

A Comparison of Past Predictions to Current Conditions at Bell Mine, British Columbia, Canada

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Abstract: Prior to mine closure in 1992, drainage chemistry at Bell Mine was assessed and predicted using a multifaceted study, including various geochemical static and kinetic tests. Also, a compilation of water monitoring data, known as an Empirical Drainage-Chemistry Model (EDCM), spanning many years showed repeating cycles, which allowed statistical assessment and predictions of future patterns. All this work showed that drainages from most of the waste-rock dumps, dams, and tailings impoundment were expected to become acidic within several decades, although many were near-neutral at the time of closure. Any water unacceptable for discharge would be pumped to the open pit, where it will be treated decades in the future as the pit fills. Predictions were made of pH and metal concentrations through many decades at various points around the site including the pit.

In 1999, new geochemical studies were undertaken to determine if current conditions are close to the original predictions. Predictions deviated by no more than a factor of two from the average measured metal concentrations. In the pit, parameters are following the predicted trends. However, the degree of acid generation and downward migration of acidic water in the tailings mass is approximately 100 times less than predicted. This can be attributed to (1) the incorrect prediction based on one humidity cell that acid generation would greatly accelerate upon exhaustion of neutralization potential (NP), (2) incorrect short-term information that NP would be consumed relatively quickly at a ratio of 4:1 to acid generation, and (3) the incorrect assumption that the rate of acid generation was zero-order (i.e., independent of oxygen level and depth in the tailings). Except for the updated prediction of much less acid generation in the tailings, all other predictions remain essentially the same as stated in 1992.

Introduction

Noranda's porphyry-copper Bell Mine is located near Granisle, British Columbia, Canada, opening in 1971 and closing in 1992. This minesite is located on the shore of a large lake which contains important fisheries for salmon and other fish stocks. Therefore, the environment surrounding the site is sensitive to any release of unacceptable metal-bearing water.

Waste rock consists of several dominant rock units including biotite feldspar porphyry, quartz feldspar porphyry, rhyodacite, siltstone, and tuff. Calcium- and iron-bearing carbonate minerals are common. Sulfide minerals identified in the Bell Mine orebody include non-economic pyrite (ferrous-iron sulfide), minor molybdenite (molybdenum sulfide), minor sphalerite (zinc sulfide), minor galena (lead sulfide), economic chalcopyrite (copper-iron sulfide), minor bornite (copper-iron sulfide), and chalcocite (copper sulfide). Tailings contain on average 4.5% S pyrite, 0.3% chalcopyrite, 4.2% neutralization potential (NP) expressed as CaCO₃, 2.1% siderite, 0.8% iron hydroxide, and 0.085% gypsum. Average tailings are predominantly silt with 50% often finer than 0.01-0.1 mm.

A few flows around the minesite were acidic by the 1980's, but most flows were near neutral pH at the time of closure in 1992. During operation, acidic waters were treated by pumping them to the tailings impoundment which contained excess lime from the mill circuit. Questions arose on how to handle the acidic water after the mill closed and on whether additional drainages might turn acidic in the future.

A multi-document Closure Plan, which was submitted to regulatory agencies in early 1993, included a main report and 10 supporting documents. Support Document E was entitled, *Mine Rock and Tailings Geochemistry and Prediction of Water Chemistry* (Morwijk Enterprises Ltd., 1993; by the same authors as this paper).

Drainage chemistry at Bell Mine was assessed and predicted using a multifaceted study, now called the “Wheel” Approach (Morin and Hutt, 1997 and 1999a). This included geochemical static tests, like acid-base accounting, total-metal contents, and mineralogy, as well as kinetic tests like standard-Sobek humidity cells and larger-sized kinetic tests. Also, a compilation of water monitoring data spanning many years showed repeating cycles, which allowed statistical assessments and predictions of future cycles (Morin and Hutt, in press; Morin et al., 2001). All this work showed that drainages from most of the waste-rock dumps, dams, and tailings impoundment were expected to turn from near-neutral pH to acidic pH within several decades, accompanied by increased concentrations of several metals. Any water unacceptable for discharge would be pumped to the open pit, where it will be treated decades in the future as the pit fills. Predictions were made of pH and metal concentrations over many decades at various points around the site.

