Tailings and Mine Waste '98 © 1998 Balkema, Rotterdam, ISBN 90 5410 922 X

Estimating contaminant concentrations in a re-flooded underground mine

Daryl Hockley & John Chapman
Steffen, Robertson and Kirsten (Canada) Inc., Vancouver, B.C., Canada
Jerry Sevick
Foth and Van Dyke, Green Bay, Wis., USA
Don Moe
Crandon Mining Company, Rhinelander, Wis., USA

ABSTRACT: Investigations were undertaken to characterize the potential for various underground components of the proposed Crandon Mine to release contaminants to groundwater that will re-flood the mine after operations cease. Methods used to characterize the sources included literature and data review, laboratory tests and simple calculations. The potential for backfilled tailings to release contaminants to the groundwater was shown to be limited by the rate at which oxygen can be transported into the backfilled stopes. In assessing the potential for the wall rock and crown pillar to release contaminants, key parameters were the proportion of wall that will be sulfidic, and the actual surface area of the walls. Conservative estimates of contaminant emissions from diesel equipment were used to show that underground emissions are not likely to contribute a significant amount of contaminants to the groundwater. The investigations also included an analysis of groundwater flow patterns in the re-flooded mine, which led to the conclusion that the groundwater quality will initially be dominated by contributions from wall rock in the access workings, but subsequently will be dominated by the backfilled tailings.

INTRODUCTION

Underground mining of the massive sulfide Zn-Cu deposit at the proposed Crandon Mine will take place below the level of the regional groundwater table. After operations cease, the groundwater table will be allowed to recover, resulting in flooding of the underground workings. Crandon Mining Company and its consultants completed investigations to characterize the potential for the underground workings to release contaminants to the groundwater. We investigated four potential sources of contaminants: backfilled tailings, wall rock in the development and access openings, the crown pillar, and emissions from diesel mining equipment and natural gas mine air heaters.

Some of the above have not, to our knowledge, been identified as potential contaminant sources at other mines. In addition, the aquifer of concern is in the overburden, and groundwater contamination from the underground workings is expected to be diluted by a factor of 75-200 times before reaching the proposed compliance boundary. The investigation therefore followed a "top down" approach designed to efficiently identify and focus effort on the most important sources. The investigation methods included literature review, review of laboratory test data, and simple but conservative calculations.

The following sections discuss our investigation of each potential source in more detail.

TAILINGS BACKFILL

Approximately half of the tailings that will be produced from the Crandon ore will be returned underground to backfill mined-out stopes. In addition to enhancing the stability of the underground workings, the backfilling will reduce the volume of tailings that need to be stored on surface, and result in favourable conditions for long term geochemical stability. In essence, the sulfide minerals in the tailings will be returned to the underground and underwater condition in which they have remained stable for millions of years.

Tailings that are returned underground have the potential to oxidize during the mine life. After the groundwater table recovers following the completion of mining, oxidation products stored in the tailings could be released. However, tailing in the backfilled stopes will be largely isolated from the air circulating through the mine. The resulting limitations to the oxygen supply will limit the extent of oxidation.

We therefore concluded that characterizing the oxygen supply was the key to assessing the potential for the backfilled tailings to oxidize and release contaminants that could be mobilized by the re-flooding groundwater. Our investigation included the followings steps:

1. The backfilling methods were reviewed in order to clarify physical restrictions to oxygen transport.

2. Simple oxygen transport models, with conservative assumptions from the literature, were used to estimate the rate of oxygen supply to the backfilled tailings.

3. The estimated "oxygen limited oxidation rates" were compared to the amount of neutralizing minerals available within the backfilled tailings, leading to estimates of the amount of tailings that would be "acidic", "oxidized but neutral", "uncemented and unoxidized", and "cemented and unoxidized".

4. Contaminant release rates from laboratory column tests were used to estimate contaminant loads from each type of tailings. The estimated loads were then divided by groundwater volumes to obtain estimates of contaminant concentrations.

5. The estimated concentrations were then input to the geochemical equilibrium model MINTEQA2 to identify solubility constraints.

