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PREDICTION OF WATER CHEMISTRY IN OPEN PITS DURING OPERATION AND AFTER CLOSURE

Kevin A. Morin

Morwijk Enterprises Ltd.
47-115 Kamehameha Highway
Kaneohe, Hawaii, USA 96744
(address current to 2/28/94)

ABSTRACT

Environmental monitoring at minesites often focuses on tailings impoundments and mine-rock piles. While these components may produce the greatest impacts on water chemistry at a minesite, the mine itself, consisting of an open pit or underground workings, can also affect water chemistry if the walls of the mine expose rock that releases metals, nonmetals, and acidity.

During mining of an open pit or underground workings, all water is typically pumped or drained from the mine to maintain optimum and safe working conditions. After closure, a mine is usually allowed to fill through time to its equilibrium level, or it may be flooded by directing water into it. The ability to predict the chemistry of the minewater during these phases of operation and closure can be valuable for potential treatment costs, engineering design, and closure bonding.

In order to predict minewater chemistry, conceptual models have been developed to address water movement to and from mines during operation and closure. The relevant geochemical aspects of unit-rock-surface reaction rates and total amount of reactive rock surface in a mine are then addressed. The compilation of these models and factors forms the basis of the MINEWALL computer program, which is currently being revised, expanded, and tested as Version 2.0. MINEWALL shows that a key factor in predicting minewater chemistry is the estimation of percentages of reactive surface that are flushed regularly, once a year, or not during operation. However, direct measurement of these percentages is not currently possible. Consequently, MINEWALL can be first calibrated to operational data to obtain the percentages and then used in predictive mode for the remainder of operation and subsequent closure.

Data from three mines in British Columbia show, for example, that (1) total reactive surface areas can range from tens of millions to hundreds of millions of square meters, (2) the percentage of these surfaces not flushed during operation range from 70 to 90%, and (3) unit-area leaching rates of copper range from 0.014 to 2.35 mg Cu/m²/wk.

KEYWORDS: acidic drainage, open pit mines, geochemical predictions, hydrogeology

1. INTRODUCTION AND OBJECTIVES

Environmental monitoring at minesites often focuses on tailings impoundments and mine-rock piles (e.g., Morin and Hutt, 1994). However, the mine itself, consisting of an open pit or underground workings, can also affect water chemistry if the walls of the mine expose rock that releases metals, nonmetals, and acidity.

During mining of an open pit or underground workings, all water is typically pumped or drained from the mine to maintain optimum and safe working conditions. After closure, a mine is usually allowed to fill through time to its equilibrium level, or it may be flooded by directing water into it. The ability to predict the chemistry of the minewater during these phases of operation and closure can be valuable for potential treatment costs, engineering design, and closure bonding.

This paper first presents the conceptual models on which the computer program, known as MINEWALL, is built. For the purposes of this paper, the discussion is limited to open pits only. Secondly, monitoring data at three pit mines in British Columbia are presented to support the approach and to illustrate MINEWALL's application. This paper is based on past and ongoing studies sponsored by the Canadian Federal Mine Environment Neutral Drainage (MEND) Program, the British Columbia AMD Task Force, BHP Minerals' Island Copper Mine, Noranda Minerals' Bell Mine, and Placer Dome's Equity Silver Mines.

2. CONCEPTUAL MODELS OF THE MINEWALL APPROACH

2.1 Physical Aspects

Based on a review of pertinent literature and applicable hydrogeologic principles (Morin, 1990), a generalized conceptual model of surface-water and groundwater movement in and around an operating open pit can be defined (Figure 1). This model includes precipitation and subsequent evaporation. Surface flow consists of runoff over the walls and benches, which is augmented by any seeps discharging from the pit walls. The seeps in fact represent an interaction of groundwater (discussed below) and surface water, and from a chemical perspective can be indicative of geochemical processes operating behind the walls (discussed later).

Any precipitation infiltrating into the ground becomes "unsaturated groundwater flow". Some percentage of this unsaturated flow will eventually discharge from pit walls as seeps and thus can be accounted for as runoff. The remainder can be expected to eventually reach the water table and join the regional "saturated" flow system which extends to the pit.

In addition to the above "inputs" of water, there are obviously "outputs" during operation which prevent flooding. The important "outputs" during operation are usually (1) pumping or gravity drainage of water and (2) evaporation.