In 1999, the authors were invited to re-evaluate the environmental geochemistry of Bell Mine, to compare those original predictions to current conditions, and to update predictions as needed. The two primary questions were:

- (1) Have the tailings been oxidizing and generating acidity as predicted?
- (2) Is drainage chemistry around the minesite at predicted concentrations?

The results of this update (Morin and Hutt, 2000a) are published for the first time in this paper.

Tailings Oxidation and Acid Generation

According to the original predictions in the Closure Plan (Morwijk Enterprises Ltd., 1993), the entire upper 2 m of tailings would oxidize at a steady rate throughout, and the neutralization potential (NP) in the upper 2 m would then be depleted at one time. At that point, acidic infiltrating water would begin moving downward into the deeper tailings below 2 m, but would be neutralized by the deeper NP. This would result in the creation of a geochemical “acid front” which migrated downward, consuming deeper NP. This would be followed in time and at depth by a “sulphide-depletion front,” above which all active acid-generating minerals were exhausted. The equations and conceptual model used to predict these fronts in the Bell tailings are described in Section 5.5.1 of Morin and Hutt (1997).

Due to factors such as oxygen diffusion, the downward migration rates of these fronts would slow with time and virtually cease decades in the future before acidic water could pass through the entire tailings mass. As a result, no net acidic water was expected to seep from the tailings mass, although the tailings are clearly net acid generating. Unfortunately, the waste-rock tailings dams were predicted to generate net acidity in the future, so the pH-neutral seepage from

the tailings is expected to become acidic as it flows through the surrounding dams.

In 1999, test pits (TP) were excavated within the tailings impoundment to observe the vertical migrations of the acid front and sulphide-depletion front since closure. Five test pits involved detailed vertical profiles, while 18 others incorporated lateral composites at specific depths. All samples were submitted for expanded standard-Sobek acid-base-accounting analyses (ABA, Sobek et al., 1978) and for total-metal contents after triple-acid digestion. According to original predictions, an average of 67% of original NP in the entire upper 2 m should have been exhausted by 1999 and some small-scale areas of shallow acidic pH should have been observed due to heterogeneities.

Vertical profiles of paste pH (Figure 1) show that two of the detailed test pits (TP6 and TP-M1, on the northern half of the impoundment) had acidic conditions in the upper 0.15 m, but near-neutral pH below that. The remaining three detailed test pits showed paste pH remained generally around 7.5 to 8.5 along their vertical profiles. In general, this means that the “acidic zone” has extended down 0.15 m at most at some locations over the eight years that the mine has been closed. The lack of shallow acidic conditions at some of the test pits is not due to a lack of sulphide minerals (Figure 2), and there is no clear trend indicating significant amounts of sulphide have been consumed at shallow depths where exposure to oxygen is greatest. Therefore, there is currently no evidence of a “sulphide-depletion zone.”

Despite the widespread lack of shallow acidity, the amount of leachable sulphate tends to be highest in the uppermost 0.5-1.0 m (not shown), except at TP4. This probably indicates the sulphide minerals are readily oxidizing and releasing sulphate, but that the amount of generated acidity has not yet overwhelmed shallow NP at all locations. This is consistent with the vertical trend in NP (Figure 3) which shows a general trend in NP depletion above 0.5-1.0 m depth.

