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Closure Planning and Implementation at CVRD Inco's Whistle Mine, Ontario, Canada

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Abstract

Approximately seven million tonnes of acid-generating waste rock remained on surface following cessation of open pit mining at CVRD Inco's Whistle Mine near Sudbury, Ontario, Canada. In light of the environmental and economic liabilities associated with release of ARD to the surrounding ecosystem, CVRD Inco elected to relocate the waste rock to the open pit as a means of mitigating environmental damage post-closure. However, because a portion of the backfilled waste rock will remain above the water table, an engineered cover system is required to further reduce the production of ARD. A multi-layer earthen cover system was constructed over the backfilled pit at Whistle Mine between June 2004 and November 2005. The primary design objective of the pit cover is to limit the ingress of atmospheric oxygen to the underlying waste rock by maintaining the barrier layer at or near saturation at all times, thereby creating an oxygen ingress barrier. Instrumentation was installed during construction of the cover system to facilitate evaluation of its performance over time under site-specific climate conditions. Based on field monitoring data collected in 2006, the influx of atmospheric oxygen and meteoric water to the waste rock backfill has been substantially reduced since construction of the cover system.

1 Introduction

Decommissioning of mine sites presents the challenge of dealing with large quantities of waste materials. Included in these materials is waste rock that, given the right circumstances, has the potential to generate acid rock drainage (ARD). Through oxidation of sulphides, the acid and residual heavy metals that are generated can be transported to surface and groundwater receptors, leading to long-term contamination of drinking and recreational water (MEND, 1997).

CVRD Inco Limited, Ontario Division (CVRD Inco) recently completed decommissioning the Whistle Mine property, which was a satellite ore deposit for their Copper Cliff Canada operations. Over the life of the mine approximately 7 million tonnes of waste rock was generated and stockpiled in two waste rock dumps (WRDs) adjacent to the open pit. The majority of the waste rock was acid-generating and after considering a number of closure options, CVRD Inco decided to relocate all waste rock to the open pit and cap it with a multi-layer earthen cover system. This paper reviews the rationale for relocating waste rock stored on the surface to the open pit, and discusses the design and construction of the pit cover system as well as the preliminary performance based on the first year of monitoring data.

2 Background

2.1 Site description and mine history

The Whistle Mine site is located approximately 30 km north of Sudbury, ON, Canada (Figure 1). The climate in the area is semi-humid, characterised by wetter conditions in the fall, winter, and spring and drier conditions during the hot summer months. The site has a mean annual precipitation and potential evaporation of 900 mm and 520 mm, respectively. Approximately 30% of the annual precipitation occurs as snow.

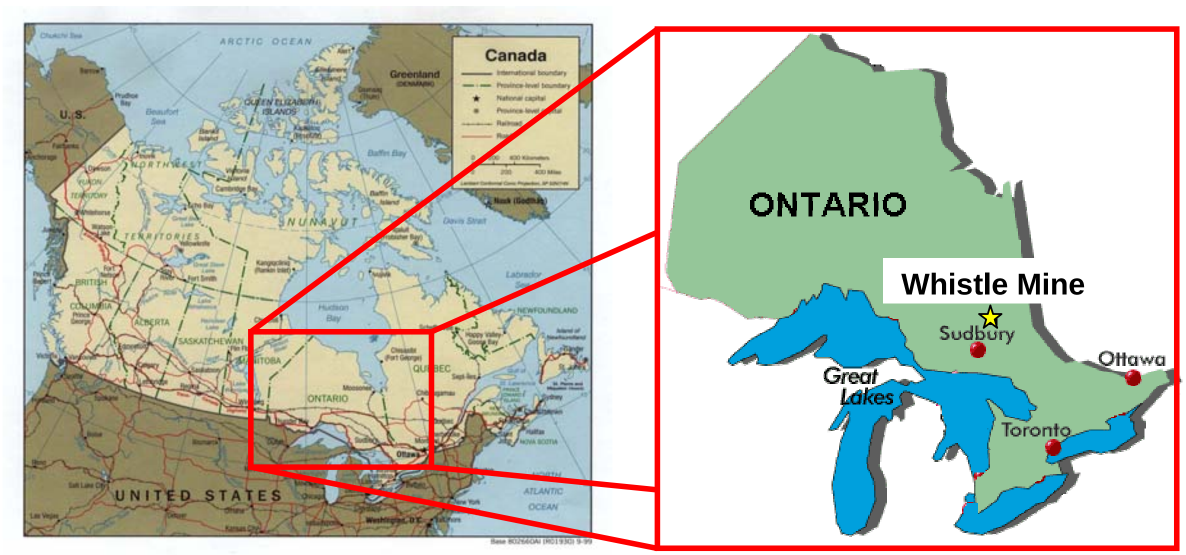

Figure 1 Location of Whistle Mine

Whistle Mine is surrounded by undeveloped wilderness and is situated in the Post Creek watershed, an area of approximately 5400 ha that drains into Lake Wanapitei, 3 km east of the mine. Bedrock outcrops are frequent and typically form hills that rise up to 50 m above the surrounding areas. A thin, discontinuous blanket of glacial till covers the bedrock. Depressions in the area are poorly drained, and as such, typically form swamps or bogs. The local groundwater system is relatively shallow, but is restricted to fissure flow within the igneous and metamorphic rock mass and Darcy flow in the overburden (MEND, 1997).

