided to tackle the problem. Some organizations have also started such as the Post-Mining Alliance. The Post-Mining Alliance is an independent not-for-profit organization with a mission to encourage and promote the regeneration of old mine sites for the sustainable benefit of the local community and the natural environment. More information can be found on their web site (<http://www.postmining.org/>).

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## REFERENCES

- Aachib M, Mbonimpa M, Aubertin M (2004). Measurement and prediction of the oxygen diffusion coefficient in unsaturated media, with applications to soil covers. *Water, Air and Soil Pollution*, 156:163-193.
- Aachib M, Aubertin M, Mbonimpa M (2002). Laboratory measurements and predictive equation for gaz diffusion coefficient of unsaturated soils. *Proc. 55th Canadian Geotechnical Conference and 3rd joint IAH-CNC and CGS Groundwater Specialty Conferences*, Niagara Falls, Ont., CD-Rom: 163-171.
- Aachib M (1997). Étude en laboratoire de la performance des barrières de recouvrement constituées de rejets miniers pour limiter le DMA. Ph.D. Thesis, Mineral Engineering Department, École Polytechnique de Montréal.
- Adu-Wusu C, Yanful EK, Mian MH (2001). Field evidence of resuspension in a mine tailings pond. *Canadian Geotechnical Journal*, 38: 796-808.
- Aguilar J, Dorronsoro C, Fernández E, Fernández J, García I, Martín F, Simón M (2004). Soil Pollution by a pyrite mine spill in Spain, evolution in time. *Environmental, Pollution*, 132: 395-401.
- Akindunni FF, Gillham RW, Nicholson RV (1991). Numerical simulations to investigate moisture-retention characteristics in the design of oxygen-limiting covers for reactive mine tailings. *Canadian Geotechnical Journal*, 28 :446-451.
- Amyot G & Vézina S (1997). Flooding as a reclamation solution to an acidic tailings pond – the Solbec case. *Proc. of the 4th International Conference on Acid Rock Drainage*, Vancouver, 2: 451-464.
- Aubertin M, Cifuentes E, Apithy S, Bussière B, Molson J, Chapuis RP (2009). Analyses of water diversion along inclined covers with capillary barrier effects. *Canadian Geotechnical Journal* (accepted and in print).
- Aubertin M, Bussière B, Bernier L (2002a). *Environnement et gestion des résidus miniers*. Presses Internationales de Polytechnique, Corporation de l'École Polytechnique de Montréal, Montréal.
- Aubertin M, Mbonimpa M, Jolette D, Bussière B, Chapuis RP, James M, Riffon O (2002b). Stabilité géotechnique des ouvrages de retenue pour les résidus miniers: problèmes persistants et méthodes de contrôle. *Proc. of Défis & Perspectives: Symposium 2002 sur l'Environnement et les Mines*, Rouyn-Noranda, on CD-ROM, paper s32a1019, p. 26, 526.
- Aubertin M, Bussière B, Joanes AM, Monzon M, Gagnon D, Barbera JM, Bédard C, Chapuis RP, Bernier L (1999). *Projet sur les barrières sèches construites à partir de résidus miniers, Phase II:*

- essais en place.” MEND Report 2.22.2c.
- Aubertin M, Dionne J, Marcoux L (1997a). Design guidelines and stability criteria of engineering works for water covers. Proc. of the 4th International Conference on Acid Rock Drainage, Vancouver, BC, 4: 1849-1866.
- Aubertin M, Bussière B, Barbera JM, Chapuis RP, Monzon M, Aachib M (1997b). Construction and instrumentation of in situ test plots to evaluate covers built with clean tailings. Proc. of the 4th International Conference on Acid Rock Drainage, Vancouver, BC, 2: 715-730.
- Aubertin M (1996). Recouvrement multicouche pour le parc à résidus du site minier Lorraine. Rapport soumis au MRNQ (SDM-R-96-23). p. 30.
- Aubertin M, Chapuis RP, Aachib M, Bussière B, Ricard J-F, Tremblay L (1995). Évaluation en laboratoire de barrières sèches construites à partir de résidus miniers. Rapport NEDEM/MEND Report 2.22.2a.
- Aubertin M & Chapuis RP (1991). Considération hydrogéotechniques pour l'entreposage des résidus miniers dans le nord-ouest du Québec. Proc. of the 1st International Conference on Acid Rock Drainage, Montréal, Québec, 3: 1-22.