Three of the five test pits still have shallow NP values above 20 t/1000 t (Figure 3), accounting for their lack of net acidity. Despite the presence of shallow NP at several locations in the tailings impoundment, the original prediction based on ABA balances (Sulphide Net Potential Ratio and Sulphide

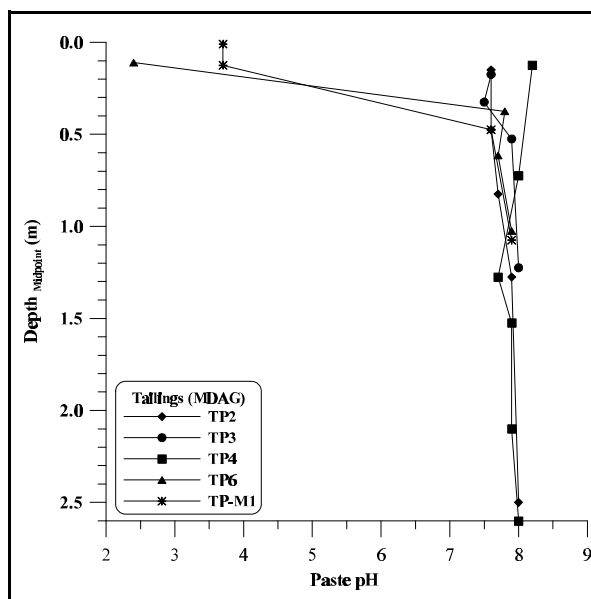


FIGURE 1. Vertical Profiles of Paste pH in the Test Pits of Bell Tailings.

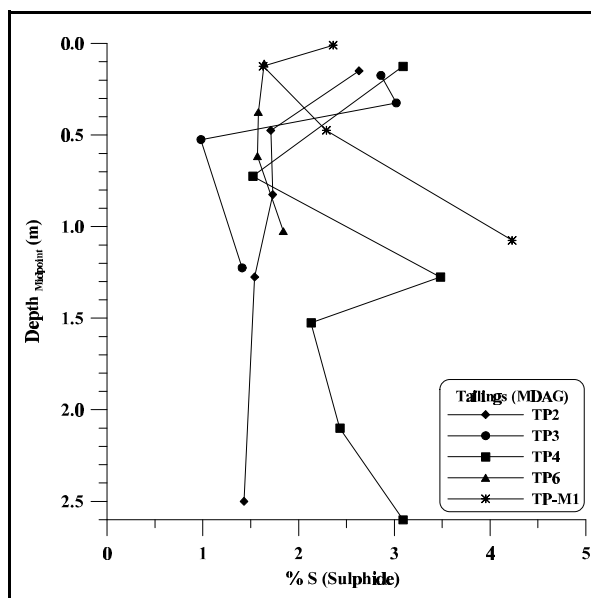


FIGURE 2. Vertical Profiles of Sulphide as Weight-Percent in the Test Pits in Bell Tailings.

Net Neutralization Potential) remains that NP in the shallow tailings will someday be overwhelmed, leading to net acidity, wherever sufficient oxygen is available and sufficient time passes.

These vertical trends in ABA parameters from 1999 (Figures 1 to 3) are not entirely consistent with those originally predicted in the Closure Plan. The Closure Plan states the “migration-rate predictions of the acid and sulfide-depletion fronts may be higher than actual rates in the future” for several reasons, namely:

- 1) An excavation of a small, acidic tailings test plot, constructed closer to the mill, revealed that the center of the plot was only 16% oxidized after 10 years, and thus 62.5 years would be required for sulphide depletion. This suggested a much slower downward migration front of 0.016 m/yr for sulphide depletion compared to the originally predicted 0.7 m/yr.
- 2) A predicted 2-m depth of initial oxidation was predicted for after closure in 1992, during which near-neutral conditions would prevail until effective neutralization potential was consumed. This prediction was based primarily on oxygen diffusion and rates of sulphide oxidation and oxygen consumption. Later observed depths of 0.5-1 m in 1993 and 1999 were less than the 2-meter prediction. This indicated an overestimation of NP consumption rates under near-neutral conditions by factors of 2 to 4, or an overestimation of oxygen diffusion by factors of 2 to 4, or violation of the assumption of zero-order oxidation (independent of oxygen level and depth).
- 3) Actual neutralizing capacity of the tailings could be higher than the measured neutralization potential (NP) due to the substantial presence of slowly-neutralizing aluminosilicate minerals.
- 4) Neutralization of acidity may not consume NP at a ratio of 4.1:1, which was used in the Closure Plan and based on the ratio measured in humidity cells. A sample of tailings placed in a standard-Sobek humidity cell, and continued for three additional years after closure, showed that a lower long-term average ratio around 1.5 was more appropriate. However, Test Pit TP4 shows no relative NP depletion in 1999 and thus its rate of NP consumption is virtually zero, highlighting heterogeneity around the tailings impoundment.
- 5) No establishment of oxygen barriers like heavy vegetation was considered.