The Whistle Mine nickel / copper orebody, originally discovered in 1897, was developed as an open pit mine in 1988. The open pit covered an area of 9.7 ha and due to natural relief in the area, sloped an average of 13% from the north to south perimeter. Mining and the production of waste rock at Whistle Mine occurred between 1988-1991 and 1994-1998. All waste rock stockpiled on surface was relocated to the open pit between July 2000 and December 2001. The collection and subsequent treatment of contaminated seepage water emanating from the former waste rock storage areas and backfilled pit is on-going.

2.2 Rationale for relocating waste rock to the open pit

An investigation of the physical and geochemical characteristics of the Whistle Mine waste rock was conducted in the mid-1990s, with the findings contained in MEND (1997). The waste rock is composed of 80% mafic norite, with an average sulphide content of 3%. The porosity of the stockpiles is greater than 20% and 92% of the material is greater than 100 mm in diameter. This results in an estimated net infiltration of >50% of annual precipitation and an unlimited supply of atmospheric oxygen. Seepage discharging from the WRDs was characterised by high sulphate (1760 to 5200 mg/L) and nickel (118 to 297 mg/L) concentrations with elevated concentrations of iron, copper, cobalt and zinc. Based on the findings of the MEND study, closure options for the WRDs consisted of re-grading the angle of repose slopes and subsequent construction of a cover system, or relocation of the waste rock to the open pit.

Several complicating issues were associated with decommissioning the WRDs in-place. First, due to the proximity of the WRDs to the open pit and a nearby creek, re-grading some of the WRD slopes to facilitate construction of an earthen cover system was not feasible. Second, a properly designed and constructed cover system would substantially reduce the infiltration of meteoric water at the cover surface, but would still allow for preferential ingress of oxygen through the underlying glacial till at the toe of the slope. Finally, seepage collection and treatment from the toe of the covered WRDs would be required for an indefinite period of time, and coupled with this fact, a spill from the collection system could result in significant environmental damage to the surrounding wetlands.

In light of the environmental and economic liabilities associated with release of ARD to the surrounding ecosystem, CVRD Inco elected to relocate the two WRDs to the open pit as a means of mitigating environmental damage post-closure. Geochemical modelling demonstrated the effectiveness of backfilling the pit and covering it in terms of isolating the acid-generating material from water and oxygen. Although the climate for this region has a moisture surplus on an annual basis, a water cover is not feasible for this site because of the absence of a pit lake and the relatively steep slope of the backfilled pit surface. Furthermore, geochemical modelling suggested that the quality of the water overflowing from the pit could be improved through the addition of lime at the rate of 0.9 kg/tonne of waste rock (Knight Piésold, 1998).

3 Design of the backfilled pit cover system

Additional geochemical modelling was conducted to assess the effectiveness of various cover options on the long-term water quality of the backfilled pit (SENES, 2003). Based on the modelling predictions, the design objectives for the backfilled pit cover system are to:

1) Reduce the ingress of atmospheric oxygen to the underlying waste material to the minimum acceptable level as determined by geochemical modelling;

2) Reduce the entry of meteoric water to the underlying waste material to less than 5% of the annual precipitation at the site; and

3) Provide a medium for establishing a sustainable vegetation cover that is consistent with the current and final land use of the area.

The first two design objectives can be achieved by incorporating a layer of fine-textured material in the cover system (MEND, 2004). The objective is to utilise the capillary barrier concept to assist with maintaining near saturation within the fine-textured layer under all anticipated climatic conditions, which in turn limits the ingress of oxygen due to low oxygen diffusion conditions. In addition, the lower hydraulic conductivity of the fine-textured soil layer (usually compacted), combined with the lower capillary barrier, provides a control on net percolation to the underlying waste material. A multi-layer system incorporating a fine-textured soil layer, hereafter referred to as a “barrier layer”, was selected as the preferred type of cover system for the backfilled pit at Whistle Mine.

Often in the design and construction of a multi-layer soil cover system the focus of the design is on the barrier layer. While the importance of the barrier should not be discounted, neither should the importance of the overlying growth medium (Ayres et al., 2004). The growth medium layer serves as protection against physical processes, such as wet/dry and freeze/thaw cycling, as well as various chemical and biological processes. An inadequate growth medium layer will not properly protect the barrier layer, leading to possible changes in its performance, as documented in INAP (2003).

3.1 Determination of the preferred barrier layer material

Cover system trials were constructed at Whistle Mine in 2000 to obtain site-specific information on the construction feasibility and potential performance of alternate soil cover systems prior to finalising the design of the full-scale cover system. Three experimental cover systems were constructed over acid-generating waste rock, with each cover having a different barrier layer overlain by a protective layer of non-compacted material. The experimental cover systems were constructed on a waste rock platform with a 20% slope. Instrumentation was installed to monitor climatic parameters, gaseous O_2 and CO_2 concentrations as well as moisture and temperature conditions within the cover and waste materials, and finally, net percolation. Further details on the construction of the cover trials can be found in Ayres et al. (2002).

Detailed cost estimates were developed to construct each of the test cover systems on a full-scale basis. The construction cost estimate for the GCL barrier, compacted silt/trace clay barrier, and compacted sand/bentonite barrier cover system was $3.3M CAD, $3.5M CAD, and $5.3M CAD, respectively. Each of these barrier layers was underlain with a geotextile and overlain by 0.9 m of granular pit-run material. Although the GCL barrier cover system was estimated to cost less to construct than the compacted silt/trace clay barrier cover system, soil-atmosphere numeric simulations demonstrated that the silt/trace clay layer would provide a much better barrier to the ingress of atmospheric oxygen over the long term.

