MINEWALL 2.0: A Technique for Predicting Water Chemistry in Open-Pit and Underground Mines[1]

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Abstract: Minesites can consist of many components including the mine itself (pits and underground workings), tailings impoundments, waste-rock dumps, ore stockpiles, plantsites, and roads. These components can affect the chemistry of water flowing over or through them by various geochemical processes. Case studies of water chemistry and geochemical processes are relatively common for tailings impoundments, less common for waste-rock dumps, and relatively rare for pits and underground workings ("mines").

In order to better understand and predict water chemistry in and around mines in Canada, the Canadian Mine Environment Neutral Drainage (MEND) Program and the British Columbia Acid Mine Drainage Task Force sponsored two projects known as MINEWALL 1.0 and MINEWALL 2.0. These projects led to a technique for predicting water chemistry in mines and a computer program to assist with predictions for complex scenarios. MINEWALL is based on literature reviews of relevant theory, testwork, and past studies, and is thus designed to be flexible and widely adaptable to many site-specific conditions.

The MINEWALL technique leads to predictions of minewater chemistry through consideration of (1) flow rates and chemistry of all relevant water pathways into, through, and from a mine and (2) additional loadings from the walls of the mine. The additional loadings from the minewalls are the result of: (1) unit-surface-area production rates, (2) total reactive rock-surface area in a mine, and (3) time-varying reaction-product retention and flushing. Data from three pits and one underground mine are presented to illustrate the requirements of the technique and to highlight site-specific variability. For example, the rate of sulfide oxidation from rock surfaces, as indicated by sulfate production, ranged from 3.61 to 2670 mg $SO_4/m^2/wk$. The rate of zinc production, which represented its leaching from rock surfaces, ranged from 0.0022 to 3.87 mg $Zn/m^2/wk$. At one site, the rate of physical weathering was equivalent to the rate of chemical weathering.

Total reactive surface area in one pit was estimated at $244x10^6$ m^2, or a factor of 161 greater than the visible rock surfaces in the pit. Also, the case studies indicated that up to 90% of weathering products are retained on the rock surfaces each year, and are thus available for relatively fast release upon closure and flooding of the mine.

The original MINEWALL references should be consulted for potential additional requirements not addressed here.

Key words: open pits, underground mines, mine walls, water chemistry, metal leaching, modelling, acidic drainage

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[1] Paper presented at Sudbury '95, Conference on Mining and the Environment, Sudbury, Ontario, May 28 - June 1, 1995

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1. Introduction

Minesites can consist of many components including the mine itself (pits and underground workings), tailings impoundments, waste-rock dumps, ore stockpiles, plantsites, and roads. Any component can affect the chemistry of water flowing over or through it by geochemical processes such as the leaching of metals and nonmetals at any pH and the oxidation of sulfide minerals.

Case studies of water chemistry and geochemical processes in tailings impoundments are generally available (e.g., Jambor and Blowes, 1994). Similar studies for mined-rock piles including roads and foundations are less common, but still available (e.g., Morin et al., 1991; Morin et al., submitted). However, geochemical investigations of pits and underground workings ("mines") are rarer (e.g., St-Arnaud and Aiken, 1991).

In order to better understand and predict water chemistry in and around mines in Canada, the Canadian Mine Environment Neutral Drainage (MEND) Program and the British Columbia Acid Mine Drainage Task Force sponsored two projects known as MINEWALL 1.0 (Morin, 1990) and MINEWALL 2.0 (Morin and Hutt, 1995). These projects led to a technique for predicting water chemistry in mines and a computer program to assist with predictions for complex scenarios. This paper summarizes the technique and presents case studies to illustrate the data requirements and their importance. This paper focusses on the approach to predictions in the case studies rather than the predictions themselves which can be found in Morin and Hutt (1995).

MINEWALL is based on literature reviews of relevant theory, testwork, and past studies, some over 30 years old (summarized in Morth et al., 1972). As a result, the technique and program were designed to be flexible and widely adaptable to many site-specific conditions.

