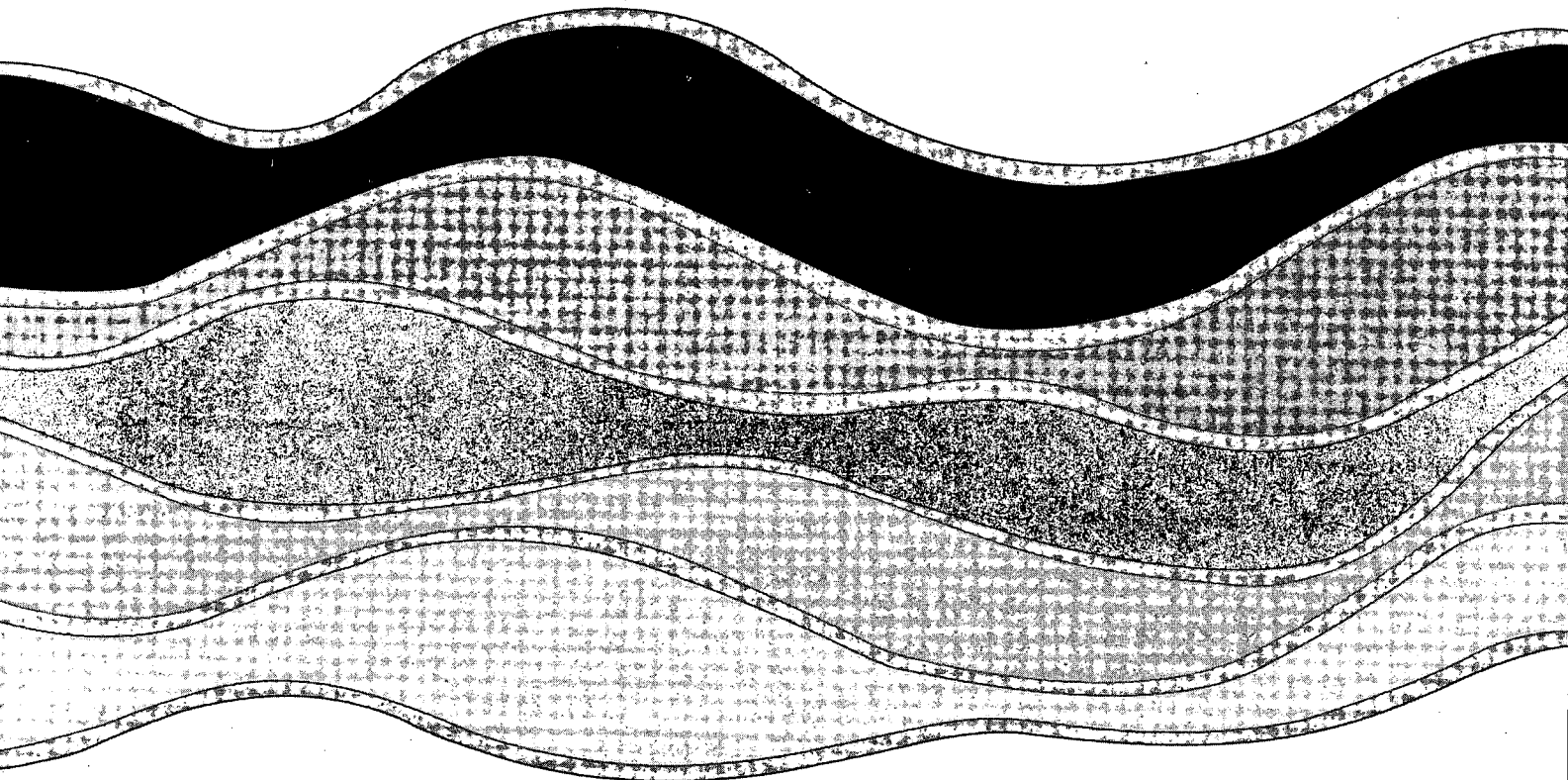
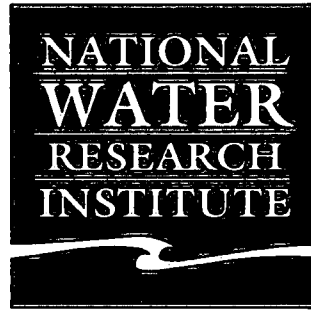