- Benson CH, Abichou T, Albright WH, Gee GW, Roesler AC (2001). Field evaluation of alternative earthen final covers. Int. J. Phytoremediation, 3: 1-21.
- Benzaazoua M & Kongolo M (2003) Physico-chemical properties of tailing slurries during environmental desulphurization by froth flotation. International Journal of Mineral Processing, 69: 221-234.
- Benzaazoua M, Bussière B, Kongolo M, McLaughlin J, Marion P (2000). Environmental desulphurization of four Canadian mine tailings using froth flotation. International Journal of Mineral Processing, 6 : 57-74.
- Benzaazoua M, Bussière B, Lelièvre J (1998). Flottation non sélective des minéraux sulfurés appliquée dans la gestion environnementale des rejets miniers. Proc. of the 30th Canadian Mineral Processors Symposium, Ottawa: 682-695.
- Bernier LR, Aubertin M, Poirier C, Bussière B (2002). On the use of limestone drains in the passive treatment of acid mine drainage (AMD). Proc. of Défis & Perspectives: Symposium 2002 sur l'Environnement et les Mines, Rouyn-Noranda, on CD-ROM, paper s32 a1031, p.540.
- Berthelin J (1987). Des bactéries pour extraire des métaux. La recherche, 188 : 720-725.
- Blowes DW & Ptacek CJ (1994). Acid-neutralization mechanisms in inactive mine tailings. Short Course Handbook on Environmental Geochemistry of Sulfide Mine-Waste, Jambor, J.L., Blowes, D.W. (eds). Mineralogical Association of Canada. Special 22: 272-292.
- Blowes DW, Reardon EJ, Jambor JL, Cherry JA (1991). The formation and potential importance of cemented layers in inactive sulfide mine tailings. *Geochemica et Cosmochimica Acta*, 55: 965-978.
- Bois D, Poirier P, Benzaazoua M, Bussière B, Kongolo M (2005). A feasibility study on the use of desulphurized tailings to control acid drainage. CIM Bulletin, 98 : 78 (<http://www.cim.org>).
- Bussière B, Potvin R, Dagenais A-M, Aubertin M, Maqoud A, Cyr J (2009). Restauration du site minier Lorraine, Latulipe, Québec: résultats de 10 ans de suivi. *Déchets, Sciences et Techniques*, 54: 49-64.
- Bussière B (2007). Colloquium 2004: Hydro-geotechnical properties of hard rock tailings from metal mines and emerging geo-environmental disposal approaches. *Canadian Geotechnical Journal*, 44: 1019-1052.
- Bussière B, Aubertin M, Zhan G (2007). Discussion: Design of inclined covers with capillary barrier effect, by S.-E. Parent and A. Cabral *Geotechnical and Geological Engineering*, 25:673-678.
- Bussière B, Aubertin M, Zagury GJ, Potvin R, Benzaazoua M (2005) Principaux défis et pistes de solution pour la restauration des sites miniers abandonnés générateurs de drainage minier acide. Proc. of the 2e Symposium sur l'Environnement et les Mines, organisé par l'ICM – Rouyn-Noranda, on CD-ROM, p. 29.
- Bussière B, Aubertin M, Chapuis RP (2003). The behaviour of inclined covers used as oxygen barriers. *Canadian Geotechnical Journal*, 40: 512-535.
- Bussière B (1999). Étude du comportement hydrique de couvertures avec effets de barrière capillaire inclinées à l'aide de modélisations physiques et numériques. Ph.D. Thesis, Mineral Engineering Department, École Polytechnique de Montréal.
- Bussière B, Benzaazoua M, Aubertin M, Lelièvre J, Bois D, Servant S (1998). Valorisation des résidus miniers : une approche intégrée – Phase II. Final report submitted to the Ministère des Ressources naturelles du Québec, p. 198.
- Bussière B, Lelièvre J, Ouellet J, Bois D (1995). Utilisation des résidus miniers désulfurés comme recouvrement pour prévenir le DMA: analyse technico-économique sur deux cas réels. *Proceedings of Sudbury'95, Conference on Mining and the Environment*, Ed. Hynes T.P. & Blanchette M.C., Sudbury, Ontario, 1: 59-68.