MINEWALL can estimate water chemistry continuously through the *Operational* and *Closure Phases* of a mine. The Operational Phase encompasses the time from when a pit or working approaches its fullest extent to the beginning of Closure. Earlier stages of mining are predicted on a step-by-step basis, rather than continuously. The Closure Phase extends from the end of Operation into the future. The MINEWALL 2.0 program can simulate up to 500 years of Operation and Closure at one time.

2. Water Movement in a Mine

Since the MINEWALL technique focusses on the chemistry of minewater, the first requirement is the delineation of the movement of affected water into, through, and from a mine. Potential pathways of water movement for a pit or underground working include precipitation, evaporation, inflow or outflow of groundwater, unsaturated subsurface flow, runoff in a pit, gravity drainage of water, and pumping (e.g., Figure 1). Delineations of groundwater inflow, for example, can be based on past flow data, hydrogeologic data, and/or computer modelling. MINEWALL does not limit any study by demanding estimates using only one or a few methods, because there are weaknesses in every method. Instead, MINEWALL uses any estimate and can, in fact, provide predictions based only on one guess of net inflow/outflow for all eternity. In other words, MINEWALL is not judgemental towards the input data, but the detail and accuracy of MINEWALL estimates reflect the detail and accuracy of the input data:

$$\text{Wild Guess In from User} = \text{Wild Guess Out from MINEWALL} \qquad (1)$$

Flow rates along water pathways can change markedly through time, especially between Operation and Closure. For example, an operating pit is usually dewatered through pumping if below the surrounding water table (Figure 1) or by infiltration to groundwater if above the surrounding water table. During Closure, a pit below the water table will begin filling naturally with water (Figure 2). This filling can be enhanced or retarded by pumping of water into or from the pit, respectively. If the pit water rises to hydraulic equilibrium with the surrounding groundwater system, water may begin flowing laterally through the pit into the downgradient portion of the system (Figure 3). If pit-water chemistry is unacceptable for discharge, ongoing pumping may be required to maintain a water level below the static equilibrium level so that no pit water is lost to the system. Case studies of these various scenarios are provided in Morin and Hutt (1995). As another example, tailings or rock may be placed into an underground mine (e.g., Hutt and Morin, 1994) or pit (e.g., Ross et al., 1994) so that only open porespace is filled during filling. Many of these complex scenarios would benefit from the MINEWALL 2.0 computer program for detailed simulations and predictions.

3. Chemistry of Mine Water

After the flow rates along water pathways have been defined for Operation and Closure (Section 2), the MINEWALL technique then focusses on the chemistry associated with the mine water. MINEWALL predicts aqueous concentrations (e.g., 10 mg Ca/L) through separate estimates of loadings (e.g., 10 mg Ca/day) and flow (e.g., 1 L/day).

During Operation, the prediction of concentrations in the drained or pumped minewater is relatively easy using the units of mg, liters, and weeks:

$$\text{Conc}_m = \{[\text{Flow}_1 \text{*} \text{Conc}_1] + [\text{Flow}_2 \text{*} \text{Conc}_2] + \ldots + \text{MW}_1\} / \{\text{Flow}_1 + \text{Flow}_2 + \ldots\} \quad (2)$$

where Conc_m = concentration in pumped/drained mine water (mg/L);

Flow_x = positive (inflow) or negative (outflow) flowrate such as precipitation or groundwater (L/week);

Conc_x = concentration associated with Flow_x (mg/L); and

MW_1 = loading from occasional flushing of mine walls (mg/wk).