Points 1, 2, and 4 above have turned out to be important, as well as two additional factors. First, the Closure Plan predicted the rates of oxidation and acid generation would accelerate by a factor of approximately 50 as pH-neutral conditions became acidic in the shallow tailings (related to Point 1 above). Second, the Closure Plan assumed that the rate of oxidation in the presence of oxygen was independent of oxygen level and thus independent of depth (related to Point 2 above). The literature was, and still is, ambiguous on this as oxygen dependence has been reported from zero to second order. These two additional factors are discussed below.

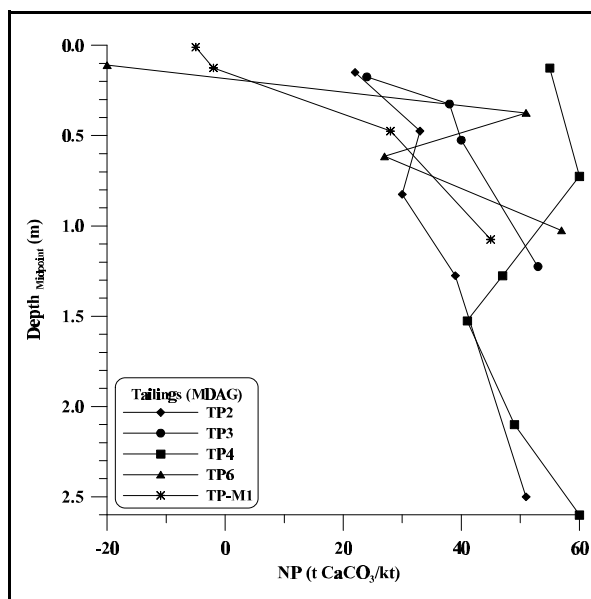


FIGURE 3. Vertical Profiles of Bulk Neutralization Potential in the Test Pits in Bell Tailings.

On the first factor of oxidation-rate acceleration, the Closure Plan used three tailings humidity cells that remained near-neutral over roughly 40 weeks of testing. A fourth tailings cell was acidic from the start and contained a sample taken from a small tailings test plot that may have been exposed to acidic drainage before collection. This one acidic cell suggested the rate of sulphide oxidation, acid generation, and underlying NP consumption would accelerate by a factor of more than 50 when some of the shallow tailings became acidic. Such acceleration is not typically observed in material from sulphide-bearing minesites, but does occur in some samples to some extent (Morin and Hutt, 1997, 1999b, and 2000b). The predicted acceleration would have caused the front of the acidic zone to migrate downwards at 3.3 m/yr.

This acceleration should have already occurred at TP6 and TP-M1, but the acidic front has actually not moved below 0.2 m although it has likely been present for at least a few years (Figure 1). Therefore, significant acceleration upon formation of acidic conditions is apparently not occurring, and thus the acidic cell from the test plot did not accurately represent rates that arise upon net acidity in bulk tailings. This factor-of-50 discrepancy represents the single largest cause of overestimation in the original predictions.