Based on estimated construction costs and the requirement for an adequate oxygen barrier, a source of local clay was chosen as the material for the pit cover barrier layer. Laboratory testing of the borrow material revealed the clay has low to medium plasticity and a saturated hydraulic conductivity of 5×10^{-8} cm/s when compacted to 95% of the standard Proctor maximum dry density.

3.2 Cover design soil-atmosphere modelling

The two-dimensional soil-atmosphere model VADOSE/W (Krahn, 2004) was used to evaluate performance of several multi-layer cover system alternatives. Field response simulations were completed prior to a preliminary and detailed cover design modelling program, to develop a calibrated model based on data collected from the Whistle Mine test cover systems. The preliminary modelling program consisted of one-dimensional simulations to determine the optimal thickness for each cover layer, based on maintaining a barrier layer degree of saturation greater than 85% after three consecutive dry years. Results from preliminary modelling indicated that the preferred cover system design with respect to oxygen ingress was a 0.45 m thick compacted clay barrier layer and a 1.2 m thick growth medium layer.

Two-dimensional simulations of the longest cross-section through the backfilled pit surface were required to confirm the suitability of the preliminary cover system design in terms of reducing both oxygen ingress and net percolation. The predicted degree of saturation in the barrier layer remained above 96% and the oxygen diffusion coefficient for the barrier layer at every point along the modelled section was lower than the minimum oxygen diffusion coefficient required (Figure 2). The predicted cumulative net percolation was less than 2.2% of the modelled precipitation for the preferred cover system design with the majority occurring in the runoff collection and sedimentation pond area. Additional details on the soil-atmosphere modelling program are provided in OKC-MDH (2004) and Ayres et al. (2005).

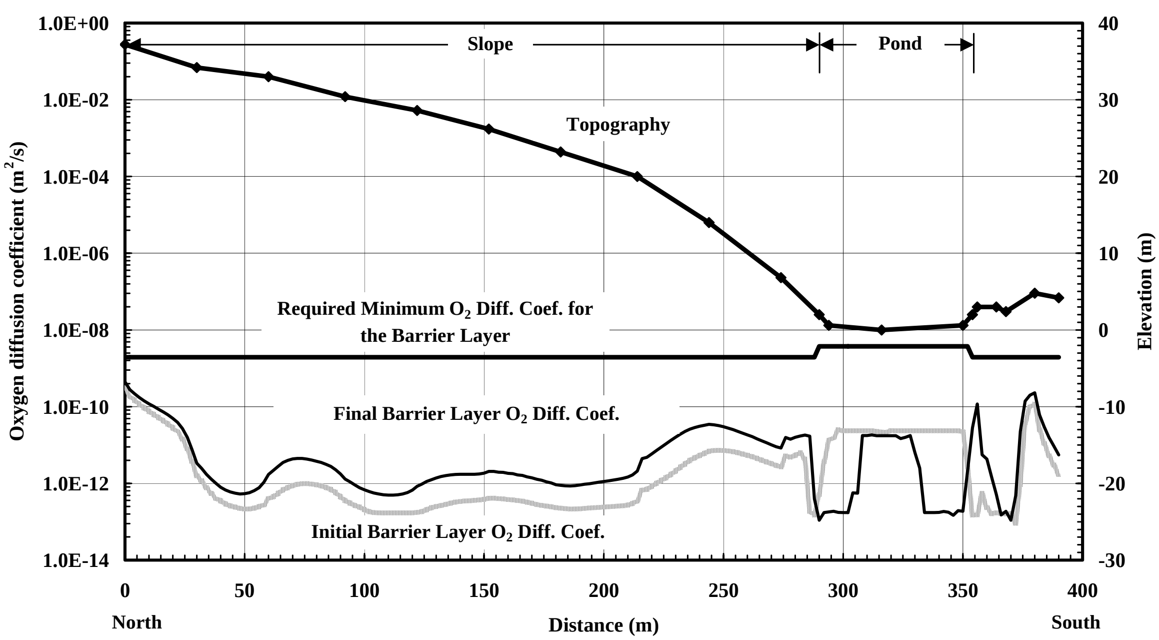

Figure 2 Initial and final predicted oxygen diffusion coefficients for the barrier layer for the driest climate year on record (from OKC-MDH, 2004)

3.3 Final cover system design

Based largely on the results of the soil-atmosphere modelling program, the final cover system design for the backfilled pit consists of a 0.1 m sand and gravel levelling course, a geosynthetic separation fabric (geotextile), a 0.45 m barrier layer comprised of compacted clay, and a minimum of 1.2 m of sand and gravel for a protective / growth medium layer. The primary purpose of the levelling course is to provide a suitable foundation for the geotextile, but it also acts as a capillary break layer. A thin layer of topsoil was admixed to the pit cover surface to assist with growth of a seeded mixture of native grass and legume species.

4 Design of the pit cover landform

4.1 Landform evolution and erosion modelling

Erosion and landform evolution numerical modelling was conducted to assist in designing a runoff management system and final landform for the pit cover system. The WEPP model (Flanagan and Livingston, 1995) was used to estimate erosion rates from the cover system, while the SIBERIA model (Willgoose et al., 1989) was used to predict the long-term landform evolution. A 100-year climate database for the site was developed using available data from the Sudbury Airport Environment Canada weather station and extrapolation from equivalent areas in the region. The surface of the cover system was assumed to be bare of vegetation for all WEPP simulations, which was felt to be reasonable over the short-term and conservative over the long-term. WEPP output data were used to generate parameters for the SIBERIA landform evolution model. Two final landform alternatives were evaluated for the pit cover system.