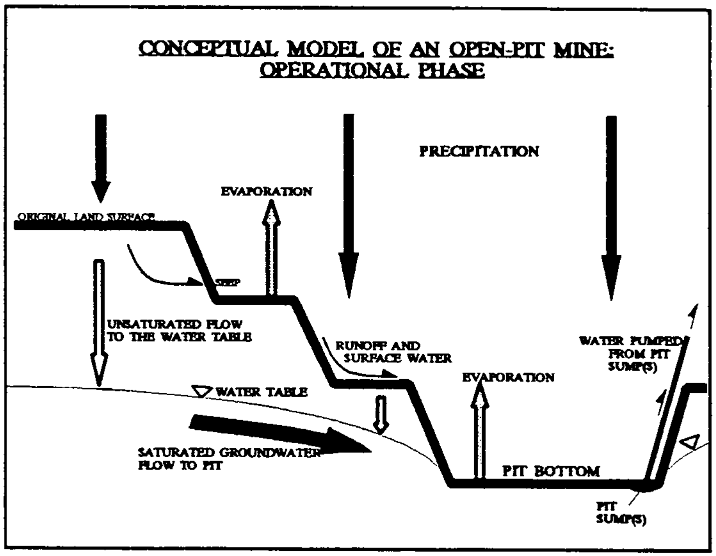

FIGURE 1. Conceptual MINEWALL Model of Water Movement In and Near Pit Walls During Operation.

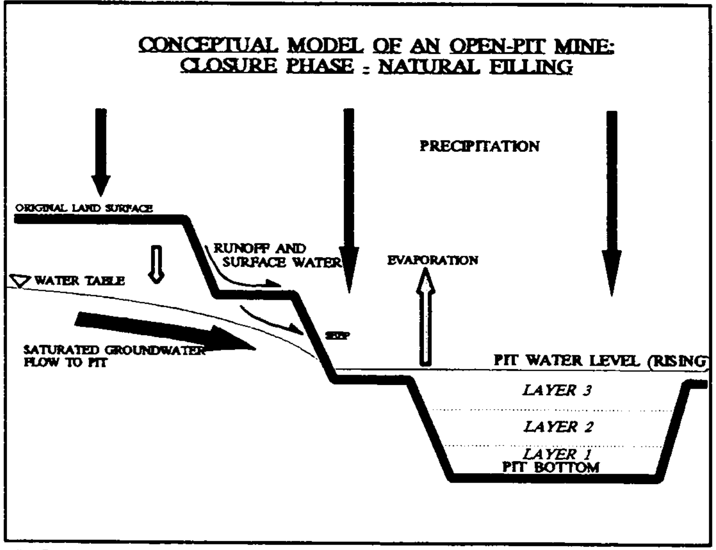

FIGURE 2. Conceptual MINEWALL Model of Pit Filling by Natural Processes During Closure.

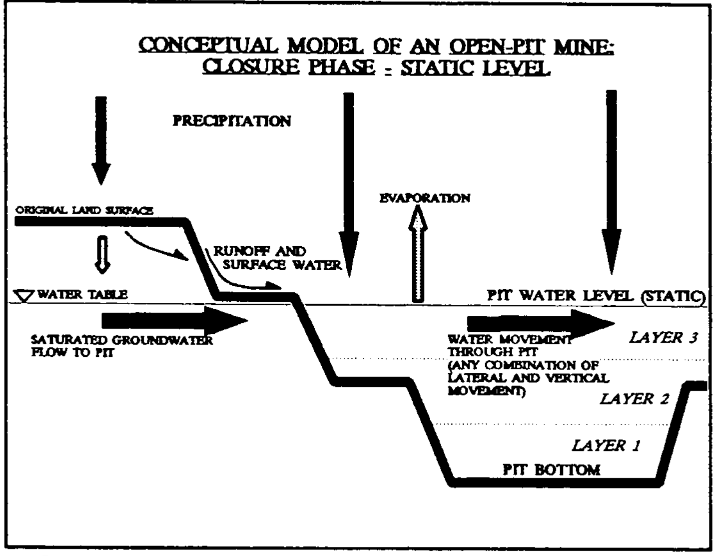

FIGURE 3. Conceptual MINEWALL Model of a Pit Filled to its Static Level.

A negative value for $Conc_m$ in Equation 2 indicates there is a net loss of water from the mine. During Closure, the prediction of concentrations in the water filling the mine is more difficult due to the accumulation of mine water, additional contributions from the mine walls, and the potential for flow reversals. With units of mg, liters, and time steps of one week, the general equation for predicting the concentrations in minewater during Closure is:

$$Conc_{m,t} = \{[Conc_{m,t-1} * Volume_{m,t-1}] + [Flow_1 * Conc_1] + [Flow_2 * Conc_2] + \ldots + MW_1 + MW_2 + MW_3\} / \{Volume_{m,t-1} + Flow_1 + Flow_2 + \ldots\} \quad (3)$$