- Catalan LJJ & Yanful EK (2002). Sediment-trap measurements of suspended mine tailings in shallow water cover. *Journal of Environmental Engineering*, 128: 19-30.
- Catalan LJJ, Buset KC, Yin G (2002). Reactivity of oxidized sulfidic mine tailings during lime treatment. *Environmental Science & Technology*, 36: 2766-2771.

- Cravotta CA III (2003). Size and Performance of Anoxic Limestone Drains to Neutralize Acidic Mine Drainage. *Journal of Environmental Quality*, 32 : 1277-1289.
- Dagenais A-M, Aubertin M, Bussière B (2006). Parametric study on the water content profiles and oxidation rates in nearly saturated tailings above the water table. *Proceedings of the 7th International Conference on Acid Rock Drainage (ICARD)*, St. Louis, Missouri, R.I. Barnhisel (Ed.). The American Society of Mining and Reclamation, CD-ROM: 405-420.
- Dagenais AM (2005). Contrôle du drainage minier acide basé sur les effets de barrières capillaires. Ph.D. Thesis, Mineral Engineering Department, École Polytechnique de Montréal.
- Dagenais AM, Aubertin M, Bussière B, Cyr J (2005). Performance of the Lorraine mine site cover to limit oxygen migration. *SME Transaction*, 318: 190-200.
- Daniel DE & Koener RM (1993). *Cover Systems. Geotechnical Practice for Waste Disposal*, Chapman & Hall: 455-497.
- Demers I, Bussière B, Benzaazoua M, Mbonimpa M, Blier A (2008). Column test investigation on the performance of monolayer covers made of desulphurized tailings to prevent acid mine drainage. *Mineral Engineering*, 21: 317-329.
- Dwyer SF (1998). Alternative landfill covers pass the test. *Civil Engineering*, September 1998: 50-52.
- Evangelou VP (1995). *Pyrite Oxidation and Its Control*. CRC Press.
- Fourrie AB & Moonsammy M (2002). Store and release covers for landfills in semi-arid climates. *Unsaturated Soils*, Juca, de Campos & Marinho (eds), Swets & Zeitlinger, Lisse, 2: 823-826.
- Frostad S, Klein B, Lawrence RW (2000a). Kinetic Testing 1. Effects of Protocol Variable on Rates of Weathering. *Proc. of the 5th International Conference on Acid Rock Drainage*, Denver, 1: 641-649.
- Frostad S, Klein B, Lawrence RW (2000b). Kinetic Testing 2. Scaling Up Laboratory Data to Predict Field Rates of Weathering. *Proc. of the 5th International Conference on Acid Rock Drainage*, Denver, 1: 651-659.
- Gazea B, Adam K, Kontopoulos A (1996). A review of passive system for the treatment of acid mine drainage. *Mineral Engineering*, 9: 23-42.
- Germain D, Tassé N, Cyr J (2004). The East-Sullivan mine site : merging prevention and treatment of acid mine drainage. *Proc. of the 57th Canadian Geotechnical Conference and 5th joint CGS/IAH-CNC Conference*, Québec, Session 8D, CD-ROM.
- Germain D & Cyr J (2003). Evaluation of biofilter performance to remove dissolved arsenic : Wood Cadillac. *Proc. of Sudbury 2003, Mining and the Environment III, Session 1A Bacteria*, Paper on CD-ROM.
- Germain D, Tassé N, Cyr J (2003). Treatment of acid mine effluents using a wood-waste cover. *Proc. of Sudbury 2003, Mining and the Environment III, Session 3A Organic Amendments*, Paper on CD-ROM.
- Goulet RR & Pick FR (2001). Changes in dissolved and total Fe and Mn in a young constructed wetland: Implications for retention performance. *Ecological Engineering*, 17: 373-384.
- Gunsinger MR, Ptacek CJ, Blowes DW, Jambor JL, Moncur MC (2006a). Mechanisms controlling acid neutralization and metal mobility within a Ni-rich tailings impoundment. *Applied Geochemistry*, 21: 1301-1321.
- Gunsinger MR, Ptacek CJ, Blowes DW, Jambor JL (2006b). Evaluation of long-term sulfide oxidation processes within pyrrhotite rich tailings, Lynn Lake, Manitoba. *Journal of Contaminant Hydrology*, 83: 149-170.
