OBSERVATIONS AND EXPLANATIONS FROM THE MONITORING DATA OF EQUITY SILVER MINE, CANADA

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ABSTRACT

The waste rock dump of Equity Silver Mine produces acid rock drainage with high concentrations of metal ions. Over the past 25 years temperature and concentrations of CO\textsubscript{2} and O\textsubscript{2} at different lateral locations and different depths of the waste rock dump have been measured, which turns out to be very valuable for understanding the acid-generating and metal leaching processes. Our observations from the monitoring data include (1) strong positive correlations among O\textsubscript{2} concentrations at different locations, strong positive correlations among CO\textsubscript{2} concentrations at different locations, and strong negative correlations between CO\textsubscript{2} and O\textsubscript{2}; (2) seasonal variations of O\textsubscript{2} concentrations and CO\textsubscript{2} concentrations with O\textsubscript{2} concentrations decreasing from March to June/July and increasing from August to February; (3) substantial temperature variations, about 20 degree C, throughout the waste rock dump. The authors provide their explanations of the above observations. These explanations are useful for identifying the conditions that could reduce the problem of acid rock drainage and metal leaching (ARD-ML).

1.0 INTRODUCTION

Collaborating with consultants, universities, Natural Resources Canada and mine owners, the National Research Council Canada is putting efforts to develop core-knowledge and technologies for tackling the problem of acid rock drainage and metal leaching (ARD-ML) through the research program “Environmental Advances in Mining”. The current focus is on fundamental understanding of the ARD-ML processes and on the development of the methods of ARD-ML testing for scaling up. This paper reflects a part of our current effort.

Since 1990 the Equity Silver Mine in BC Canada has been monitoring the ARD-ML processes inside the main waste rock dump through the on-going measurement of temperature, O\textsubscript{2} concentration, CO\textsubscript{2} concentration, infiltrated water and ground water level. They have been regularly measured using thermistors, O\textsubscript{2} sensors, CO\textsubscript{2} sensors, lysimeters and piezometers, respectively. This set of data has allowed us to develop a fundamental understanding of ARD-ML processes. This understanding assists the mining industry in mitigating the ARD-ML problem.
The ARD-ML problem begins with the extraction of minerals from the ground. The acidity is produced by the action of air and water upon sulfur compounds, for example, iron sulfide, in the rocks. The result is acid drainage with high concentrations of metals. This problem was recognized as early as in 1920’s, but its threat to the environment was then relatively little because of relatively low tonnage of ores processed then. Today the problem has escalated in scale due to the accumulation of mine waste over the past 100 years of mining activities plus the 2-3 orders of increase in tonnage of ores and waste rock processed today. One current practice to manage ARD-ML is to collect and treat the drainage and then release it back to the environment. Collecting and treating the drainage is very costly and requires the proper handling of the treatment sludge. It is not uncommon that the operating cost for treating the drainage at one mine site can reach $1M to $2M per year (GoldCop Inc., 2013, Morin and Hutt, 2006). Note that the ARD-ML problem is a type of rock weathering, and as a consequence it could continue for a few decades to a few centuries, at least.

In order to address the prevention or control of the ARD-ML problem, one needs to understand a few things that include (1) how are oxygen O\textsubscript{2} and water H\textsubscript{2}O transported to sulfide minerals? (2) the mechanisms of the ARD-ML processes, and (3) the factors that influence the rate of ARD-ML.

In this paper, we focus on the question (1) and (3). Through analyzing the set of monitoring data, this paper reveals some insights into the behaviors of the waste rock dump in terms of producing ARD-ML.

**Figure 1** The Equity Silver mine site

**2.0 THE EQUITY SILVER MINE**

**2.1 Site Description**

The Equity Silver Mine site is described in detail in O’Kane (1998) and Price (2003). The site is located in the central interior of British Columbia, Canada, approximately 575 km north-northwest of Vancouver BC. An old view of the mine property during its operation is illustrated in Figure 1. There is approximately 80 Mt of waste rock, covering an area of approximately 1.4 Km square. A soil cover system was installed on the waste rock dump
starting in 1991 with average thickness of 0.5 m compacted till and 0.3 m uncompacted till for reducing the amount of infiltrated water and oxygen.

The mine is situated on a plateau in a humid alpine environment. Historical site records indicate the average annual precipitation is about 600 mm with approximate 60% of the precipitation occurring as snow. It snows from November to April. Snow starts to melt in April. Rainy season starts from late April and ends by the end of June.

The waste rock in the waste rock dump is relatively coarse. The $D_{80}$ ranges from 127 to 28 mm and the $D_{10}$ ranges from 3.5 to 4.0 mm, indicating a lack of silt- and clay-sized particles (O’Kane et al. 1998). Note that pore sizes inside the waste rock dump are generally proportional to the sizes of waste rock. As a result, the gas permeability inside the waste rock dump is a few orders larger than that of the cover system. In the next section, we will discuss what role the large gas permeability plays in producing ARD-ML.