$$\text{and } Volume_{m,t} = Volume_{m,t-1} + Flow_1 + Flow_2 + \ldots \quad (4)$$

where $Conc_{m,t}$ = Closure concentration in ponded minewater at current week, t (mg/L)
$Conc_{m,t-1}$ = Closure concentration in ponded minewater at previous week, t-1 (mg/L)
MW_2 = loading from major flushing of recently submerged mine walls (mg/week)
MW_3 = loading from previously submerged mine walls (mg/week)
$Volume_{m,t-1}$ = volume of ponded mine water from previous week (L)

All $Flow_x$ and $Conc_x$ in Equations 2 to 4 must be known for predictions of minewater chemistry. Most of this required information on flows and concentrations, such as for precipitation and groundwater, often comes from routine monitoring of proposed, operating, and closed mines. Also, concentrations in precipitation and evaporation are often negligible and can thus be ignored, and concentrations in runoff and unsaturated flow can be set to zero and their contributions can be more easily estimated as part of MW_x as explained below. As a result, the key $Conc_x$ is for groundwater flow, which can come from monitor wells at the minesite. Therefore, most of the data requirements for MINEWALL, except the MW_x factors, can be relatively easily obtained or estimated. In fact, because operating mines often monitor flow and chemistry ($Conc_m$) in mine drainage/pumpage, Equations 2 and 3 can sometimes be solved in reverse to obtain an unknown $Conc_x$ or $Flow_x$ (Morin and Hutt, 1995).

As a result, the primary unknown factors in Equations 2 to 4 are often the MW_x factors, which reflect loadings from the rock surfaces on and behind the mine walls. These loadings are considered to be *release rates* into the minewater, such as 300 mg Ca/week. These rates are determined by three factors which are discussed in the following subsections: (1) unit-surface-area production rates, (2) total reactive rock-surface area in a mine, and (3) reaction-product retention and flushing. In other words, for one week of time:

$$\text{Release rate (mg/wk)} = \{[\text{Production rate (mg/m}^2\text{ surface/wk)} * \text{Total rock surface (m}^2\text{)}] + [\text{Previously retained products (mg)}]\} * \{\%\text{Flushed from surface}/100\%\} \quad (5)$$

3.1 Unit-surface-area Production Rates

As shown in Equation 5, one primary factor in estimating the effect of minewalls on minewater chemistry is the production rate from a unit area (1 m^2) of wall. In accordance with MINEWALL's flexibility, this rate can be obtained from any type of laboratory or in-field test. Nevertheless, for the MINEWALL field studies, a custom test was designed involving "MINEWALL Stations" (Morin and Hutt, 1995). These stations used relatively inexpensive materials including pure silicon caulking and plastic trimming to isolate roughly 0.1 to 0.5 m^2 of minewall. Most stations were rinsed periodically by mine personnel as part of routine site monitoring, and the rinse water was filtered to obtain dissolved concentrations and analyzed for pH, various metals, nonmetals, and titratable parameters.

In many ways, the rinsing of the stations is a kinetic test which yields primary reaction rates (e.g., Morin et al., 1995a, these proceedings). The resulting production rates for three pits and one underground mine are listed in Tables 1 through 4 in order to illustrate the variability in production rates among parameters, stations, and mines. For example, the rate of sulfate production, which reflects the

TABLE 1

AVERAGE PRODUCTION RATES ($mg/m^2/wk$) FOR PIT #1

Parameter ($mg/m^2/wk$)	Station 1	Station 2	Station 3	Station 4	Station 5
pH (units)	4.9	5.2	6.1	5.0	6.0
Acidity	53.9	10.2	3.62	15.9	16.6
Alkalinity	26.4	8.79	23.9	6.97	73.1
Sulfate	49.7	203	538	48.2	133
Nitrate	0.330	0.0800	3.17	0.111	0.831
Aluminum	0.132	0.0131	0.0290	0.0729	0.0720
Antimony	0.0144	0.000509	0.0109	0.0263	0.0122
Arsenic	0.00180	0.000218	0.000181	0.000317	0.00111
Cadmium	0.00420	0.000945	0.0326	0.0225	0.00609
Copper	0.0600	0.00872	0.0326	2.35	0.0332
Iron	0.360	<0.022	<0.27	0.0951	<0.17
Zinc	0.719	0.196	2.79	3.87	0.775