As with any conceptual model, there is a myriad of variations. For example, Figure 1 shows the water table joining the pit near its base, whereas Lopaschuk (1979) reported a drawdown of only 10 m in a 90 to 150 m-deep pit. Also, Kipp et al. (1983) reported on pits located above the water table so that no groundwater flow from the saturated zone reported to them. These pits then contained an "output" of gravity drainage to the deeper saturated zone. Consequently, Figure 1 is considered sufficiently general and flexible in nature to describe most pit mines. The computer-based MINEWALL program simply requires that each flow shown in Figure 1 be identified and monitored at a site. The flows, which can vary with time, are then entered as positive or negative values.

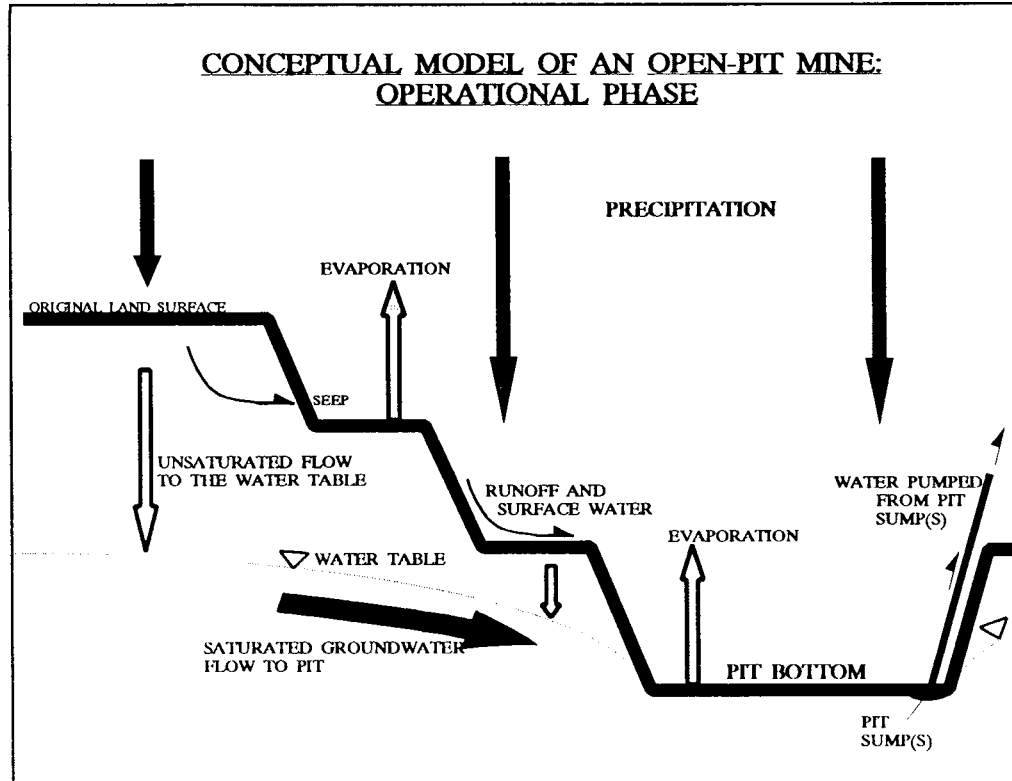


FIGURE 1. Conceptual MINEWALL model of water movement in and near pit walls during operation.

Upon cessation of mining and initiation of closure, pit pumps will be turned off and gravity drainage may be halted. This causes the water level in a pit to rise out of the sump(s), cover the pit bottom, and progressively submerge the walls. As an example, Davis and Ashenberg (1989) reported that the water level in the large Berkeley Pit in Montana was rising 22 m a year and that total water storage was expected to reach 5×10^8 m³ of acidic water. Filling of a pit can be accomplished through natural processes (Figure 2) or enhanced by pumping of water into the pit (Figure 3). The "assisted" pumping of Figure 3 may reflect the intent to quickly submerge the pit for water-quality control or may reflect the intent for long-term storage of acidic or metal-laden water until treatment can begin.

The primary difference between natural and assisted filling during closure lies in the local direction of groundwater movement near the pit. Because the quality of water contacting the wall rock could be degraded, the direction of local groundwater movement would thus determine whether this affected water would directly enter the pit or be temporarily carried away from the pit to a temporary stagnant zone in the system.