![Simplified Layout of the Equity Waste-Rock Dumps](image)

**Figure 2** Locations at which O$_2$ and CO$_2$ stations and thermistors are installed
2.2 The Instrumentation and the Monitoring Data

O’Kane et al. (1998) described in detail the instrumentation for measuring temperature, gaseous oxygen concentrations, gaseous carbon dioxide concentrations within the main waste rock dump and the backfilled southern tail waste rock dump. In addition, field lysimeters were installed at the base of the soil cover system for measuring infiltrated water. At each of the nine locations shown in Figure 2, temperature, O₂ concentration and CO₂ concentration were measured at different depths ranging from one meter to twenty meters. The sensors are situated in each of the areas of the waste rock dump.

The data we used for this study include the readings from fifty four O₂ stations, fifty four CO₂ stations and nine thermistors. The time period within which the data was used for this analysis is from 1992 to 2009. The time interval between two adjacent measurements is approximately one month. Within the 17 years from 1992 to 2009, approximately 160 readings from each station were recorded and used for this analysis.

3.0 OBSERVATIONS FROM THE MONITORING DATA

3.1 Correlations among O₂ Concentrations and CO₂ Concentrations

Treating the readings of gas concentration at each station as a time-series, we calculated the correlation coefficients of the fifty four O₂ concentration readings and the fifty four CO₂ concentration readings. The time period covers 1992-2009. They give 1431 correlation coefficients \([1+53)\times53/2=1431\]

Here we treat those correlation coefficients larger than + 0.6 as positively correlated and mark them by pink color. We treat those correlation coefficients smaller than − 0.6 as negatively correlated and mark them by green color. It can be seen from Figure 3 that approximate 70% of the area in Figure 3 is covered by pink color and green color. That is to say, majority of the O₂ concentrations and the CO₂ concentrations are correlated statistically. More importantly, Figure 3 indicates that (1) all of the pink color data, the positively correlated data, are associated with a correlation coefficient between O₂ concentration at one station and O₂ concentration at another station, or associated with a correlation coefficient between CO₂ concentration at one station and CO₂ concentration at another station; (2) all of the green color data, the negatively correlated, are associated with correlation coefficients between O₂ concentration at a station and CO₂ concentration at a station. That is to say: all of the O₂ sensors’ readings increase together or decrease together in a statistical sense even though they are situated laterally at different locations; all of the CO₂ sensors’ readings increase together or decrease together in a statistical sense even though they are situated at different lateral locations; when a O₂ sensor’s reading increases, a CO₂ sensor’s reading would decrease in a statistical sense.
Figure 3 The pattern of the correlation coefficients of O₂ concentrations and CO₂ concentrations at different lateral locations and at different depths: pink color indicates correlation coefficient higher than +0.6; green color indicates correlation coefficient smaller than –0.6; the rest of the correlation coefficients are indicated by white color. (a) the pattern of the correlation coefficients; (b) the zoomed-in pattern
3.2 Seasonal Variations of O$_2$ Concentrations

Figure 4(a) shows the seasonal variations of oxygen concentrations at different depths (5 m, 6 m, 10 m, and 17 m) at P-7 location near the central location of the main waste rock dump from 1997 to 2004. One of the pronounced features of the O$_2$ variation with time is its periodic pattern with one year as its time period. Figure 4(b), zoomed in, shows that the highest O$_2$ concentration appears around March; and the lowest O$_2$ concentration occurs around July. The highest O$_2$ concentration is about 12% and the lowest O$_2$ concentration is about 2%.

Figure 4 The seasonal variations of O$_2$ concentrations at P-7 location, depth 5 m, 6 m, 10 m, and 17 m; (a) O$_2$ concentrations from April 1997 to 2004; (b) O$_2$ concentrations and ambient temperature (dark green color) from April 1997 to April 2000

3.3 Uneven Temperature Distribution across the Waste Rock Dump

The temperature measurements across the waste rock dump indicate that temperature varies with depth and with lateral location. The temperature variation with depth is not difficult to understand: the temperature at shallow depths varies with ambient temperature, seasonal temperature changes. The temperature below a certain depth is not
affected much by the change of ambient temperature. However, an interesting phenomenon is: the temperature below a certain depth, though not affected by ambient temperature, varies substantially across the extent of the waste rock dump. For example, the temperature at 17 m depth at P-6 location was about 4 degree C. In comparison, the temperature at 17 m depth at P-7 location was about 54 degree C, which is a huge difference.

3.4 Decreasing Temperature with Time

From Figure 5 it can be seen that temperature inside the waste rock dump has been decreasing at a relatively steady rate. In 1993 it was about 54 degree C at 17 m depth at P-7 location, but it dropped to about 30 degree C in 2009. In other locations, temperature has also dropped.