On the second factor of zero-order (depth-independent) oxidation, the vertical trends in NP (Figure 3) and sulphate levels show vertical gradients, which indicate acid generation and neutralization are not occurring evenly throughout the shallow oxidizing zone. This can be attributed to at least two factors: (1) preferential dissolution of NP by infiltrating precipitation and (2) reaction rates that decrease with depth. However, mass-balance calculations using the minesite's precipitation show that infiltration could account for only 1% of observed NP depletion, so the second factor is the apparent cause. The effect of this is to focus most of the reactivity into the uppermost tailings. Nevertheless, infiltration can still cause a very thin NP-depleted layer to develop at the surface.

Revised predictions for the acid and sulphide-depletion fronts, using this information not available in the Closure Plan, can now be made. Based on the above rates remaining constant through time, the fronts of the acidic zone at already-acidic TP6 and TP-M1 should now move downwards at a rate of 0.029 m/yr instead of 3.3 m/yr, or around 110 times slower. At near-neutral TP2 and TP3, NP in the upper 0.2 m should be depleted by 2007, and their acidic fronts will then appear and should then move downward at 0.014 to 0.029 m/yr instead of 3.3 m/yr. At TP4, the apparent lack of NP consumption suggests this area is not reactive and will not generate net acidity.

Based on mass-balance calculations and an average initial sulphide level of 2.5 %S, the revised rates should have consumed all sulphide only in the upper 0.05-0.10 m of tailings by 1999, which is equivalent to sulphide-depletion-front migration of 0.007-0.014 m/yr. Very shallow samples were not collected to verify this, since deeper migration was expected, but the shallowest sample in TP6 at 0.09-0.13 m is consistent with a lack of depletion. The revised rate of 0.007-0.014 m/yr agrees with the rate of 0.016 m/yr from the center of the small tailings test plot, but is much less than the initially predicted rate of 0.7 m/yr. These new revised sulphide-depletion rates are close to, or somewhat slower than, the rates for the acid front, which precede sulphide depletion in time and space (previous paragraph).

Although field observations in 1999 and the results of the longer-term humidity cell have been used to adjust the original geochemical predictions, there remain two issues not included in current predictions that could affect the future geochemical behaviour of the tailings. First,

no establishment of oxygen barriers over the decades, such as organic soil and pervasive vegetation, has been included in the predictions. While vegetation has been established in places at this time, it is not yet a good barrier to oxygen and infiltration. Alternatively, the near-arid condition noted on the tailings impoundment during summer months may actually cause shallow reactions to virtually cease due to the lack of moisture. If reactions ceased for three months every year, for example, the yearly migration-rate predictions can be lowered by 25%. However, this is a minor adjustment in light of typical factor-of-two variations in geochemical data (Morin and Hutt, 1997, 1999b, and 2000b). The second important point is that, as explained in the Closure Plan, the downward migration rates of the acid and sulfide-depletion fronts will decrease due to a slowing supply of oxygen with depth. Therefore, annual production of acidity and metal leaching in the shallow tailings has been substantially less than originally expected and will decrease further with time.

Minesite-Drainage Chemistry

One objective of this paper is to compare predicted concentrations and pHs around the minesite to observed values since closure. The Closure Plan (Morwijk Enterprises Ltd., 1993) contained a compilation of all available drainage chemistry during Bell's years of operation. Plots of flow and metals showed that flow did not significantly affect concentrations. Also, plots of time and metals showed that concentrations varied from season to season, but repeatedly produced similar ranges from year to year. Combined with calculations from the U.S. EPA speciation model, MINTEQA2 (Allison et al., 1990), this indicated concentrations of many metals were controlled in part by the site-specific solubilities of secondary minerals that had accumulated over the years.

One important implication of the secondary minerals at Bell Mine was that, if all metal leaching ceased immediately, these minerals would begin dissolving to maintain concentrations near existing levels. This simplified the predictions of future concentrations to focussing on the site-specific mineral solubilities, while incorporating all the effects that caused a repeating range of seasonal concentrations.