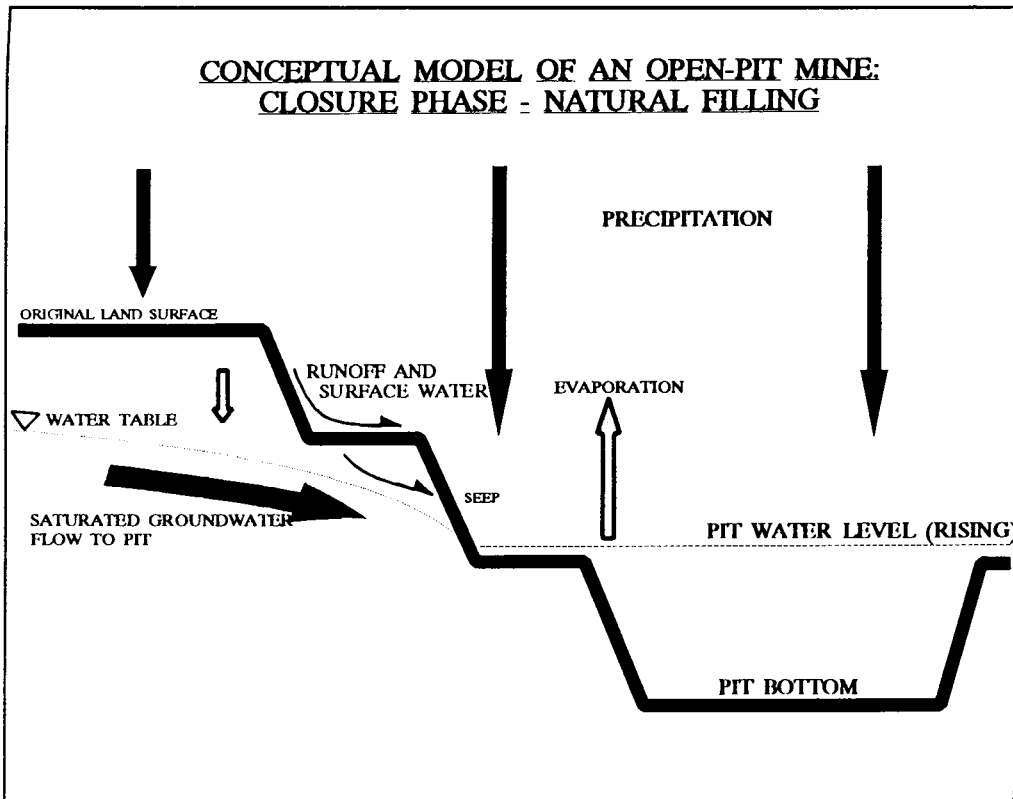


FIGURE 2. Conceptual MINEWALL model of pit filling by natural processes during closure.