The first landform alternative that was examined consisted of a highly engineered system to manage runoff generated from spring snowmelt and rainfall events. The landform has lateral diversion berms to capture runoff water and divert it laterally to one of two collection channels oriented parallel to the slope. Output from the SIBERIA model (Figure 3) shows breaching of the lateral berms, development of gullies and rills, and overall failure of the landform over a 100-year period.

The second and final landform alternative consists of a number of catchments oriented parallel to the slope in a pattern of crests and troughs. To achieve this topography, an additional 0.6 m of sand and gravel was placed in the crests. This micro-topography is beneficial for revegetation efforts because snow accumulates in the troughs, thereby increasing soil moisture levels, and wind velocities are reduced across the ground surface, thus reducing potential erosion of topsoil and grass seeds. The objective was to develop a landform with catchments that are analogous to natural systems (i.e. avoid "fighting" nature).

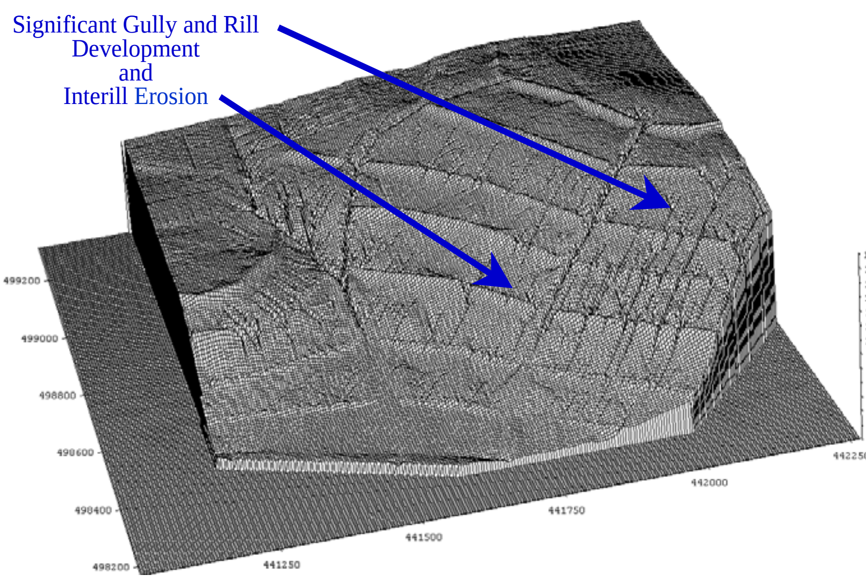

Figure 3 Predicted landform evolution of the first landform alternative for the pit cover system after 100 years (from OKC-MDH, 2004)

4.2 Surface water management system

In conjunction with the design of a sustainable final landform, a system was required to minimise fluvial erosion on the pit cover and manage suspended sediment in runoff waters over the short and long term. Progressively higher levels of erosion protection were used in the hillslope channels as the contributing area and associated design flow velocities increased towards the south. This included the use of temporary erosion control blankets, a 150 mm thick layer of 60 mm diameter riprap, and finally, a 300 mm thick layer of 125 mm diameter riprap. All riprap was underlain with geotextile to act as a filter medium.

A series of three containment ponds were designed at the south end of the backfilled pit for management of suspended sediments in the pit cover runoff water. The base of each pond consists of a minimum 0.6 m layer of compacted clay and slopes gradually east to west, towards individual hydraulic control structures (overshot gates) and the final discharge point (Post Creek wetlands). The Collection Pond is the primary catchment designed to accommodate a 1 in 50 year, 24-hour duration storm event. The long and narrow Sedimentation Pond was designed to optimise the settlement of suspended particles. Finally, the Polishing Pond serves as a final settling area, but primarily as a sampling location prior to water being released to the environment. It is anticipated that the runoff ponds will be decommissioned in 5 to 10 years, once a mature grass cover establishes and erosion from the cover decreases to acceptable levels. Over time, a wetland area will establish to provide long-term attenuation of peak surface flows and diversified habitat for wildlife.

5 Construction of the pit cover system

Construction of the pit cover system was completed during the snow-free periods of 2004 and 2005. A local contractor completed all the earthworks, while two engineering firms from Saskatoon, Canada joined resources to provide construction supervision and on-site QA/QC testing services. A portable soil testing laboratory was on-site for the duration of construction to routinely check that borrow materials conformed to specifications. Testing of completed work areas, particularly the barrier layer, consisted of in situ density, water content and permeability measurements, as well as surveying to check that the specified minimum layer thickness was achieved. Figure 4 shows different aspects of pit cover construction. Based on inspections by the engineer and the records of construction, the Whistle Mine pit cover system and ancillary infrastructure were constructed in general accordance to the design and specifications.

Figure 4 Photos showing cleaning of the pit perimeter prior to barrier layer construction (top left), cross-slope ripping of topsoil into the granular cover material (top right), and the finished pit cover in Sept-06 with the Collection Pond overshot gate in the foreground (bottom)

6 Cover system performance monitoring

A performance monitoring system was installed for the Whistle Mine pit cover to achieve the following objectives: 1) obtain a water balance for the site; 2) develop confidence with all stakeholders with respect to cover system performance from a micro- and macro-scale perspective; 3) enhance understanding of the key characteristics and processes that control cover system performance at this site; and 4) track the evolution of the cover system in response to various site-specific physical, chemical, and biological processes. The system includes a meteorological station, two weirs for measuring runoff flows, two automated stations for monitoring net percolation rates and in situ moisture and gas concentrations within and below the cover system, 13 secondary stations to monitor spatial performance, and four groundwater monitoring wells. Collection of data from all monitoring sites, shown in Figure 5, commenced in the fall of 2005. Minimal erosion as a result of runoff has occurred on the pit cover, and although the vegetation cover has developed slower than anticipated, considerable growth occurred during the summer of 2006. Key data collected in 2006 are presented below to illustrate the preliminary performance of the pit cover system.