94-04

CCIW
FEB 21 1995
LIBRARY



**POTENTIAL USE OF CROWN PILLAR PIT
IN A DEMONSTRATION PROJECT OF
THE FEASIBILITY OF SUBAQUEOUS
DISPOSAL OF ACID GENERATING
METAL MINE TAILINGS**

P. Brassard and A. Mudroch

NWRI Contribution No. 94-04

TD
226
N87
No. 94-
04
c.1

**POTENTIAL USE OF CROWN PILLAR PIT IN A DEMONSTRATION PROJECT OF
THE FEASIBILITY OF
SUBAQUEOUS DISPOSAL OF ACID GENERATING METAL MINE TAILINGS**

Pierre Brassard

**Department of Chemistry
McMaster University, Hamilton, Ontario**

and

Alena Mudroch

**Lakes Research Branch
National Water Research Institute
Burlington, Ontario**

NWRI Contribution No. 94-04

Abstract

A simple model is proposed to predict the rate of oxidation of metal mine tailings disposed on the bottom of a meromictic pit at a mining site near Ignace, Ontario. The consumption of oxygen in the pit water by disposed tailings is limited by diffusion across the thermocline, and can only reach a maximum value depending on the depth and morphometry of the pit. The standard acid-base accounting method is used to characterize the neutralization potential of the disposed tailings. Theoretical calculation shows that the amount of calcite needed to neutralize the generated acid by oxidation of the tailings has to be considered, and is related to the desired ambient pH.

The oxidation of the tailings on the bottom of the pit with subsequent acid generation does not depend on the amount of disposed tailings because the oxygen flow towards the bottom of the pit is limited. It was calculated that the tailings on the bottom of the pit would generate the acid equivalent of 87 Kg of calcite per year in water of pH 6. However, the neutralization potential of the tailing material increases with total amount of the disposed tailings. If the 25-m deep pit was filled to a depth of about 21 m, the amount of calcite in the tailings would be sufficient to neutralize the generated acid for a period of several thousand years. The disposal of the tailings thus appears to be practical and feasible as long as the meromictic character of the pit can be maintained.

Introduction

Many base, precious metal and uranium bearing ores with surrounding rock contain sulfide minerals. Tailings and waste rock generated by mining and extraction of metals and uranium from these ores contain different quantities of sulfides. During exposure to air and water, the water insoluble sulfides in the tailings and waste rock become converted to water soluble sulfates. These sulfates acidify surface and groundwater which is subsequently further contaminated by different metals and trace elements leached from the tailings and waste rock. Uncollected and untreated acid drainage can further contaminate surface and groundwater and negatively affect the receiving ecosystem.

For several past years, the Canadian mining industry, in cooperation with federal and provincial government agencies, has sponsored research of economical and environmentally safe disposal of acid generating mine tailings and waste rock. Results of the research indicate that the subaqueous disposal of acid generating mine tailings is a possible solution. However, some problems, such as the effects of tailings disposed of under water on benthic organism and other biota and food chain in the lake, remain to be solved before the technique for the subaqueous disposal of the tailings and waste rock can be accepted as the final solution for the prevention of acid mine drainage.

One of the major tasks in the subaqueous disposal of acid generating tailings and waste rock is to prevent oxidation of sulfides in disposed material with the subsequent migration of metals and trace elements into lake water. Consequently, ideal conditions for subaqueous disposal of tailings would be in a lake (or a man-made reservoir) with a sufficiently deep layer of anoxic bottom water containing high concentrations of sulfides and a sulfate-reducing microbial population to maintain an equilibrium between the sulfides in disposed tailings on the lake bottom and those in the overlying water. Natural meromictic lakes appear to be the water body satisfying these conditions.

A study was initiated at the National Water Research Institute to evaluate the economical and environmental feasibility of the disposal of acid generating mine tailings and waste rock into natural meromictic lakes and man-made reservoirs. The objectives of the study were following:

- To determine the biogeochemical processes in a meromictic man-made reservoir located at a particulate geological and climatic settings.
- To investigate the effects of the disposal of fresh (nonoxidized) and presently on-land disposed (oxidized) sulfur-containing mine tailings on the biogeochemistry of the meromictic man-made reservoir.