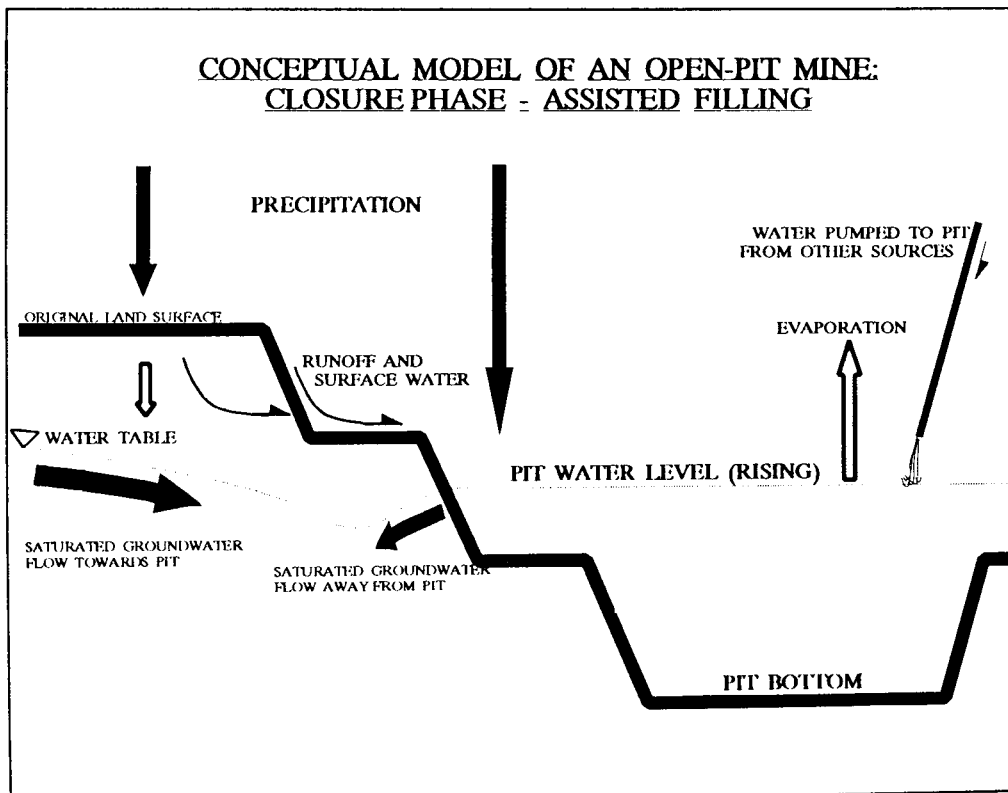


FIGURE 3. Conceptual MINEWALL model of pit filling by assisted methods during closure.

As the input of water continues, the water level rises until an equilibrium or "static" level is attained (Figure 4). At that point, the rate of water entering the pit is generally balanced with water leaving the pit, and the water level remains relatively steady from year to year. However, an equilibrium level is only meant in a general sense, and some season-to-season and year-to-year variations can be expected. As with the operational phase (Figure 1), there is a myriad of variations. Nevertheless, Figures 2 through 4 are considered sufficiently general and flexible in nature to describe most mines during closure. The MINEWALL program simply requires that each flow shown in Figures 2-4 be identified and monitored at a site. The flows, which can vary with time, are then entered as positive or negative values.

For the MINEWALL program, the flows associated with the arrows of Figures 1 through 4 should be known or estimated for proper calculations and simulations. However, because of mass-balance relationships, the flow associated with one arrow can be estimated if all other flows are known. MINEWALL 2.0 will calculate the uncertain flow if desired.

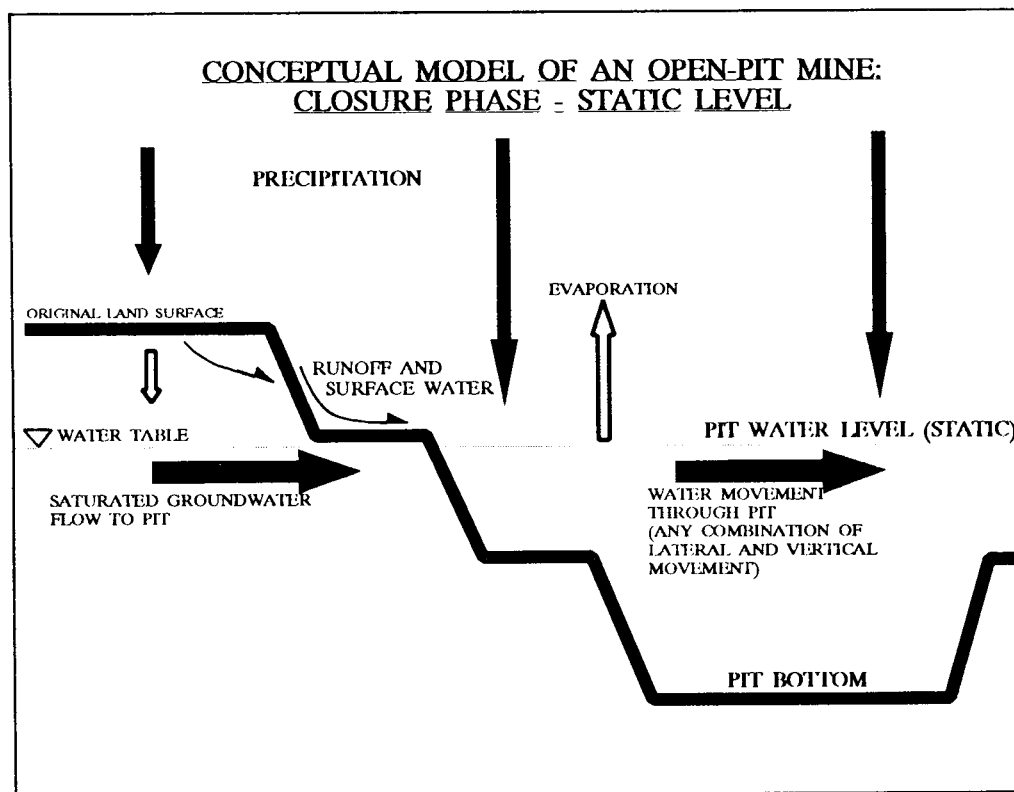


FIGURE 4. Conceptual MINEWALL model of a pit filled to its Static Level.