- Hakkou R, Benzaazoua M, Bussière B (2008). Acid mine drainage at the abandoned Kettara mine (Morocco), 1: Environmental characterization. *Mine Water and the Environment*, 27: 149-159.
- Hamblin CD & Kord MG (2003). The rehabilitation of Ontario's Kam Kotia Mine: an abandoned acid generating tailings site. *Proc. of Sudbury 2003, Mining and the Environment III, Paper on CD-ROM*.
- Humber AJ (1995). Separation of sulphide minerals from mill tailings. *Proc. of Sudbury'95, Conference on Mining and the Environment*, Ed. Hynes T.P. & Blanchette M.C., Sudbury, Ontario, 1: 149-158.
- Jambor JL, Dutrizac JE, Groat LA, Raudsepp M (2002). Static tests of neutralization potentials of silicate and aluminosilicate minerals. *Environmental Geology*, 43:1-17.
- Jerz JK & Rimstidt JD (2004). Pyrite oxidation in moist air. *Geochimica et Cosmochimica Acta*, 68:701-714.
- Johnson DB & Hallberg KB (2005). Biogeochemistry of the compost bioreactor components of a composite acid mine drainage passive remediation system. *The Science of the Total Environment*, 338: 81-93.
- Kalin M (1993). *Treatment of Acidic Seepages Using Wetland Ecology and Microbiology: Overall Program Assessment*. Final Report, MEND project 3.11.1.
- Kleinmann RLP, Crerar DA, Pacellil RR (1981). Biogeochemistry of acid mine drainage and a method to control acid formation. *Mining Engineering*: 300-304.
- Kleinmann RLP & PM Erickson (1981). Field evaluation of a bactericidal treatment to control acid drainage. *Proceedings of the 1981 Symposium on Surface Mining Hydrology, Sedimentology and Reclamation*, D.H. Graves (ed.), Lexington, KY: 325-329.
- Koerner RM (1993). *Geomembrane liners. Geotechnical Practice for Waste Disposal*, Chapman & Hall: 164-186.

- Koerner RM (1994). *Designing with Geosynthetics*. 3rd edition, Prentice Hall, Englewood Cliffs, N.J.
- Kwong Y TJ (1993). Prediction and prevention of acid rock drainage from a geological and mineralogical perspective. (MEND Report 1.32.1 CANMET, Ottawa), p. 47.
- Lapakko KA (1994). Evaluation of neutralization potential determinations for metal mine waste and a proposed alternative. *Proc. of the International Land Reclamation and Mine Drainage Conference and 3<sup>rd</sup> International Conference on the Abatement of Acidic Drainage*, Pittsburgh, 1 : 129-137.
- Lawrence RW & Scheske M (1997). A method to calculate the neutralization potential of mining wastes. *Environmental Geology*, 32: 100-106.
- Lee G & Faure G (2007). Process controlling trace-metal transport in surface water contaminated by acid-mine drainage in the Ducktown mining district. *Water Air and Soil Pollution*, 186: 221-232.
- Lowson RT (1982) Aqueous oxidation of pyrite by molecular oxygen. *Chemical Reviews*, 5-82:461-497.
- Maqsoud A, Bussière B, Aubertin M, Potvin R, Cyr J (2007). Evaluation of the hydraulic residence time in the limestone drains of the Lorraine site, Latulippe, Québec. *Proc. of the IV International Conference on Mining and the Environment*, Sudbury, 1-11.
- Maurice R (2002). Restauration du site minier Poirier (Joutel) – expériences acquises et suivi des travaux. *Proc. of Défis & Perspectives: Symposium 2002 sur l'Environnement et les Mines*, Rouyn-Noranda, on CD-ROM, paper s32 a1021 p545.
- Mbonimpa M, Aubertin M, Aachib M, Bussière B (2003). Diffusion and consumption of oxygen in unsaturated cover materials. *Canadian Geotechnical Journal* 40: 916-932.
- McLaughlin J & Stuparyk R (1994). Evaluation of low sulphur rock tailings production at INCO's Clarabelle mill. *Proc. of the Innovations in Mineral Processing Conference*, Sudbury, 129-146.