Solubilities of many secondary minerals are affected by pH and/or other "master" parameters like aqueous sulphate (Morin et al., 2001). It is important to delineate this effect because pH, for example, will decrease in places as neutralization potential is depleted, and pH will later increase as acid-generating sulphide is depleted. As these pH variations occur, it remains important to predict average-annual and seasonal concentrations through time.

All these observations and data were combined into an Empirical Drainage-Chemistry Model (EDCM, Table 1) for Bell Mine, providing pH- and sulphate-dependent equations for average-annual concentrations of dissolved metals and for total metals based on the corresponding dissolved levels. The theory and procedure for EDCMs are discussed elsewhere (e.g., Morin and Hutt, 1997, in press; Morin et al., 2001). The EDCM for Bell Mine also included standard deviations to represent the seasonal fluctuations around the annual average concentrations caused by all other natural and artificial factors such as temperature variations. Thus, the task of this section can be simplified to comparing predicted and observed average-annual equations and season-based standard deviations.

TABLE 1 Update of Bell Mine's Empirical Drainage-Chemistry Model (EDCM) for Parameters with Sufficient Post-Closure Analyses				
Parameter	Time Period	pH Range	Best-Fit Equation to Predict Concentration (mg/L) from pH or SO ₄	Log ₁₀ (Std Deviation)
Alkalinity	Operation	pH > 4.5	$\log(\text{alk}) = +0.698\text{pH} - 3.141$	0.654
	Closure ¹	pH > 4.5	$\log(\text{alk}) = +0.698\text{pH} - 2.958$	0.346
Dissolved Calcium	Operation		$\log(\text{Ca}) = +0.619\log(\text{SO}_4) + 0.524$	0.375
	Closure		Same as above	0.173
Dissolved Copper	Operation	pH < 3.4	$\log(\text{Cu}) = -1.485\text{pH} + 6.605$	0.692
		3.4 < pH < 5.4	$\log(\text{Cu}) = -0.327\text{pH} + 2.666$	
		pH > 5.4	$\log(\text{Cu}) = -1.001\text{pH} + 6.307$	
	Closure ¹	pH < 3.4	$\log(\text{Cu}) = -1.485\text{pH} + 6.296$	0.837
		3.4 < pH < 5.4	$\log(\text{Cu}) = -0.327\text{pH} + 2.357$	
		pH > 5.4	$\log(\text{Cu}) = -1.001\text{pH} + 5.998$	
Total Copper	Operation		$\log(\text{CuT}) = +0.962\log(\text{CuD}) + 0.180$	0.230
	Closure		Same as above	0.251
Dissolved Iron	Operation	pH < 4.4	$\log(\text{Fe}) = -1.429\text{pH} + 6.286$	0.807
		pH > 4.4	$\log(\text{Fe}) = -0.455\text{pH} + 2.000$	
	Closure	pH < 4.4	Same as above	0.753
		pH > 4.4	Same as above	
Total Iron	Operation		If diss Fe > 1.0, total Fe = diss Fe	
	Closure		Same as above	0.205
Dissolved Lead	Operation		Pb < 0.05 mg/L	
	Closure	pH < 5.0	Pb < 2 mg/L	
		pH > 5.0	Pb < 0.2 mg/L	
Total Lead	Closure	pH < 5.0	Pb < 4 mg/L	
		pH > 5.0	Pb < 4 mg/L	
Dissolved Zinc	Operation		$\log(\text{Zn}) = -0.441\text{pH} + 1.838$	0.667
	Closure		Same as above	0.717
Total Zinc	Operation		total Zn = dissolved Zn	0.144
	Closure		Same as above	0.148

¹ New equations result in factor-of-two changes or less in initial predictions.

Scatterplots of water chemistry during operation (1992 and earlier) and after closure (post 1992) show similar trends for metals with abundant data (e.g., Figure 4). However, there is little to no data for several metals after closure, indicating they have been rarely to never analyzed since closure. Also, some metals like aluminum have dozens of analyses since closure, but they span only a narrow range of pH. For these metals, it is not possible to determine if the EDCM continues to apply to them.