2.2 Geochemical Aspects

Since pit walls are composed of rock, they may contain minerals capable of releasing metals and nonmetals to water passing over their surfaces. Acid generation and metal leaching can occur on the surfaces, or outer boundaries, of rock particles and fracture planes, as well as within grains or blocks of rock. Consequently, there are two localities where the geochemical reactions take place: *surficial* and *internal* relative to the smallest divisible particle or block at a site (Figure 5). The overall effects of surficial reactions are generally a function of exposed surface area relative to the water volume, whereas the effects of internal reactions are functions of exposed surface area, distance to the center of a grain, and the volume of the grain relative to the water volume. Perhaps due to practicality and ease, surficial reactions seem to be more often addressed in field-oriented studies (e.g., Morth et al., 1972), whereas internal reactions appear more often in theory-oriented studies (e.g., Cathles, 1982).

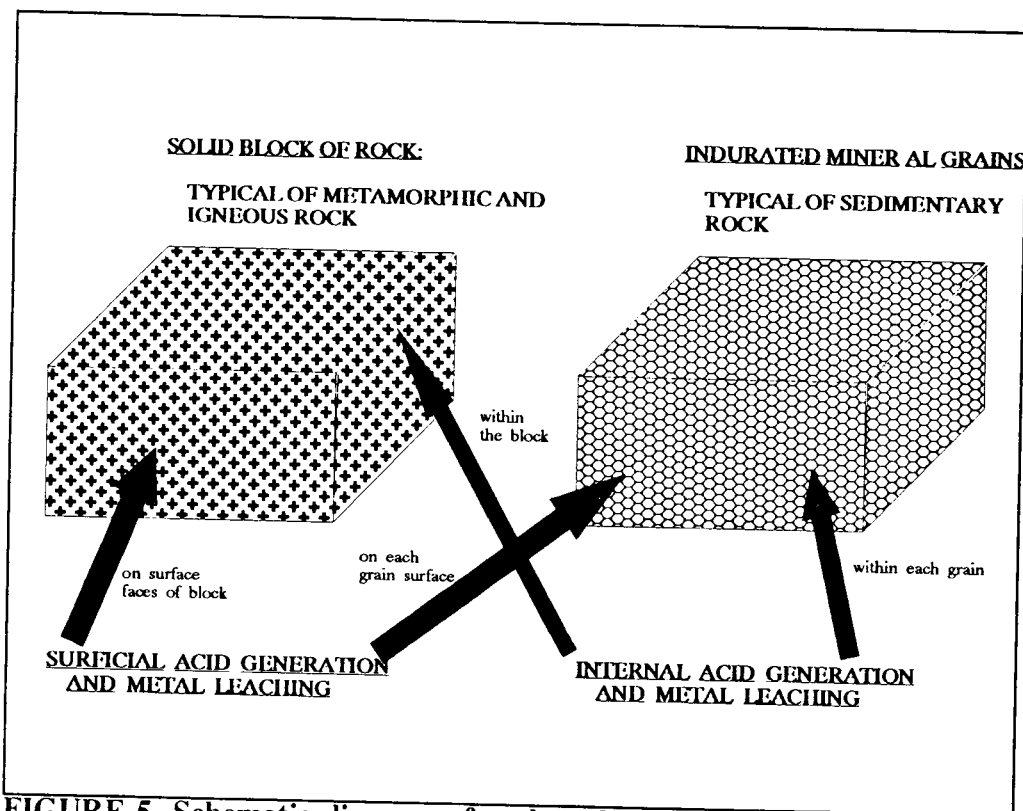


FIGURE 5. Schematic diagram of rock and mineral surfaces in various rock types.

In "soft-rock" mines such as bituminous coal, the rock is typically composed of indurated mineral grains which can have relatively high grain-surface areas per unit weight of rock (Figure 5). In "hard-rock" mines such as silicified copper, the fracture surfaces along which the rock has broken into blocks will provide the exposed area for minerals, and this area will often be less per unit weight than for soft rock. For this reason, soft-rock pits may have a greater impact on their water chemistry; however, other factors can affect this ranking as discussed below.

For the MINEWALL studies to date, only hard-rock pits have been examined and these pits typically have relatively large blocks of rock. Therefore, the current work focuses on surficial, rather than internal, reactions, and the empirical surficial reactions are simply addressed by isolating portions of rock surfaces in the pits for monitoring (discussed later). Nevertheless, Version 2.0 of the computer program will allow the alternative use of some theory and internal reactions as options.