- MEND (2001). Manual report 5.4.2, Volume 1: Summary, Volume 2: Sampling and Analysis, Volume 3: Prediction, Volume 4: Prevention and Control, Volume 5: Treatment, Volume 6: Monitoring. Canada Centre for Mineral and Energy Technology, Ottawa, Canada.
- MEND (1996). Review of use of an elevated water table as a method to control and reduce acidic drainage from tailings, *Mine Environment Neutral Drainage Report 2.17.1*. Canada Centre for Mineral and Energy Technology, Ottawa, Canada.
- Mermillod-Blondin R, Kongolo M, de Donato P, Benzaazoua M, Barrès O, Bussière B, Aubertin M (2005). Pyrite flotation with xanthate under alkaline conditions - application to environmental desulfurization. *Proc. of the Centenary of Flotation Symposium*, Brisbane, QLD.
- Mian MH & Yanful EK (2004). Analysis of wind-driven resuspension of metal mine sludge in a tailings pond. *Journal of Environmental Engineering and Science*, 3: 119-135.
- Moncur MC, Ptacek CJ, Blowes DW, Jambor JL (2005). Release, transport and attenuation of metals from an old tailings impoundment. *Applied Geochemistry*, 20: 539-659.
- Morin KA & Hutt NM (1997). *Environmental Geochemistry of Minesite Drainage. Practical Theory and Case Studies*. MDAG Publishing.
- Morris CE & Stormont JC (1997). Capillary barriers and Subtitle D covers: estimating equivalency. *Journal of Environmental Engineering*, 123: 3-10.
- Morth AH & Smith EE (1966). Kinetic of the sulphide-to-sulfate reaction. *American Chemical Society, Division of Fuel Chemistry. Preprints*. 10:83.
- Nastev M & Aubertin M (2000). Hydrogeological modelling for the reclamation work at the Lorraine mine site Québec. *Proc. of the 1st Joint IAH-CNC-CGS Groundwater Specialty Conference*, Montréal, Québec: 311-318.
- Neculita CM, Zagury GJ, Bussière B (2007). Passive treatment of acid mine drainage in bioreactors using sulfate-reducing bacteria: critical review and research needs. *Journal of Environmental Quality*, 36: 1-16.
- Nicholson RV, Gillham RW, Cherry JA, Reardon EJ (1989). Reduction of acid generation in mine tailings through the use of moisture-retaining cover layers as oxygen barriers. *Canadian Geotechnical Journal*, 26: 1-8.
- Nicholson RV, Gillham RW, Reardon EJ (1988). Pyrite oxidation in carbonate-buffered solution. *Geochimica Cosmochimica Acta*, 52:1077-1085.
- Oakley RE (1987). Design and performance of earth-lined containment systems. *Geotechnical Practice for Waste Disposal*, ASCE, 117-136.
- Orava DA, Tremblay GA, Tibble A, Nicholson R (1997). Prevention of acid rock drainage through the application of in-pit disposal and elevated water table concepts, *Proc. of the 4th ICARD*, Vancouver, Canada, 3: 973-983.
- Ouangrawa M, Molson J, Aubertin M, Bussière B, Zagury GJ (2009). Reactive transport modelling of mine tailings columns with capillarity-induced high water saturation for preventing sulphide oxidation. *Applied Geochemistry*, 24: 1312-1323.
- Ouangrawa M (2007). Étude expérimentale et analyse numérique des facteurs qui influencent le comportement hydro-géochimique des résidus miniers sulfureux partiellement saturés. Ph.D. Thesis, Department of Civil, Geological & Mining Engineering, École Polytechnique Montréal.
- Ouangrawa M, Molson J, Aubertin M, Zagury GJ, Bussière B (2006). The effect of water table elevation

- on acid mine drainage from reactive tailings: A laboratory and numerical modeling study. Proc. of the 7th International Conference on Acid Rock Drainage (ICARD), St. Louis, Missouri, R.I. Barnhisel (Ed.). The American Society of Mining and Reclamation, CD-ROM.
- Perkins EH, Nesbitt HW, Gunter WD, St-Arnaud LC, Mycroft JR (1995). Critical review of geochemical processes and geochemical models adaptable for prediction of acidic drainage from waste rock. Mine Environment Neutral Drainage (MEND) Report 1.42.1. Secretariat CANMET, Ottawa, Ont.