TABLE 2

AVERAGE PRODUCTION RATES ($mg/m^2/wk$) FOR PIT #2

Parameter ($mg/m^2/wk$)	Station 1	Station 2	Station 4	Station 5	Station 6
pH (pH units)	7.31	6.61	6.25	6.23	6.45
Alkalinity	25.3	9.95	4.82	5.66	16.9
Sulfate	79.8	70.7	8.90	42.1	187
Silicon	11.0	-	1.48	1.86	10.6
Aluminum	0.500	1.07	0.130	0.157	0.420
Cadmium	<0.01	<0.01	<0.01	<0.01	<0.01
Calcium	51.2	32.0	9.23	23.1	75.2
Copper	0.0102	0.0191	0.00886	0.0143	0.0619
Magnesium	1.84	0.388	0.153	0.824	3.30
Zinc	<0.1	<0.1	<0.1	0.11	0.170

TABLE 3

AVERAGE PRODUCTION RATES (mg/m^2/wk) FOR PIT #3

Parameter (mg/m^2/wk)	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
pH (units)	7.25	6.95	7.28	6.43	7.20	7.00
Particulates	878	1060	1250	3930	821	622
Alkalinity	85.5	276	252	21.4	118	62.6
Acidity	2.14	2.47	2.15	8.23	1.36	21.6
Sulfate	181	122	334	2670	200	195
Silicate	$<$0.3	$<$1.0	$<$0.9	$<$0.6	$<$0.3	$<$0.8
Nitrate	0.407	0.00823	1.53	0.360	0.168	0.0807
Aluminum	$<$0.06	$<$0.3	$<$0.2	$<$0.12	$<$0.06	$<$0.16
Cadmium	$<$0.003	$<$0.014	$<$0.008	$<$0.006	$<$0.003	$<$0.008
Calcium	98.1	214	249	69.1	127	40.8
Copper	0.0086	0.0211	0.0244	0.308	0.0423	0.881
Magnesium	17.3	28.7	44.2	525	21.0	51.5
Manganese	0.0149	0.109	0.0346	2.10	0.0522	0.0384
Molyb.	0.240	$<$0.04	0.356	0.038	0.00828	$<$0.025
Potassium	1.97	$<$3.0	2.31	3.80	1.09	$<$3
Sodium	1.28	$<$3.0	2.45	4.18	1.21	$<$3
Strontium	0.929	0.840	1.46	0.563	1.45	0.344
Zinc	0.0061	0.00829	0.00712	0.0915	0.00219	0.0174

rate of sulfide oxidation, ranges from 3.61 to 2670 mg SO_4/m^2/wk, or almost three orders of magnitude. The rate of zinc production, which indicates its leaching from the rock surfaces, ranges from 0.0022 to 3.87 mg Zn/m^2/wk. Detectible production rates for nitrate are apparently derived from blasting residue. For Pit #3 (Table 3), the production rates for particulates represent physical weathering of the rock surface and the average rate of 1710 mg/m^2/wk corresponds to an erosional rate of roughly 3×10^{-5} m/yr on the rock surface based on a specific gravity of 2.7. This rate of physical weathering is generally equivalent to the rate of chemical weathering defined by the sum of all dissolved-parameter production rates.

For Pit #2, the average sulfate production rate from the in-field MINEWALL Stations was 77.7 mg SO_4/m^2/wk. There were also a series of laboratory-based humidity cells and columns operated for this pit, yielding an average weight-based rate of 367 mg SO_4/kg/wk with an average grain-surface area of 4.9 m^2/kg. A conversion of the average laboratory weight rate to a surface-area rate leads to 75 mg SO_4/m^2/wk, which is within 4% of the average field rate. This agreement suggests that laboratory tests can substitute for Stations if particle-surface area in the laboratory test is known.