The remaining parameters in the EDCM, with at least several dozens of analyses spanning at least several pH units, are: total alkalinity, sulphate, calcium, copper, iron, lead, and zinc. As shown in Table 1, calcium is better predicted using sulphate concentrations than pH. For these remaining parameters, all equations and standard deviations during closure agree with those from operation within a factor of two. The difference of a factor of two may reflect changes in real processes, like secondary-mineral solubilities, or may reflect the fewer analyses over a shorter span of years for closure.

For example, dissolved copper (Figure 4) remains generally consistent with operational trends within a factor of two. The dissolved copper best-fit equation can be improved by decreasing the predictions by a factor of two (Table 1), but the seasonal variation around this average-annual equation increases to 0.837 from 0.692 log cycles.

Pit Water

Another part of drainage-chemistry predictions is to compare the original predictions of pit-water chemistry to actual concentrations and pH. As specified in the Closure Plan, all water in collection ponds that is not acceptable for discharge is pumped to the pit. This includes acidic drainage as well as near-neutral water with elevated metal concentrations. Because the pit receives all this water from around the minesite, it represents the main point of accumulation, the primary location for future water treatment after the pit fills to its specified level, and the main test for overall reliability of chemical predictions.

The chemistry of pit water is monitored at one station at the base of the ramp. As the pit fills, the elevation and lateral position of this station change. It is also important to note that the water samples are shallow, surficial water, which likely represent mostly undiluted site runoff and snowmelt during the spring and presumably better mixed pit water later in the year.

Temporal trends in the shallow pit water for pH (Figure 5) and dissolved copper (Figure 6) show that predictions through 1999 are consistent with measured late-year values. Earlier each

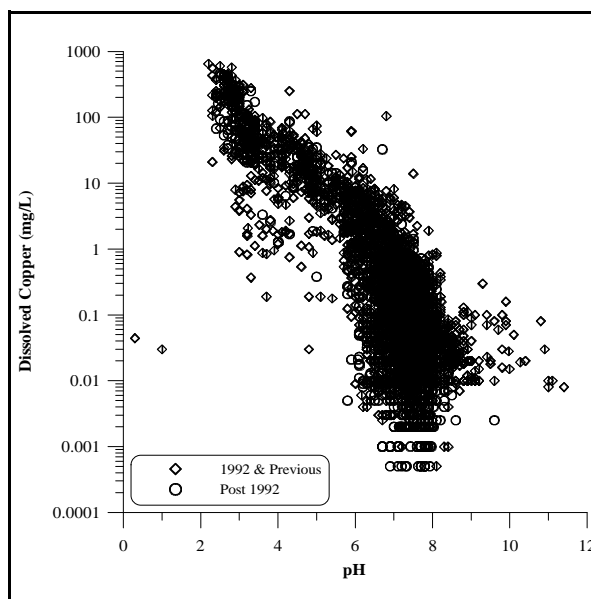


FIGURE 4. Measured Dissolved Copper vs Aqueous pH in Bell Mine's Database during Operation (to 1992) and Closure (data for both Operation and Closure closely overlap and are mostly indistinguishable).

year, pH is roughly one pH unit lower than predicted and copper concentrations are roughly 5 mg/L higher than predicted, although the predicted trends in values over the years are still followed. Because it is unlikely the entire pit-water column could display such significant seasonal variations, the variations likely reflect seasonal mixing of pit water with shallow spring runoff and snowmelt. If so, data collected later in each year are more representative of the pit water. Generally increasing sulphate concentrations (not shown) with significant seasonal variations also support these observations.