Example 1 below illustrates the first two steps, and Example 2 illustrates the fourth and fifth steps. The third step consisted of a comparatively straightforward volume calculation, and so is not shown herein. Table 1 shows the resulting estimates of the volumes of each type of tailings, and examples of the estimated contaminant concentrations upon re-flooding of the tailings backfill.

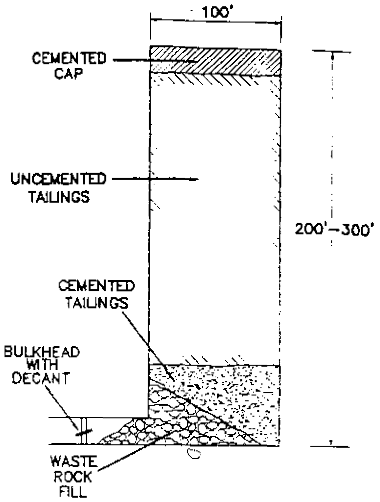
Table 1 - Contaminant Contributions from Backfilled Tailings

Tailings Component	Tailings	Pore	Estimated Porewater Concentration (mg/L)					
	Volume (ft^3)	Volume (ft^3)	SO_4	As	Ca	Cu	Fe	Zn
Cemented Acidic	1.1E+05	4.2E+04	200,000	1,200	100	390	26,000	32,000
Cemented Oxidized/Neutral	2.6E+06	1.1E+06	120,000	1.8	66	3.6	0.70	9.1
Cemented Unoxidized	3.1E+08	1.3E+08	330	0.038	300	0.004	0.05	0.020
Uncemented Unoxidized	2.1E+08	8.3E+07	1400	0.05	290	0.063	0.41	0.45
Volume-weight average	5.3E+08	2.1E+08	1400	0.29	290	0.12	5.4	6.5

Example 1 - Oxygen transport into the bottom of a backfilled open stope

Blasthole open stoping methods will be used to mine most of the ore. Mined out stopes will be backfilled with tailings and waste rock. Primary stopes will be backfilled with cemented tailings. After the cemented backfill has cured, the remaining stopes will be mined, then backfilled with uncemented tailings.

As shown at right, the stope entries will be sealed with bulkheads, and waste rock will be deposited at the base of the stope to prevent the tailings from flowing to the bulkhead. Cemented tailings will be placed at the bottom of each stope, nominally the lower 20 feet, to help ensure stability in stopes that remain largely uncemented. Higher strength cemented fill caps will also be placed on otherwise uncemented stopes to provide for subsequent equipment re-entry and extraction of the overlying ore.



We estimated oxygen diffusion into stopes using Fick's Law with a first order oxygen consumption term:

$$\frac{dC}{dt} = \frac{\partial}{\partial x}\left(D\frac{\partial C}{\partial x}\right) - r * C$$

where: C is oxygen concentration (mol m^{-3}); t is time (s); D is the effective diffusion coefficient (m^2s^{-1}); and r is a reaction rate constant with units s^{-1}.

Oxygen concentrations at the bulkhead were assumed to be in equilibrium with the atmosphere. We obtained conservative estimates of other model parameters from literature:

- The first order rate constant was assumed to be $1.07\text{x}10^{-4}$ s^{-1}, equivalent to the upper end of the range cited by Nicholson (1994). Oxygen consumption in the waste rock was conservatively neglected (r=0).
- Diffusion coefficients in the backfilled waste rock were assumed to be $6\text{x}10^{-6}$ m^2/s. That value is near the upper end of the range of measurements in waste rock piles reported by Ritchie (1994).
- Diffusion coefficients were assumed to be $2.88 \text{ x } 10^{-6}$ m^2/s in uncemented tailings and 10 to 100 times lower in the cemented tailings. The former value was estimated by assuming that the tailings were at 15% water saturation, and applying the relationship derived by Reardon & Moddle (1985). Gas phase diffusion coefficients were estimated to be reduced by a factor of 100 in a study of tailings cemented by gypsum precipitation (Blowes et al. 1990). Studies by Archibald & Nantel (1984) found that radon diffusion coefficients in cemented uranium tailings were 6 to 100 less than in uncemented tailings.