- Potvin R (2009) Évaluation à différentes échelles de la performance de systèmes de traitement passif pour des effluents contaminés par le drainage minier acide. PhD thesis, Université du Québec en Abitibi-Témiscamingue (to be published).
- Rastogi V (1996). Water quality and reclamation management in mining using bactericides. Mining Engineering, 48: 66-71.
- Rogowski AS & Pionke HB (1984). Hydrology and Water Quality on Strip-mined Lands. U.S. Environmental Protection Agency.
- Rowe RK, Quigley RM, Brachman RWI, Booker JR (2004). Barrier Systems for Waste Disposal Facilities, Taylor & Francis Books Ltd (E & FN Spon) London, p. 587.
- Ritcey GM (1989). Tailings Management, Problems and Solutions in the Mining Industries. Elsevier.
- Scanlon BR, Reedy RC, Keese KE, Dwyer SF (2005). Evaluation of evapotranspirative covers for waste containment in arid and semiarid regions in the Southwestern USA. Vadose Zone Journal, 4: 55-71.
- Sherlock EJ, Lawrence RW, Poulin R (1995). On the neutralization of acid rock drainage by carbonate and silicate minerals. Environmental Geology, 25: 43-54.
- SRK (Steffen, Robertson and Kirsten) (1989). Draft Acid Rock Technical Guide. BC AMD Task Force, Vol. 1.
- Strachan C (2002). Review of tailings dam incident data. Mining Environmental Management, Tailings Management Guide, January 2002: 7-9.
- Sverdrup HU (1990). The Kinetics of Base Cation Release Due to Chemical Weathering. Lund University Press.
- Tassé N & Germain D (2004). The East-Sullivan mine site : from abandonment to restoration. Proc. of the 57th Canadian Geotechnical Conference and 5th joint CGS/IAH-CNC Conference, Québec, Session 8D, CD-ROM.
- Tassé N, Isabel D, Fontaine R (2003). Wood Cadillac mine tailings: designing a biofilter for arsenic control. Proc. of Sudbury 2003, Mining and the Environment III, Session 1A Bacteria, Paper on CD-ROM.
- Tassé N, Germain D, Dufour C, Tremblay R (1997). Hard-pan formation in the Canadian Malartic mine tailings: Implication for the reclamation of the abandoned impoundment. Proc. of the 4th International Conference on Acid Rock Drainage, Vancouver. IV: 1797-1812.
- Tremblay GA & Hogan CM (2009). Approaches for the remediation of abandoned mines and NAOMI. Déchets, Sciences et Techniques, 54: 3-9.
- Van Zyl D, Sassoon M, Digby C, Fleury AM, Kyeyune S (2002). Mining for the future. Paper prepared for Mining, Minerals and Sustainable Development (MMSD), Appendix C: Abandoned Mines, p. 19.
- Vick SG (1990). Planning, Design and Analysis of Tailings Dams. BiTech Publishers Ltd. Vancouver, B.C.
- Ward AL & Gee GW (1997). Performance evaluation of a field-scale surface barrier. Journal of Environmental Quality, 26: 694-705.
- Watzlaf GR (1986). Control of acid drainage from mine wastes using bacterial inhibitors. Proc. of the 1986 National Meeting of the American Society for Surface Mining and Reclamation: 123-130.
- Williams DJ, Currey NA, Ritchie PJ (2003). Kidston waste rock dump design and "store and release" cover system seven years on. Proc. of 6th International Conference on Acid Rock Drainage, Cairns, Australia: 419-426.
- Yanful EK & Catalan LJJ (2002). Predicted and fieldmeasured resuspension of flooded mine tailings. Journal of Environmental Engineering, 128: 341-251.
- Zaluski MH, Trudnowski JM, Harrington-Baker MA, Bless DR (2003). Post-mortem findings on the performance of engineered SRB field-bioreactors for acid mine drainage control. Proc. of the 6th International Conference on Acid Rock Drainage, Cairns Australia: 845-853.
- Zhan G, Aubertin M, Mayer A, Burke K, McMullen J (2001). Capillary cover design for leach pad closure, SME Transaction 2001, 1: 104-110.
- Ziemkiewicz PF, Skousen J, Brant DL, Sterner PL, Lovett RJ (1997). Acid Mine Drainage Treatment with Armored Limestone in Open Limestone Channels. Journal of Environmental Quality, 26: 1017-1024.