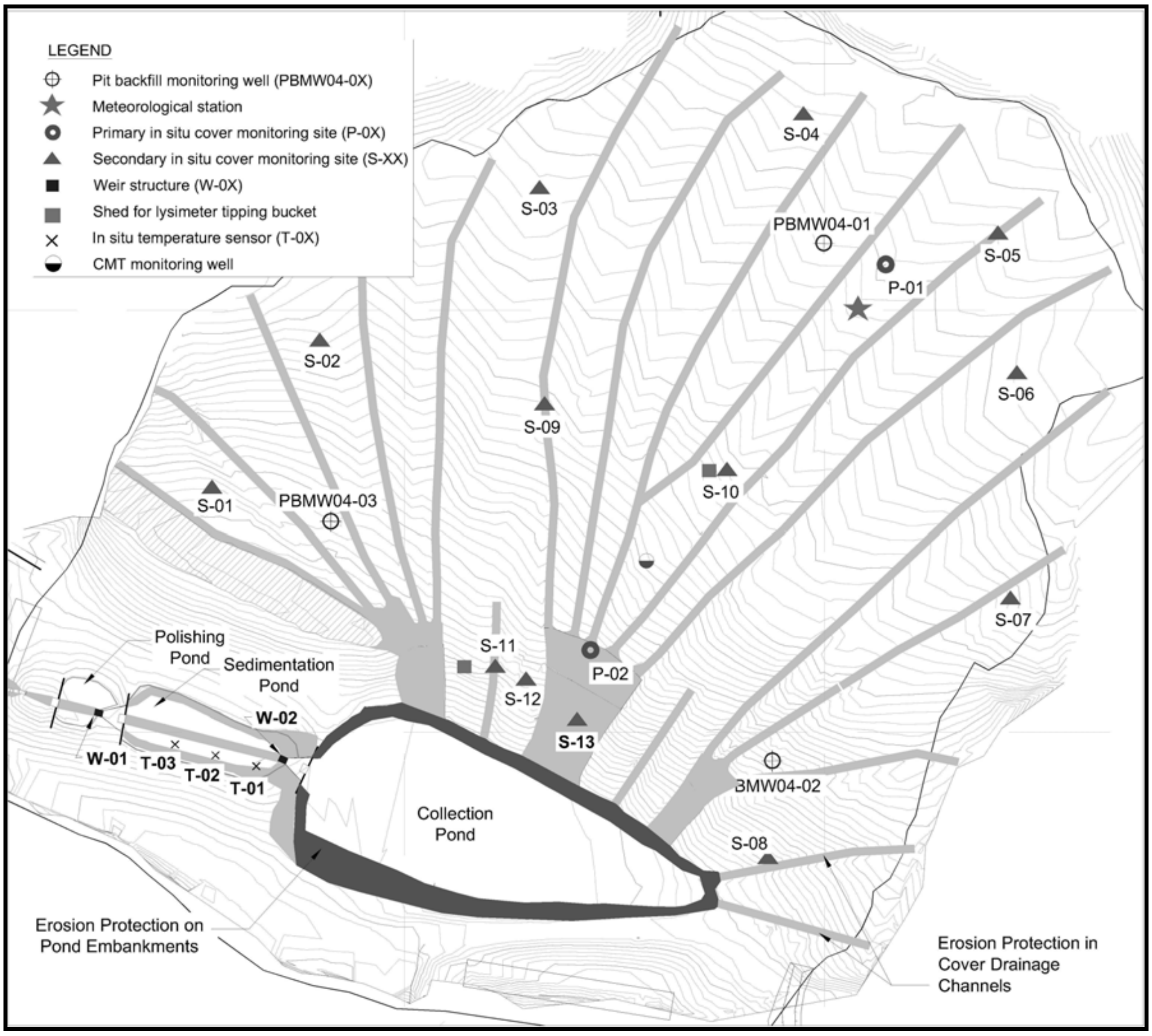

Figure 5 Location of monitoring stations on the pit cover system (from OKC-MDH, 2006)

6.1 Oxygen ingress to the backfilled waste rock

The primary design objective of the Whistle Mine pit cover is to limit oxygen diffusion into the underlying reactive waste rock by maintaining the compacted clay layer at or near saturation at all times, thereby creating an oxygen ingress barrier. The diffusion of oxygen through a soil layer will be minimised if the degree of saturation remains greater than 85% to 90% (Nicholson et al., 1989; Mbonimpa et al., 2003). Volumetric water content values measured at the P-01 upslope, crest location, and the P-02 downslope, drainage channel location allow for the calculation of the degree of saturation in the top and bottom of the barrier layer (Figure 6). In general, the degree of saturation in the barrier layer degree increased during the hot and dry summer months when atmospheric and plant demands for soil water are greatest. Maintenance of near-saturated conditions in the barrier layer confirms what was predicted during the cover design modelling program.