TABLE 4

AVERAGE PRODUCTION RATES (mg/m^2/wk) FOR UNDERGROUND MINE #1

Parameter (mg/m^2/wk)	Station 1	Station 2	Station 3	Station 4
pH (pH units)	5.00	6.39	4.49	5.83
Alkalinity	3.87	52.6	0	199
Acidity	1.62	3.94	27.6	19.6
Sulfate	6.65	6.75	35.3	3.61
Nitrate	0.0321	0.105	0.059	0.0785
Aluminum	0.0937	0.00783	1.96	0.434
Antimony	0.00019	0.00062	0.000217	0.00151
Barium	0.0122	0.0708	0.0260	0.0288
Cadmium	0.0054	0.00486	0.0374	0.0288
Calcium	3.55	34.2	9.08	123
Chromium	0.0012	0.00213	0.00260	0.00251
Copper	0.0191	0.0154	1.40	0.462
Iron	0.0212	0.0113	0.0517	0.192
Lead	0.00950	0.00276	0.00816	0.0342
Magnesium	0.242	1.53	0.985	9.91
Manganese	0.0251	1.03	0.138	0.818
Molybdenum	0.00528	0.00021	0.0000204	0.0000174
Nickel	0.00300	0.00687	0.00752	0.300
Potassium	0.222	0.228	0.0066	0.355
Selenium	$<$0.003	$<$0.0007	0.000479	0.000407
Silver	$<$6E-06	0.0000355	0.000019	8.14E-6
Sodium	0.389	0.9	1.02	1.98
Strontium	0.0193	0.178	0.0483	0.110
Zinc	0.0733	0.220	3.19	2.68

3.2 Total Reactive Surface Area in a Mine

Once the unit-surface production rates are known (Section 3.1), the total reactive surface area in a mine must be determined. This area, when combined with the rates and the reaction-product retention and flushing (Section 3.3), provides the release rate of Equation 5 which in turn leads to the MW_x factors needed in Equations 2 and 3 for minewater predictions.

Sulfide oxidation and metal leaching can occur on fracture surfaces up to roughly 10 m behind the mine walls based on a few studies (Morth et al., 1972) and on unpublished observations of pit-wall collapse and pushbacks. As a result, each 1 m^2 of minewall can be associated with tens to hundreds of m^2 of reactive rock-surface area (Figure 4). While the concept is simple, an accurate estimation of fracture occurrence surface area is very difficult even with costly meter-by-meter studies (summarized in Hutt and Morin, 1994). Therefore, rough visual estimates using the concept in Figure 4 must suffice at this time.

For the three pits in Tables 1 to 3, the rough estimates of the ratio of reactive surface to visible mine wall range from 27:1 to 133:1 (Table 5). The total reactive surface based on these ratios and the dimensions of the pits leads to total reactive surface areas of tens to hundreds of millions of m^2.

3.3 Reaction-Product Retention and Flushing

The final step in solving Equation 5 and then Equations 2 and 3 lies in the concept of retention and flushing of reaction products from the rock surfaces. As with mine-rock dumps and dams, there are various forms of physical and geochemical retention of reaction products on minewall surfaces (Morin et al., 1995b, these proceedings).