After geochemical reaction rates are obtained for unit surface areas, the major issue in MINEWALL becomes the amount of rock surface that is reactive. A first impression might be that the total reactive surface is equal to the exposed walls of a pit. However, the fractures that are inevitably present in pit faces provide additional reactive surfaces. Morth et al. (1972), for example, found reactive fracture surfaces that extended as far as 15 m from the mine wall. Also, visual observations by the author at a mine in British Columbia during a pushback of a pit wall revealed fractures oxidized as far back as 10 m from the wall. Consequently, the fracture surfaces behind the mine walls can provide a much greater reactive surface than that indicated simply by the exposed walls. As a numerical example, a pit wall that has (1) spacings for vertical and horizontal fractures of 1 m and (2) oxidation occurring to 10 m behind the wall will have 41 m² of reactive surface for each square meter of exposed wall (Figure 6).

For rock with ongoing sulfide oxidation, acid generation, and metal leaching, the products of these reactions usually remain in a relatively soluble form on the rock surfaces. These products will only be removed from the surfaces if water contacts and carries them away. For ease of calculations, MINEWALL assumes that during operation (Figure 1) certain

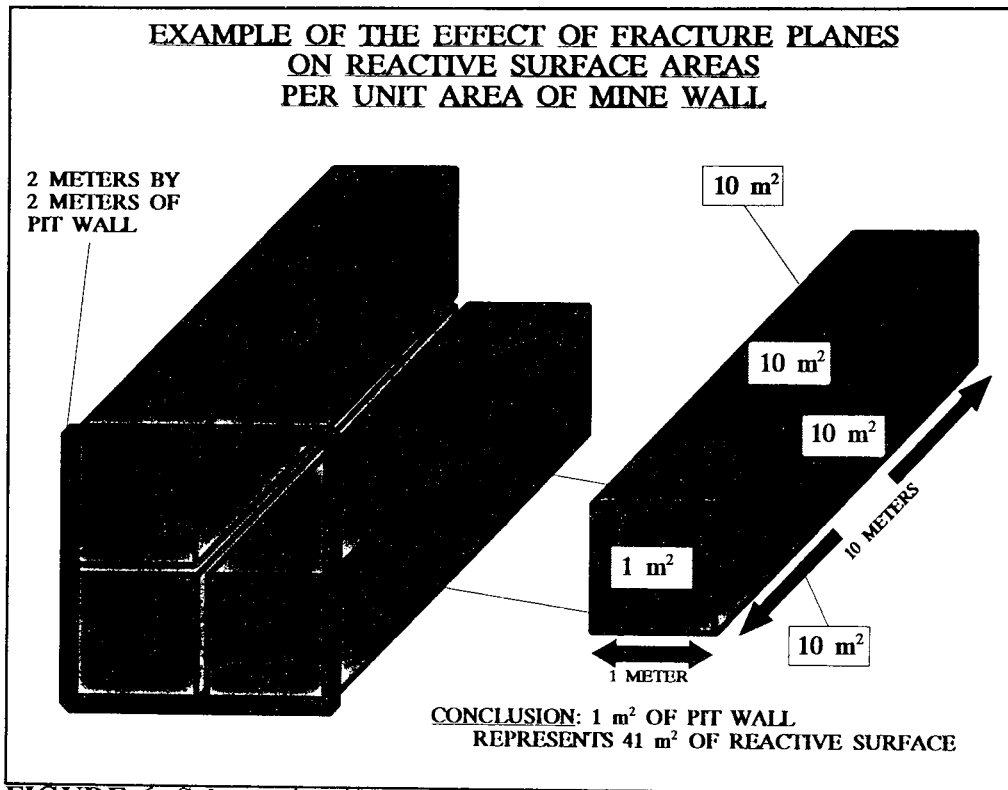


FIGURE 6. Schematic effect of fracture planes on reactive surface area per unit area of mine wall.

percentages of the total reactive rock surfaces are flushed (1) regularly by precipitation, condensation, etc., (2) once a year such as during snowmelt or a high-precipitation week, and (3) not at all during operation. During closure (Figures 2 and 3), the third category can have a significant effect on water chemistry as pit-water levels rise and flush up to decades of accumulated reaction products from the surfaces. During and after closure (Figures 2-4), the first two categories can affect pit-water chemistry on an ongoing basis from the pit walls that remain exposed.

2.3 The MINEWALL Program

The preceding concepts were first developed as part of the original MINEWALL study, based on the findings of a literature review and a field study at Equity Silver Mines in British Columbia (Morin, 1990). The corresponding computer program, MINEWALL Version 1.0, was written in Fortran and included a preprocessor to assist with data input. However, the program had site-specific coding that limited it to Equity Silver, and was not fully tested and verified.