Geochemical modelling determined that the desired oxygen diffusion coefficient for the barrier layer is 3.76×10^{-9} m^2/s or lower, based on predicted long-term solute concentrations in the backfilled pit. The average oxygen diffusion coefficient for the barrier layer at stations P-01 and P-02 in 2006 was 3.56×10^{-11} and 5.69×10^{-11} m^2/s, respectively, based on the computational method outlined in Aachib et al. (2004) and in situ volumetric water content measurements. These values are nearly two orders of magnitude lower than the minimum required for closure. Based on degrees of saturation for the barrier layer at stations P-01 and P-02 it is reasonable to conclude that oxygen diffusion into the backfilled waste rock was minimal in 2006.

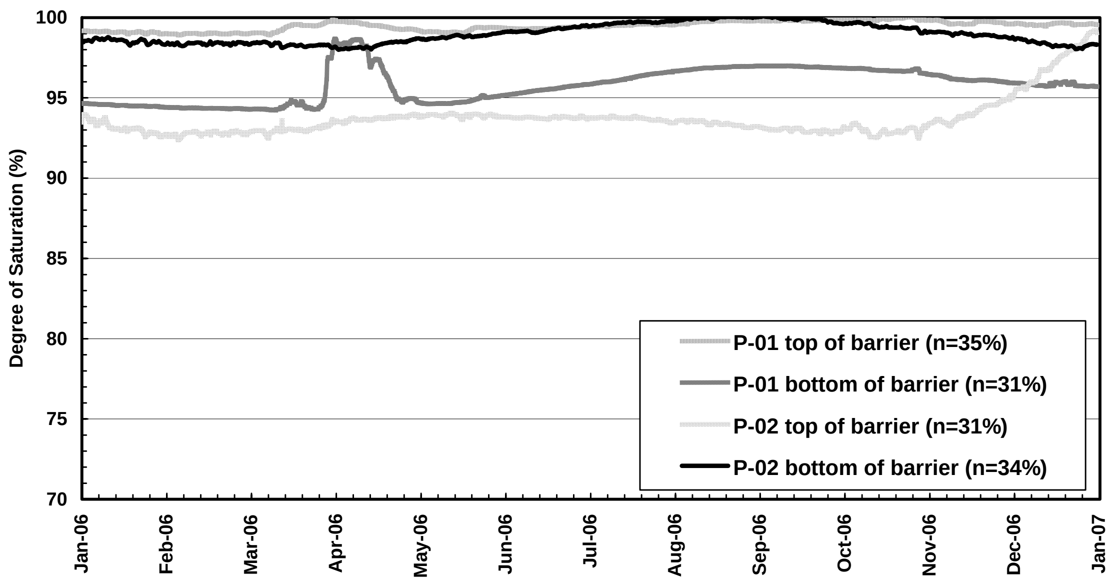

Figure 6 Degrees of saturation in the pit cover barrier layer at stations P-01 and P-02 in 2006 (from OKC, 2007)

6.2 Pore-gas concentration measurements

Concentrations of O_2 and CO_2 were measured at the two primary and 13 secondary monitoring sites on top and at the base of the barrier layer and 90 cm below the barrier layer, using a portable gas analyser. During the oxidation of sulphide minerals, atmospheric O_2 (20.9% concentration) is consumed and CO_2 (0.03% concentration in atmospheric air) is produced when the acid generated reacts with carbonates in the system. Prior to covering the backfilled pit, atmospheric O_2 was able to enter the upper waste rock profile via several mechanisms, including barometric pumping, wind action, volume displacement during infiltration, and with infiltrating water containing dissolved oxygen. Following construction of the cover system and provided the barrier layer remains tension-saturated, the influx of atmospheric O_2 will be substantially reduced owing to the relatively low solubility of oxygen in water and the low bulk diffusion coefficient of the barrier layer.

In general, O_2 pore-gas concentrations below the barrier layer have decreased since construction of the cover system (see Figure 7). Overall, O_2 and CO_2 concentrations measured to date exhibit high spatial variability, attributed primarily to local differences in mineralogy (i.e. sulphides and carbonates), quantity of residual lime added during the backfilling operation, the gas permeable porosity of the waste rock backfill, and timing for completion of construction of the cover system. It is anticipated that spatial differences in O_2 and CO_2 pore-gas concentrations will be less pronounced in 2007.