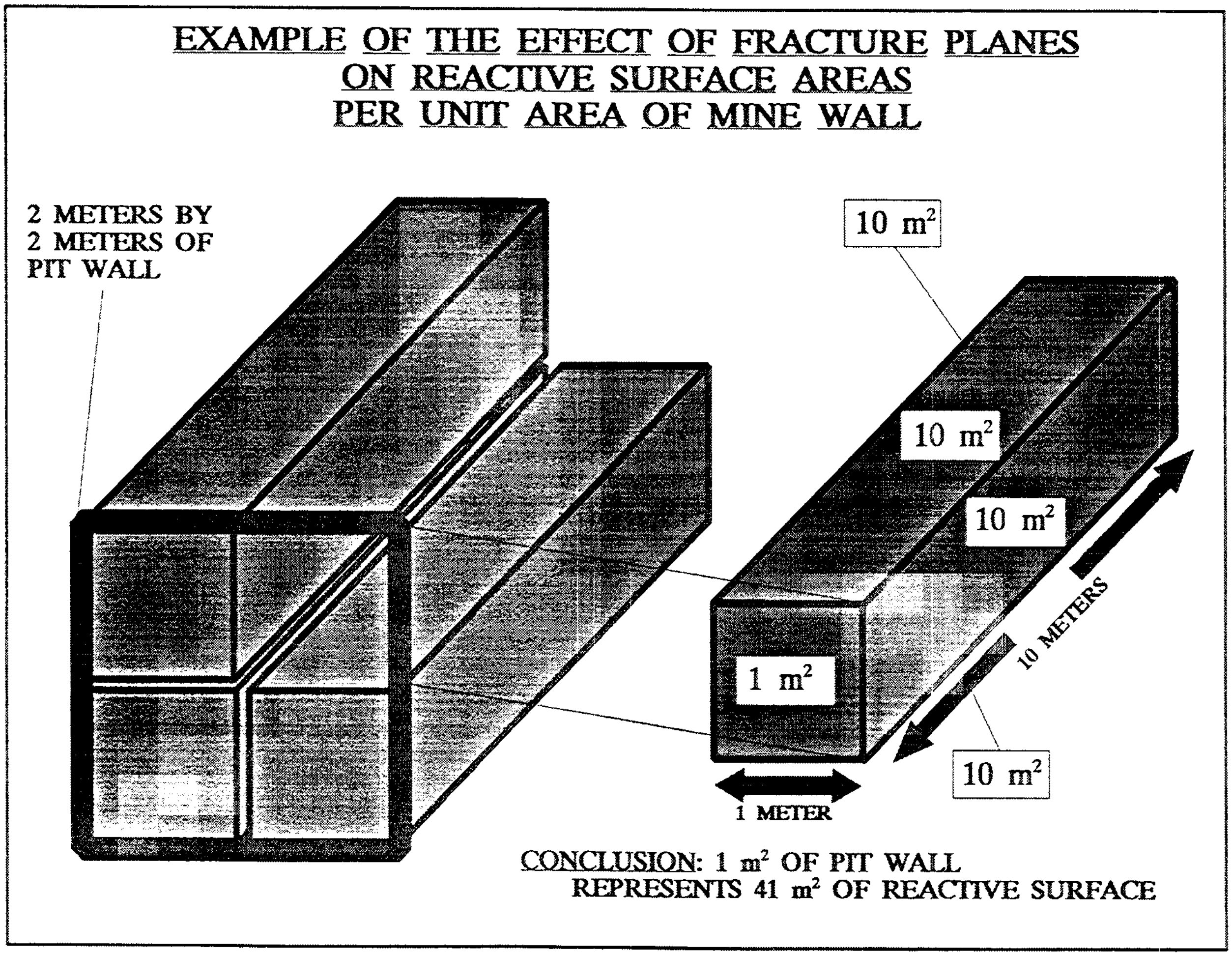

FIGURE 4. Schematic Effect of Fracture Planes on Reactive Surface Area Per Unit Area of Mine Wall.

TABLE 5

REACTIVE SURFACE AREAS AT THREE OPEN-PIT MINES

Pit	Reactive Surface : Visible Surface	Total Reactive Surface (m^2)
#1	33:1	24,000,000
#2	161:1	244,000,000
#3	27:1	10,500,000

At this point, the mechanisms of retention are not important, but the occasional removal ("flushing") of the retained products is critical in predicting release rates through time (Equation 5). There are three basic modes of flushing, defined by Morth et al. (1972) as *trickle*, *leaching*, and *inundation*, which are simplified in MINEWALL to *regular flushing*, *periodic flushing*, and *not during operation*. Regular flushing occurs as a result of normal movement of precipitation, runoff, and/or groundwater flow into and through a mine. Occasional repeating events such as major storms and snowmelt lead to periodic flushing. Finally, a portion of the retained products can only be removed by major flushing and submergence of the minewalls during Closure.

The percentage of retained reaction products that respond to the three modes of flushing can be estimated from operational monitoring data (Morin and Hutt, 1995); special field studies would be difficult and expensive. However, the case studies for MINEWALL show a relatively minor variation in the percentages (Table 6) so that these values can be assumed for proposed mines in lieu of operational data.