The model estimated oxygen flux to the cemented tailings at the base of the stope to be 1-3x10^{-}[illegible] mol $m^{-2}s^{-1}$, with oxidation occurring over a depth of approximately 1 m. Making the stoichiometric conversion to units of acid generation, it was concluded that the maximum oxygen limited acid generation potential would be than 100 kg $CaCO_3$ equivalent per tonne of tailings. That value is less than the laboratory determined carbonate neutralization potential of 125 kg $CaCO_3$ equiv./tonne. Although net acidic conditions seem improbable, subsequent calculations conservatively assumed that acidic conditions could develop near the entry points in up to 20% of the stopes.

Example 2 - Groundwater quality within acidic tailings backfill

	SO_4	As	Ca	Cu	Fe	Zn
Sample Content (mg/kg)	2,900	2,600	5,600	500	270,000	6,000
Weekly Release (mg/kg)	1,300	0.29	240	0.094	24	130
Total Release(mg/kg)	1,000,000	230	190,000	73	19,000	100,000
Max Total Release(mg/kg)	980,000	230	5600	73	19,000	6,000
Maximum Concentration (mg/L)	5,200,000	1200	29,000	390	100,000	32,000
MINTEQA2 Conc. (mg/L)	200,000	1,200	100	390	26,000	32,000

The above table shows the steps required to estimate contaminant concentrations in groundwater that will flood the acidic backfilled tailings.

- The first row shows the concentration of constituents in the tailings solids, as reported by Foth & Van Dyke (1995).
- The second row shows the rates of constituent release under oxidizing conditions, as estimated from unsaturated column tests reported in Foth & Van Dyke (1995). The tests were initiated with two weeks of wet/dry cycles, and the contaminant release rates were estimated from that data. The estimates are conservative for most contaminants because oxidation products stored in the tailings were also released during that period.
- The third row shows the mass of constituent that could be released under the conservative assumption that the above rates would be sustained for 15 years. Fifteen years is the average period that tailings will remain above the groundwater table.
- For some constituents, the predicted release exceeded the total amount present in the tailings. The fourth row shows the maximum total release.
- The fifth row shows the concentrations that would be attained under the assumption that the maximum total release could be dissolved in the groundwater that fills the tailings pores.
- The bottom row shows the results of MINTEQA2 calculations. Even under the conservative assumption that the pH will be as low as 1.7, the geochemical equilibrium model predicts that the minerals gypsum, melanterite, anglesite, and epsomite would form, limiting the solubility of some of the constituents.

We carried out similar calculations to estimate contaminant concentrations in the pore water associated with oxidized but neutral tailings; unoxidized uncemented tailings; and unoxidized cemented tailings.

Example 3 - Contaminant contributions from wall rock

The potential for sulfide oxidation and accumulation of soluble constituents within each formation was investigated using a simple calculation method:

$$\text{Contaminant Release (mg)} = \sum \text{Specific Release } (mg\ ft^{-2}\ yr^{-1}) * \text{Exposed Surface } (ft^2) * \text{Time (yr)}$$

where the summation indicates that both the high sulfide and average rock were considered. This approach is similar to that used in studies of contaminant release from pit walls (e.g. Morin & Hutt, 1995). Although the method is quite simple, it does allow the importance of surface area, time, and material properties (as represented by the specific release) to be taken into consideration.

- Estimates of specific release rates were obtained from the results of column tests on the high sulfide and master composite samples of each formation. The amount (mg) of each contaminant released from a column over the approximately one year of testing was calculated.

- To convert to per surface area units, the grain size distribution of each sample was measured. We assumed particles to be spherical, and particles passing the finest seive to have a diameter equal to one-half the seive opening. Both assumptions lead to low estimates of surface area, hence high estimates of the specific release rate. Our estimates of specific surface area ranged from 14 to 24 ft^2/kg.