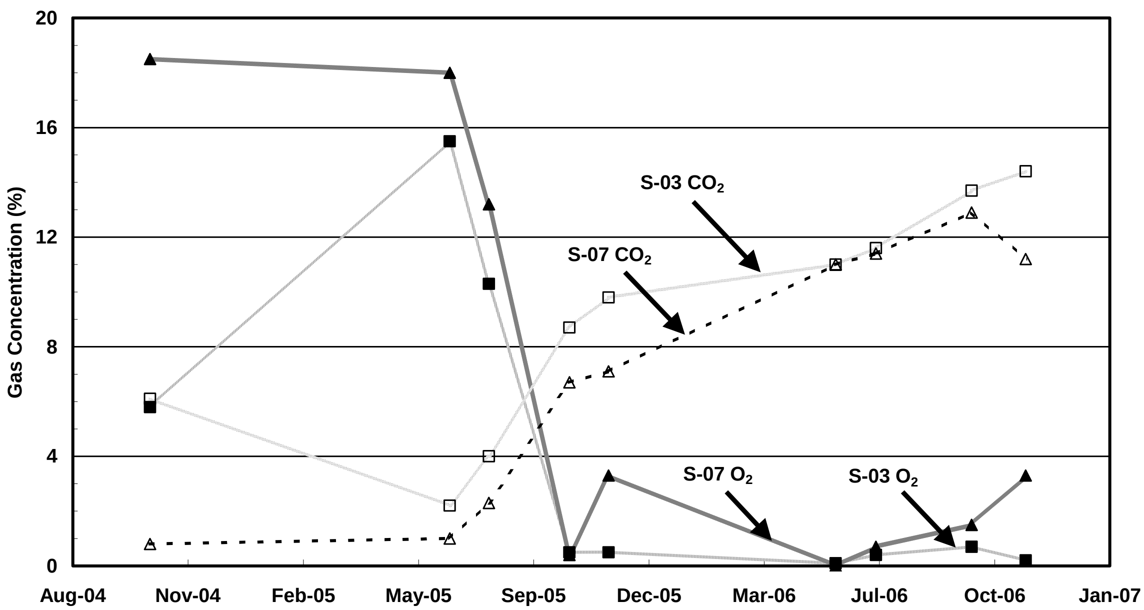

Figure 7 Concentrations of O_2 and CO_2 measured 90 cm below the barrier layer (from OKC, 2007)

6.3 Net percolation to the backfilled waste rock

The net volume of meteoric water percolating through the cover system and into the waste rock backfill is continually monitored with tank lysimeters at stations P-01 and P-02. As a check on data recorded by the lysimeter tipping buckets, the volume of water discharged from each lysimeter is manually recorded on a routine basis during non-freezing conditions.

The cumulative net percolation measured at station P-01 during the monitoring period is 21 mm, which is equal to 2.7% of the total precipitation measured at the site in 2006. The net percolation measured in 2006 at station P-01 also compares well with the annual net percolation of 2.2 % of precipitation that was predicted for a normal climate year during the cover design modelling program. It is anticipated that net percolation rates for the pit cover will decrease over time as vegetation develops and translocates additional water stored in the growth medium layer.

6.4 Extent of freezing and drying with depth

The extent and magnitude of temperature and water content variations in the cover system, particularly for the barrier layer, are important for tracking the evolution of the cover and its performance over time. Seasonal freeze/thaw and wet/dry cycling can diminish barrier layer performance over time as a result of a macro-pore structure developing in the compacted clay material (INAP, 2003).

In situ temperature and water content throughout the pit cover and upper waste rock profile are recorded at station P-01 and P-02. The freezing front in the growth medium extended to a maximum depth of 40 cm at both monitoring stations during the monitoring period. Consequently, the freezing front did not penetrate to the barrier layer, and indeed, the minimum temperatures recorded in the barrier layer at P-01 and P-02 in 2006 were 5.9°C and 3.1°C, respectively. It is apparent that based on in situ temperature data collected, the growth medium layer along with the annual snow cover at the site is sufficient to prevent the pit cover barrier layer from freezing.

Volumetric water content in the pit cover and upper waste rock profile at stations P-01and P-02 is continuously monitored using calibrated Sentek EnviroSCAN® capacitance sensors. There was little variation in water content of the cover profile over the summer of 2006 (Figure 8). The majority of wetting and drying in the cover profile occurs in the upper 50 cm where the atmospheric and plant demands for soil water are greatest. The drying of the growth medium layer above the barrier layer during the summer is primarily attributed to lateral drainage or interflow as a result of the slope of the cover system and the low permeability of the barrier layer. There is no evidence of wet/dry cycling in the barrier layer based on data collected to-date at stations P-01 and P-02.

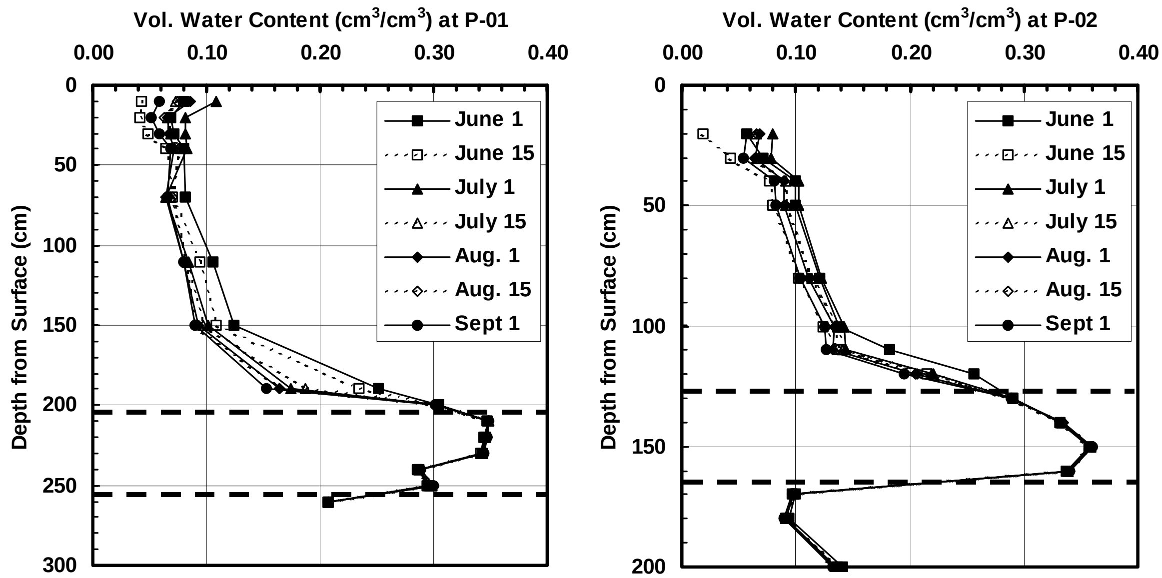

Figure 8 Volumetric water contents measured at P-01 and P-02 in 2006 (from OKC, 2007)