Conclusion

This paper has presented an update to the geochemical studies and 1992 predictions in the Bell Mine Closure Plan. Test pits excavated in the tailings in 1999 led to revisions of acid generation and NP consumption in the tailings, resulting in greatly decreased rates of reaction and vertical migration rates for the zones of net acidity and sulphide depletion. The reasons for the revisions can be traced to three primary factors for which there was no available data or erroneous data at the time of closure, namely (1) the rate of sulphide oxidation and acid generation does not accelerate by a factor of 50 as originally predicted, (2) NP is not consumed at a ratio of 4.1:1 as acidity is produced, but at roughly 1.5:1, and (3) oxidation is focussed in the shallowest tailings and is not zero order (independent) with depth as assumed in the Closure Plan.

Predictions of aqueous concentrations remain within a factor of two, on average, using the EDCM approach. These relatively minor differences between predicted and observed values are typical of geochemical data, and may be a statistical artifact of fewer samples during closure to this point or a real change in mineral solubility or other process affecting aqueous concentrations.

Measured pH and concentrations in the pit, in which all water not acceptable for discharge is accumulated, follow the trends predicted at closure. Not all actual values agree

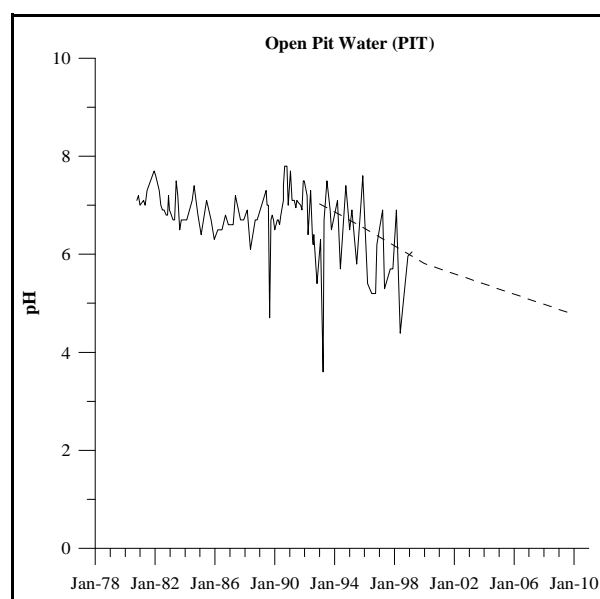


FIGURE 5. Temporal Trend of Aqueous pH in Bell Mine's Pit Filling with Water.

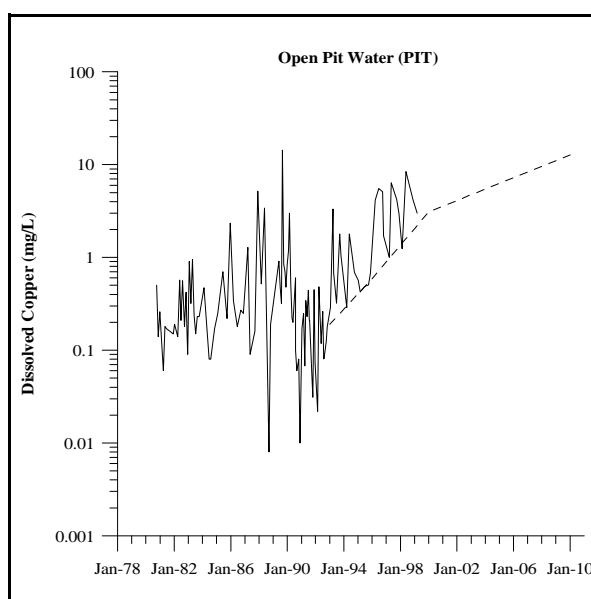


FIGURE 6. Temporal Trend of Dissolved Copper in Bell Mine's Pit Filling with Water.

exactly with pit values due to seasonal fluctuations in the samples collected only from the shallowest water layer. This layer includes water from runoff, snowmelt, precipitation, and pumpage of water from other watersheds, and thus concentrations in it fluctuate substantially on a seasonal basis. It is unlikely this fluctuation reflects the entire pit water column.

Acknowledgments

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