A current contract for MINEWALL Version 2.0 is now underway. Version 2.0 is written in Visual Basic 1.0 for DOS and includes standard pull-down menus, push buttons, and dialog boxes. The program will also be well tested, verified, and documented. The philosophy behind Version 2.0 is that there are many variations on concepts and approaches, and that many useful options and alternatives should be included to provide flexibility in site-specific simulations and planning. This contrasts with the other common approach to modelling which provides only one equation and approach for the simulation of a particular concept.

3. EXAMPLES OF MINEWALL-BASED STUDIES

At this time, the most detailed and best documented of the MINEWALL-based studies is the simulation of the Main Zone Pit at Equity Silver Mines. Values of all parameters discussed in Section 2 were based on measured data or estimated from related data (Morin, 1990). Some input data are reproduced in Table 1.

The major parameter that could not be estimated or measured was the percentages of rock surfaces that were flushed regularly, once a year, or not during operation (discussed at the end of Section 2.2). Consequently, these percentages were obtained by calibrating MINEWALL to operational conditions and adjusting the percentages until reasonable matches to operation water chemistry were obtained. For example, an unreasonably high percentage of frequently flushed and yearly flushed surfaces created anomalously low pH values in the pit sump, which had never been measured. Conversely, an unreasonably low percentage created anomalous, continually alkaline pH values, which did not mimic the periodic flushing of accumulated reaction products. The best-fit calibration indicated that 70% of the rock surfaces were not being flushed during operation (Table 1).

After the calibration to operational data, MINEWALL was then used in predictive mode for closure. The simulations indicated there would be an initial flushing of accumulated acidity, depressing pH to below 6.0, but the pH would afterwards recover and remain alkaline (Figure 7). As a result, the estimated 70% of reactive surfaces that had accumulated reaction products year after year were not flushed at a sufficient rate by the slowly rising pit-water level to offset

TABLE 1

PARTIAL INPUT DATA FOR THE SIMULATION OF THE
MAIN ZONE PIT AT EQUITY SILVER MINES (Morin, 1990)

PARAMETER	ROCK UNIT #1	ROCK UNIT #2	ROCK UNIT #3
Rock Type	Gabbro	Volcanics	Volcanics
NNP from Acid-Base Accounting (t CaCO ₃ /1000 t)	NNP > 0.0	-40 < NNP < 0.0	NNP < -40
Orientation on Pit Wall	Vertical	Vertical	Vertical
Exposed Surface Area (m ²)	315,000	234,000	214,000
Sloping Walls - Percentage of Total Area	35%	35%	35%
Sloping Walls - Angle from Horizontal (degrees)	70	70	70
Exposed Acid-Generating Sulfur (g S/m ²)	48	64	144
Exposed Neutralization Potential (g CaCO ₃ /m ²)	225	100	25
Reactive Surface (m ²) for Each m ² of Pit Wall	21	41	41
Fracture Flushed*: - percentage flushed monthly	28%	28%	28%
- percentage flushed once a year	2%	2%	2%
- percentage not flushed during operation	70%	70%	70%

* These best-fit values were obtained from calibration: see text.

the alkalinity brought into the pit by saturated groundwater flow (Morin, 1990).

Since the original study at Equity Silver Mines, two other open-pit mines have initiated data collection for simulations by MINEWALL Version 2.0. These mines are BHP Minerals' Island Copper Mine (Morin et al., 1994a) and Noranda Minerals' Bell Mine (Morin et al., 1994b). Island Copper has the greatest estimated reactive area of the three sites (Table 2).

Island Copper Mine has been gathering MINEWALL-related data over one year. Preliminary results show that a higher percentage of reactive surfaces relative to Equity Silver have not been flushed during operation (Figure 8). However, unit-area metal leaching rates are generally