6.5 Water balance

A simple water balance was completed for the pit cover system in 2006 using the performance monitoring data collected at the site (Table 1). Precipitation (PPT) is comprised of both rainfall and water content of the snowpack measured at the site. Net percolation (NP) through the pit cover system is based on lysimeter measurements. The change in moisture storage (ΔS) is calculated based on the volume of water in the cover profile at the start and end of the monitoring period (Figure 9). Lateral drainage and surface runoff (R) from the pit cover system can be estimated based on data collected by the weirs. Actual evapotranspiration (AET) from the cover system is not directly measured at the site, but can be back-calculated from the water balance equation ($AET = PPT - R - \Delta S - NP$).

A total AET of 269 mm (35% of total precipitation) was calculated for the pit cover in 2006. The amount of potential evaporation (PE) in 2006, which is a theoretical maximum assuming free water on the surface at all times, was 650 mm based on the Penman (1948) method and climate data collected at the site. This equates to an AET/PE ratio of 0.41, which is reasonable given the upper soil profile on the pit cover and the current state of the vegetation community. It is anticipated the AET/PE ratio will increase over time as the vegetation cover matures and transpiration rates increase.

Table 1 Water balance for the pit cover system in 2006

	Value (mm)	Percentage of Total Precipitation
Precipitation	765	-
Runoff and interflow	475	62.1
Evapotranspiration	269	35.2
Net percolation	21	2.7
Change in storage	0	0

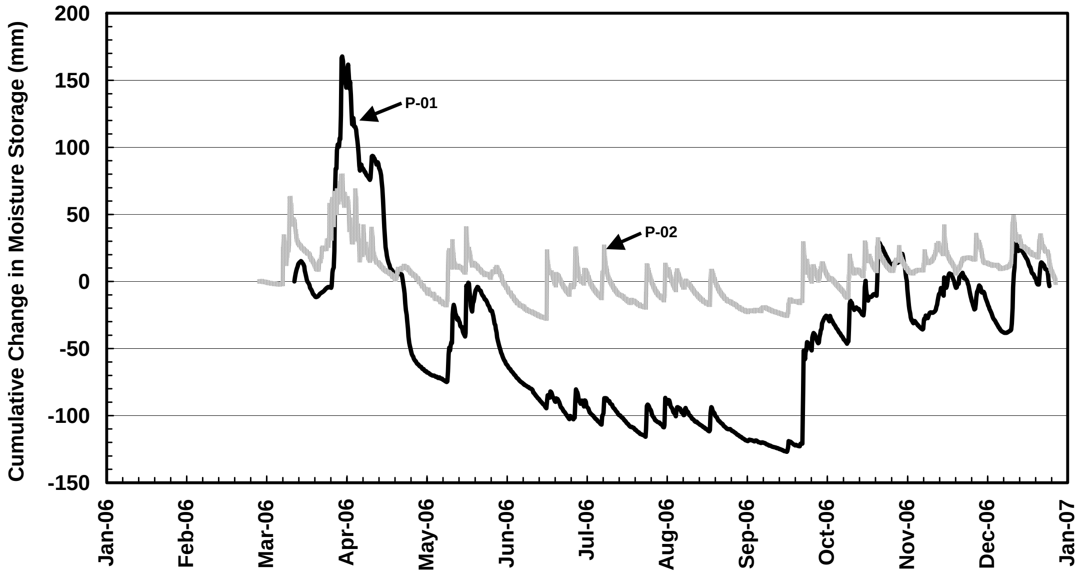

Figure 9 Cumulative change in water storage recorded at stations P-01 and P-02 (from OKC, 2007)

7 Summary and conclusions

Decommissioning the Whistle Mine site presented CVRD Inco with the challenge of dealing with a relatively large volume of acid-generating waste rock. Due to the sensitivity of the ecosystem surrounding the mine site, the decision was made to relocate the waste rock to the open pit. To further limit the interaction of atmospheric O_2 and water with the waste rock, an engineered cover system was required. A multi-layer earthen cover system was designed with input from geochemical, soil-atmosphere, erosion and landform evolution numerical modelling, as well as monitoring data from pilot-scale test plots. Potential impacts resulting from site-specific physical, chemical and biological processes were also considered in the design of the pit cover from a sustainable performance perspective.

A QA/QC program was in place to monitor construction of the pit cover system and ancillary infrastructure, including a surface water management system and performance monitoring system. These items were constructed in general accordance to the design and specifications based on inspections by the engineer and the records of construction.

The Whistle Mine pit cover system is performing as expected in its first full year since construction, based on field data collected up to December 2006. The influx of atmospheric oxygen and meteoric water to the waste rock backfill has been substantially reduced since construction of the cover system. Minimal erosion as a result of runoff has occurred on the pit cover, and although the vegetation cover has developed slower than anticipated, considerable growth occurred during the summer of 2006. Net percolation rates through the cover system should decrease over time as the vegetation cover matures and transpiration rates increase.

A detailed and multi-disciplinary approach was used in the design and implementation of closure works at Whistle Mine. Collection and treatment of seepage from the backfilled pit overflow is expected to continue for tens of years. However, provided the current performance of the pit cover system is sustainable and based on geochemical modelling predictions, it is anticipated that CVRD Inco will be able to “walk away” from the site in the next 100 years.

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