4.0 OUR EXPLANATIONS

4.1 The Correlations among O₂ and CO₂ Concentrations

The negative correlations between the O₂ concentrations and the CO₂ concentrations basically tell that the CO₂ concentrations increase when the O₂ concentrations decrease in a statistical sense. Why? The CO₂ is primarily produced by the neutralizing reactions between metal carbonates and the produced acidity. The ARD reactions consume O₂. As a result, when more O₂ is consumed, more CO₂ would be produced. This explanation is in agreement with the negative correlations between the O₂ concentrations and the CO₂ concentrations. However, it seems that additional factors contribute to CO₂ variability, because CO₂ levels can be significantly higher than, and lower than, that expected from simple stoichiometry (Morin, et al., 2010 and 2012).
The positive correlations among the O₂ concentrations and the positive correlations among the CO₂ concentrations basically tell that when the O₂ concentration at one location goes up, the O₂ concentrations at the other locations would go up as well in a statistical sense; when the CO₂ concentration at one location goes up, the CO₂ concentrations at the other locations would go up as well in a statistical sense. The two factors that definitely contribute to these positive correlations are as follows. First, the sizes of rocks inside the waste rock dump are quite large (the D80 ranges from 127 to 28 mm and the D10 ranges from 3.5 to 4.0 mm). This makes the waste rock dump interconnected in terms of gas flow. An interconnected gas-flow system tends to make its O₂ concentrations at different locations follow a common trend. Second, the temporal variations of O₂ concentrations at different locations are driven by the common driving force: the temperature difference between the ambient air temperature and the temperature inside the waste rock dump. This temperature difference drives the flow of gas between the ambient air and the inside of the waste rock dump, thus transferring heat between the ambient air and the inside of the waste rock dump.

4.2 Seasonal Variations of O₂ Concentrations

There are seasonal variations of the O₂ concentrations inside the waste rock dump. O₂ starts to decrease starting from March and keeps decreasing until July, and then it starts to increase from August and keeps increasing until the following March. Why? The O₂ concentrations are affected by two dominant factors. First, convective gas flow between the ambient air and inside the waste rock dump is seasonal. From March to August, the gas convective flow rate is gradually reduced with time because the temperature difference between the ambient air and inside the waste rock dump decreases with time from March to August. That is to say, the amount of O₂ entering into the waste rock dump decreases with time from March to August. This factor tends to make the O₂ concentrations inside the waste rock dump decrease from March to August. Second, infiltrated water that flushes waste rocks is much more available from March to July than from the rest of the year. This would lead to relatively higher O₂ consumption rate from the ARD reactions due to more fresh water available (Chandra and Gerson, 2010). Note that there is relatively larger amount of water infiltration into the waste rock dump from March to July than from August to the following February. In addition, in spring season, water from melting snow may increase the degree of saturation of the cover and decrease the gas permeability and the oxygen diffusion coefficient. As a result, the O₂ concentrations decrease from March to July. From November to the end of February it snows there and in those months water infiltration into the waste rock dump is low. As a consequence, rock surfaces are not frequently flushed from August to the end of February as in the time period of March to July.

4.3 Uneven Temperature Distribution across the Waste Rock Dump

The temperatures among locations vary substantially. We thought that this would be due to uneven ARD reactions only inside the waste rock dump. It is a fact that some locations are associated with the rocks that do not produce or produce little ARD reactions due to relatively low and naturally variable sulphide levels, and other locations are associated with the rocks that contain high percentage of metal sulfides. But we have found an
additional factor that also contributes to the unevenness of temperature distribution. Our numerically simulated results of the gas-flow and heat transfer inside the waste rock dump show that the temperature distribution inside the waste rock dump is in agreement with the monitoring data of temperature when a uniform chemical reaction rate is assumed across the waste rock dump. This indicates that a very uneven temperature distribution across the waste rock dump does not have to be caused by an uneven ARD chemical reaction rate only. This seems to imply that there is an inherent pattern of gas flow and heat transfer inside the waste rock dump, which constitutes partially the pronounced temperature pattern inside this waste rock dump.

Figure 6 shows the temperature distribution inside the waste rock dump, obtained from our numerical modeling. Here we assume a uniform ARD reaction rate across the waste rock dump and thus uniform heat generation rate. The modeling counted the air diffusion, convection, heat transfer by conduction through the rocks and in the convecting air. The modeling domain only included the dump and assuming no heat exchange between the dump and the bedrock. The detailed modeling results of the waste rock dump will be published in our next paper. It can be seen that the temperature distribution is not uniform at all. The location with the highest temperature is P-7 location, in agreement with the temperature monitoring data. This match makes us not doubt the modeling result and makes us believe that the temperature pattern inside the waste rock dump is partially the result of an inherent property of the waste rock dump in terms of gas flow and heat transfer.

![Figure 6 Temperature distribution inside the waste rock dump simulated with a uniform ARD reaction rate (temperature unit: degree K)](image)
5.0 CONCLUDING REMARKS

This paper is a preliminary work of our on-going research on the fundamental understanding of the ARD-ML processes inside a waste rock dump. The explanations provided here should not be considered as proven conclusions at this time. But we hope our explanations generate in-depth discussions so that the understanding of the ARD-ML processes can be advanced.

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