- Estimates of specific release rates are not common in the literature. Our sulfate release rates were from 1.6 to 4.4 mg ft^{-2} $year^{-1}$ for the master composite samples, and 47 to 180 mg ft^{-2} $year^{-1}$ for the high sulfur samples. For copper, master composite samples gave 0.004 to 0.008 mg ft^{-2} $year^{-1}$,,and high sulfur samples 0.005 to 3.8 mg ft^{-2} $year^{-1}$. For zinc, master composite samples gave 0.006 to 0.032 mg ft^{-2} $year^{-1}$, and high sulfur samples 0.18 to 6.5 mg ft^{-2} $year^{-1}$.

- The nominal surface areas of wall rock within each formation were calculated directly from the mine plan. The total surface area is expected to be greater. Measurements in open pits have shown the ratio of total surface area to nominal surface area to range from 27:1 to 161:1 (Morin and Hutt, 1995). Because the extent of wall fracturing in underground workings is less than in pits, it was assumed that the total surface / nominal surface ratio for the Crandon mine would be 30:1.

- In order to take the summation over the high sulfide and average rock, we also needed to estimate the proportion of surface associated with each. Crandon geologists reviewed the logs of all drill holes passing through the hanging wall formations and determined the length of intercepts with sulfide in the 3-4% range measured in the high sulfide samples. They estimated the high sulfur material to comprise 0.75% of the Lower Mole Lake formation, 0.5% of the Upper Mole Lake formation, and 0.1% of the Rice Lake formation. Note that this method effectively double counts the high sulfide material, since it occurs both in the high sulfur samples and as a component of the master composites.

The above calculation results in an estimate of the mass of each contaminant that would be released to the wall rock within each formation, during the mine life. To estimate concentrations in the re-flooding groundwater, it was assumed that all of the estimated mass of contaminants would be accumulated in the wall rock, and would dissolve in the groundwater volume required to fill the workings. Again the approach is simple but conservative, since it neglects the flushing of contaminant to the to the minewater treatment system during operations, the possibility that secondary phases will not be immediately soluble, the additional volume of groundwater required to fill the porosity in the adjacent rock, and the alkalinity of the re-flooding groundwater.

WALL ROCK

The mining methods selected for the Crandon deposit will require construction of shafts, vent raises, drifts, cross-cuts and ramps in the hanging wall. The access workings will intercept four stratigraphic units, known as the Lower Mole Lake, Upper Mole Lake, Rice Lake and Skunk Lake formations. Wall rock in the access workings will be exposed to oxidation throughout the mine life, and therefore could release contaminants to the groundwater upon re-flooding.

To estimate the amount of contaminants that could be released, we made use of data gathered in earlier investigations of waste rock (Foth & Van Dyke 1995). In the earlier investigations, geologists from Crandon Mining Company and regulatory agencies had selected both master composite and high sulfur composite samples from the drill core that intercepted each stratigraphic unit. The former samples represented the average composition of the formation (including mineralized areas); the latter were hand picked to over-represent mineralized areas. All samples were subjected to static tests and 54-week column tests.

The calculations that we used to relate results of the column tests to estimates of contaminant concentrations in the re-flooding groundwater are outlined in Example 3. As was the case in the tailings backfill calculations, several assumptions were required. We researched available literature in order to support the assumptions, and to ensure that selected parameters were conservative, (i.e. that they would lead to conservatively high estimates of contaminant concentrations).

Table 2 shows the resulting estimates of groundwater volumes and contaminant concentrations in the re-flooded access workings.

Table 2 - Estimated contaminant concentrations attributable to wall rock in access workings

Description	Est. Volume	Estimated Concentrations in Flooded Workings (mg/L)					
	(ft^3)	SO_4	As	Ca	Cu	Fe	Zn
Mole Lake	5,300,000	24	0.021	14	0.11	1.5	0.23
Rice Lake	5,100,000	7.5	0.015	8.1	0.061	4.4	0.043
Skunk Lake	2,200,000	20	0.007	6.1	0.037	0.90	0.031
Total Wall Rock	12,600,000	17	0.016	10	0.078	2.6	0.12

CROWN PILLAR

The crown pillar area is covered by glacial overburden, which varies in thickness from 75 feet to over 250 feet. The overburden cover is expected to minimize the direct access of oxygen to the deeper, sulfidic parts of the crown pillar. Through a series of simple calculations we were able to demonstrate that areas where ventilation air is in direct contact with the crown pillar, i.e. the uppermost stope backs, will see the most significant oxidation and therefore have the most potential for contaminant release.