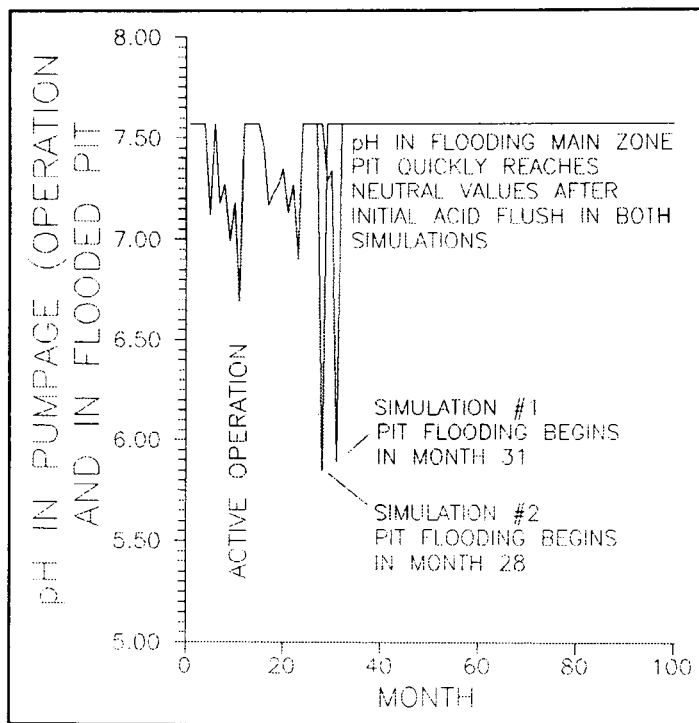


FIGURE 7. Best-fit simulation of pH in the Main Zone Pit During operation and decommissioning (from Morin, 1990).

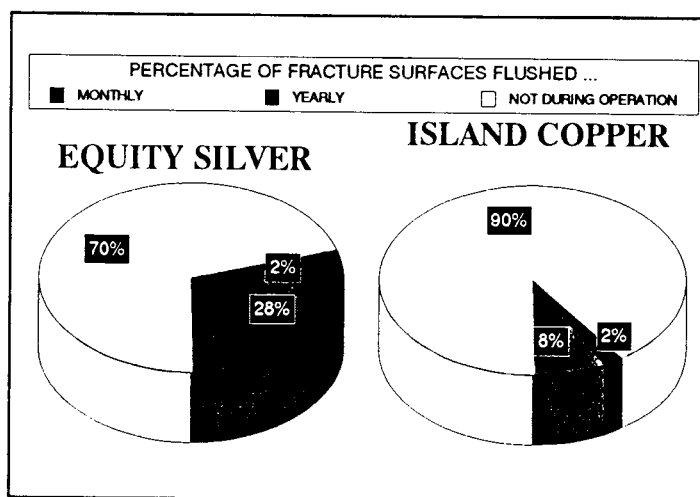


FIGURE 8. Comparison of reactive-surface flushings at Equity Silver and Island Copper Mines.

TABLE 2		
COMPARISON OF TOTAL REACTIVE SURFACE AREAS AT THREE MINES		
<u>MINE</u>	<u>REACTIVE SURFACE : EXPOSED SURFACE</u>	<u>TOTAL REACTIVE SURFACE (m²)</u>
Main Zone Pit, Equity Silver Mines	33:1	24,000,000
Island Copper Mine	161:1	244,000,000
Bell Mine	27:1	10,500,000

TABLE 3		
COMPARISON OF SULFIDE-OXIDATION AND METAL-LEACHING RATES FROM PIT WALLS AT TWO MINES		
<u>PARAMETER</u>	<u>EQUITY SILVER</u>	<u>ISLAND COPPER</u>
Number of Wall Stations	3	5
Number of Wash Events	1	5
Sulfate Production (mg/m ² /wk)	49.7-133	7-127
Copper Leaching (mg/m ² /wk)	0.033-2.35	0.014-0.153
Zinc Leaching (mg/m ² /wk)	0.719-3.87	0.094-0.267

lower at Island Copper (Table 3). Meanwhile, data collection and interpretation continue at Island Copper and Bell Mines.

4. CONCLUSION

This paper has described the conceptual models and data requirements for simulating and

predicting minewater chemistry during operation and closure. From the physical perspective, the conceptual models address the various pathways of water movement to and from a pit that should be monitored or estimated for proper calculation of the water balance. From a geochemical perspective, unit-area reaction rates and total reactive surface area should be obtained. All of the conceptual models are being coded into the MINEWALL Version 2.0 computer program at this time.

Previous work and results of Version 1.0 simulations indicated the percentages of reactive surface flushed regularly, once a year, and not during operation can be obtained through calibration to existing operational data. After calibration, MINEWALL can then be used in a predictive mode to estimate chemistry during later operation and closure. Preliminary data from minesites reveal most reactive surfaces are not flushed during operation. As a result, these surfaces accumulate reaction products year after year, awaiting flooding to release the products to the minewater.

Data collection and interpretation for the MINEWALL project continue.

'Ua mau ke ea o ka 'āina i ka aloha 'āina

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