TABLE 6

PERCENTAGE OF REACTION-PRODUCT REMOVAL BY FLUSHING MODES

Flushing Mode	Pit #1	Pit #2
Regular	2%	2%
Periodic	28%	8%
Not During Operation	70%	90%
TOTAL	100%	100%

At this point, all requirements of Equations 2 through 5 have been met and thus these equations provide predictions of minewater chemistry through Operation and Closure. In Equations 2 and 3, MW_1 can now be defined as both regular and periodic flushing of reactive rock surfaces exposed to air. MW_2 (from submergence of rock surfaces) is the loading of reaction products not flushed during Operation. MW_3 represents any loading from submerged rock surfaces that may oxidize in contact with dissolved oxygen (e.g., Morin, 1993) or actively leach metals and nonmetals. Because of the potential complexity of some calculations, the MINEWALL 2.0 computer program was designed to guide and manage these simulations.

4. Conclusion

This paper has summarized many of the points in the MINEWALL technique and computer program for estimating minewater concentrations during Operation and Closure. There are other factors not addressed in detail here, such as the exposure of both acid-generating and acid-neutralizing rock types on the walls of a mine and the eventual depletion of metals on stable walls. The reports by Morin and Hutt (1995) should be consulted for detailed information on other potential complexities.

5. References

Jambor, J.L., and D.W. Blowes, eds. 1994. The Environmental Geochemistry of Sulfide Mine-Wastes. Mineralogical Association of Canada, Nepean, Ontario, Volume 22, May. 438 p.

Hutt, N.M., and K.A. Morin. 1994. Assessment of the Underground Disposal of Tailings. AECB Report 5.147.1.

Morin, K.A. 1993. Rates of sulfide oxidation in submerged environments: Implications for subaqueous disposal. Proceedings of the 17th Annual Mine Reclamation Symposium, Port Hardy, British Columbia, May 4-7, p.235-247. Mining Association of British Columbia.

Morin, K.A. 1990. Acid Drainage from Mine Walls: The Main Zone Pit at Equity Silver Mines. British Columbia Acid Mine Drainage Task Force Report. 109 p.

Morin, K.A., and N.M. Hutt. 1995. MINEWALL 2.0: Literature Review, Conceptual Models, User's Guide, and Programmer's Notes. MEND Reports.

Morin, K.A., N.M. Hutt, and K.D. Ferguson. 1995a. Measured rates of acid generation and neutralization in kinetic tests: Statistical lessons from the database. IN: Proceedings of the Conference on Mining and the Environment, Sudbury, Ontario, May 28-June 1.

Morin, K.A., N.M. Hutt, and R. McArthur. 1995b. Statistical assessment of past water chemistry to predict future chemistry at Noranda Minerals' Bell Mine. IN: Proceedings of the Conference on Mining and the Environment, Sudbury, Ontario, May 28-June 1.

Morin, K.A., E. Gerencher, C.E. Jones, and D.E. Konasewich. 1991. Critical Literature Review of Acid Drainage from Waste Rock. Canadian MEND Report 1.11.1, CANMET, Government of Canada, Ottawa.

Morin, K.A., N.M. Hutt, and I.A. Horne. Submitted. Onset of acidic drainage from a mine-rock pile, British Columbia, Canada. Submitted to the Journal of Applied Geochemistry.

Morth, A.H., E.E. Smith, and K.S. Shumate. 1972. Pyrite Systems: A Mathematical Model. Contract Report for the U.S. Environmental Protection Agency, EPA-R2-72-002.

Ross, A., S. Matte, and F. Belle-Isle. 1994. Monitoring the Solbec pit: first year observations. Preprint for the Third International Conference on the Abatement of Acidic Drainage, Pittsburgh, Pennsylvania, USA, April 24-29.

St-Arnaud, L.C., and S.R. Aiken. 1991. Hydrogeology and geochemistry of the Brunswick Mining No. 6 open pit mine site. IN: Proceedings of the Second International Conference on the Abatement of Acidic Drainage, Montreal, Quebec, September 16-18, Volume 1, p.401-420.