To estimate contaminant release from the stope backs, we used the calculation method developed for wall rock and shown in Example 3. Estimates of specific release rates were obtained from column tests of ore samples. Surface area estimates were as described in Example 3. In contrast to the wall rock, the crown pillar stope backs will be exposed to oxidation for relatively short period. The uppermost stopes will be mined using cut and fill methods, and the period between exposure (cut) of the crown pillar and tight-filling of the back is estimated to be about six weeks. The shorter exposure time leads to considerably lower contaminant releases. Example concentration estimates are shown in Table 3.

Table 3 - Estimated contaminant concentrations from crown pillar

Source	Est. Volume	Estimated Concentration in Groundwater (mg/L)					
	(ft^3)	SO_4	As	Ca	Cu	Fe	Zn
Crown Pillar	950,000	35	0.001	2.7	1.5	0.80	13

COMBUSTION RESIDUES

During operation of the mine, air emissions will occur from the combustion of natural gas for mine air heating, and the combustion of fuel oil by mobile equipment. The potential for air emissions to influence groundwater quality has not, to our knowledge, been addressed at other mines. In fact, despite considerable efforts, we could find no mine where the issue had even been raised.

To quantify the metals emitted from combustion processes, we carried out simple calculations such as are common in air quality permits. The results indicated that the amount of metals released by combustion and accumulated in the underground would be 4 - 6 orders of magnitude less than would be present in the tailings backfill. Even those estimates conservatively neglect removal of metals through transport of or binding with particulate matter. We therefore concluded that combustions residues are a relatively insignificant source of contaminants, warranting no additional consideration.

GROUNDWATER FLOW PATTERNS

The impact of the contaminant loads from each source on the surrounding groundwater will be determined by flow patterns in and around the mine. SRK created a model of the local groundwater flow patterns in representative levels of the mine. Stope boundaries and access workings were obtained from mine plans, and rock types were identified from geological sections. The results were input to GMS (Groundwater Modeling Software, Brigham Young University) and used to construct inputs for MODFLOW. Transmissivity parameters and boundary conditions for the local model were obtained from regional groundwater studies carried out by HIS GeoTrans (GeoTrans 1996).

Results are illustrated in Figure 1, which shows the flow field predicted for the 1250 foot level of the re-flooded mine. It is clear from the figure that groundwater will flow predominantly through the mine access workings. Similar results were obtained for other levels and for a variety of sensitivity runs. The implication is that initial discharges from the mine area are expected to carry contaminants from the wall rock.

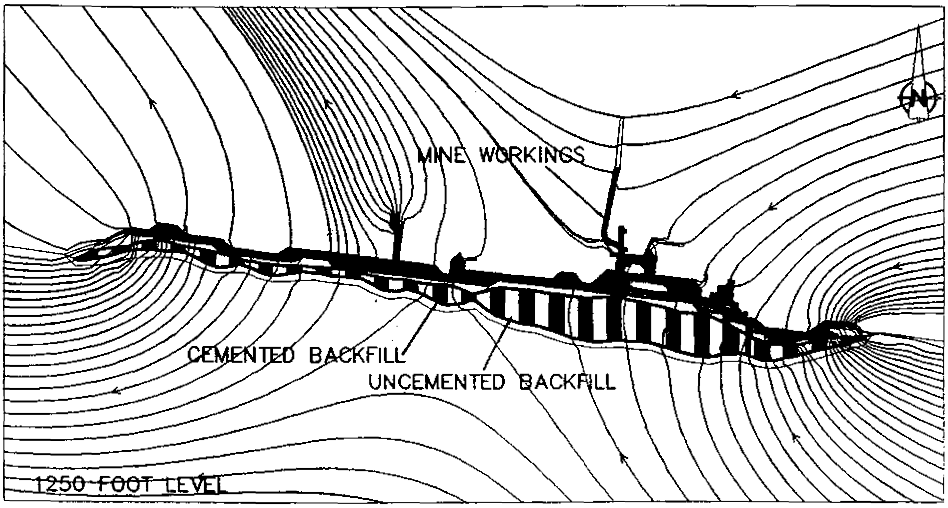


Figure 1 - Example groundwater flow patterns after re-flooding

CONCLUSIONS

Table 4 summarizes the results obtained in our study of the potential contaminant sources in the underground Crandon Mine. Estimates of the contaminant concentrations that will be contributed to the re-flooding groundwater by the backfilled tailings, wall rock, and crown pillar are shown in the first three rows. Contributions from underground emissions were concluded to be negligible.

Hydrogeological modeling of the re-flooded mine predicted that groundwater flow will be predominantly through the mine workings. Hence initial groundwater discharges from the mine area are expected to carry contaminants contributed by the wall rock. The much greater volume of backfilled tailings would dominate contaminant concentrations over the long term.

When the concentrations in Table 4 are reduced by the available dilution of 75 - 200 times, they fall one to two orders of magnitude below the anticipated groundwater standards. In short, groundwater contamination from the re-flooded mine is predicted to be insignificant.

Perhaps of broader interest, the combination of literature review, laboratory data, and simple but conservative calculations proved to be a powerful method to distinguish among many potential contaminant sources, and put reasonable estimates on concentrations. This approach may be applicable to other sites where many potential sources need to be characterized.

Table 4 - Summary of estimated contaminant concentrations

Source	Est. Volume	Estimated Concentrations on Reflooding (mg/L)					
	(ft^3)	SO4	As	Ca	Cu	Fe	Zn
Backfilled Tailings	210,000,000	1400	0.29	290	0.12	5.4	6.5
Total Wall Rock	12,600,000	17	0.016	10	0.078	2.6	0.12
Crown Pillar	950,000	35	0.001	2.7	1.5	0.80	13
Weighted Average	224,000,000	1300	0.28	277	0.12	5.1	6.2

REFERENCES

Archibald, J.F. and Nantel, J. H., 1984. Prediction of Radiation Levels and Ventilation Requirements in Underground Uranium Mines. *CIM Bulletin*, Vol. 77, No. 861, January 1984, pp. 60-64.

Blowes, D,W., Reardon, E.J. Jambor, J.L., Cherry, J.A., 1990. The Formation and Potential Importance of Cemented Layers in Inactive Sulfide Mine Tailings. *Geochemica et Cosmochimica Acta*, Vol. 55, pp. 965-978.

Foth and Van Dyke, December 1995. Waste Characterization Update Report, Crandon Project.

GeoTrans, 1996. Numerical Simulation of the Effect on Groundwater and Surface Water of the Proposed Zinc and Copper Mine near Crandon, Wisconsin.

Morin, K.A., 1990. Acid Drainage from Mine Walls: The Main Zone Pit at Equity Silver Mines. British Columbia Acid Mine Drainage Task Force.

Morin, K.A. and Hutt, N.M., 1995. A Technique for Predicting Water Chemistry in Open Pit and Underground Mines. In: Sudbury '95 Mining and the Environment Conf. Proc.

Nicholson, R.V., 1994. Iron Sulfide Oxidation Mechanisms: Laboratory Studies. In Short Course Handbook on Environmental Geochemistry of Sulfide Mine Wastes, Mineral Association of Canada, 438 pp.

Reardon, E.J. and Moddle, P.M., 1985. Gas Diffusion Coefficient Measurement on Uranium Mill Tailings: Implications to Cover Layer Design. *Uranium*, Vol. 2 pp 111-131.

Ritchie, A.J.M, 1994. Sulfide Oxidation Mechanism-Controls and Rates of Oxygen Transport. In "The Environmental Geochemistry of Sulfide Mine Wastes", D.A. Blowes J.L. Jambor, Eds., Mineralogical Association of Canada, Nepean, Ontario, 1994.