- To develop a model for the long-term management of a meromictic lake or man-made reservoir containing disposed acid generating mine tailings and waste rock on the bottom.

Data collected in spring, summer and fall of 1993 on water and sediment quality in two pits at a mining site near Ignace, Ontario, showed that one of the pits, the Crown Pillar pit, is a meromictic water body. Therefore the pit appears to be a suitable man-made reservoir for studies of the feasibility of subaqueous disposal of the tailings. In considering of a demonstration project involving disposal of land-based mine tailings into the Crown Pillar pit, the capacity of the pit to retain the tailings on the bottom under anoxic conditions needs to be assessed.

This report examines the possibility of confining acid-generating mine tailings and waste rock at the bottom of deep meromictic lakes or man-made reservoirs. The meromictic conditions occur when a lake is sufficiently narrow and deep to prevent any mixing of the bottom and surface waters. The result is a section of water above the bottom depleted of oxygen. Tailings deposited within this section would not become oxidized and generation of sulfuric acid generation would not occur. However, some minimal flow of oxygen to the section of the water near the bottom and a slow generation of acid in tailings disposed on the bottom would occur. Ideally, the amount of the acid should be sufficiently small to become absorbed safely in the lake's or reservoirs environment.

The purpose of this study is to estimate the capacity of a well characterized meromictic pit to contain acid-generating mine tailings, and to predict the changes that would occur in the tailings after their disposal into the pit. It is further planned to dispose metal mine tailings on the bottom of the pit and monitor the changes in the water quality in the pit and the geochemical changes in the tailings over certain time. However, a preliminary estimate needs to be made on the quantity of tailings disposed in the pit and on the rate at which they will become oxidize after their disposal.

The Crown Pillar pit

The Crown Pillar pit (Fig. 1) was dug out during the mining operations near Ignace, Ontario. The pit is about 300 m long and 180 m wide with a maximum depth of about 25 m, and is surrounded by bentonite dykes to prevent infiltration of acid drainage from the tailings stored on the adjacent land. Several profiles of pH, conductivity, temperature and concentrations of dissolved oxygen in the pit water were obtained in the spring and summer of 1993 to determine its meromictic character (Fig. 2). The results suggested that the water column in the pit can be separated into distinct layers. The first two metres of the surface water are well mixed by winds as indicated by the measured variables. The second layer, the thermocline, extends from 2 to about 8 m water depth, and shows a sharp decline of the temperature from about 9 to 4°C. The hypolimnion extends from the 8 m water depth to the bottom of the pit with a relatively constant temperature (Fig. 3).

The conductivity represents the sum of all dissolved chemical species in the water. In the Crown Pillar pit, the conductivity is high in the hypolimnion and decreases sharply in the thermocline. Meromictic lakes owe their stability to the density gradient between the hypolimnion and the upper layers of water. The increase in water density is caused by degradation of organic matter originating from primary production in the surface water or by dissolution of different minerals (Cole 1983). In the Crown Pillar pit, it is important to maintain this density gradient to prevent mixing the water by overturning with subsequent exposure of the hypolimnetic water to oxygen.

The profile of the concentration of dissolved oxygen in the pit waters is separated into two main regions (Fig. 3). The upper region, comprising the mixed water layer, and the thermocline contain an essentially constant concentration of oxygen with a maximum at the start of the thermocline. This behavior is called positive heterograde and results from oxygen saturation, and sometimes oversaturation, originating from an intense productivity of blue-green algae. The blue-green algae exist at a sufficient water depth to escape the turbulence of the mixed surfacial layer, but still get adequate light to be productive (Eberly 1964). Dubay and Simmons (1979) have observed a similar heterograde produced by macrophytes rooted at certain depth. Fry (1986) analyzed the food web at the top of the monimolimnion of a meromictic lake in the New York Finger Lakes, and concluded

that although most of the primary productivity was due to an intense layer of bacterioplankton, the remainder of the food web derived its nutrition from a mixture of terrestrial detritus, phytoplankton and littoral vegetation. At the Crown Pillar pit, there is little terrestrial detritus and no littoral vegetation. A food web in the pit is likely to be limited to one layer of autotrophic plankton coinciding with the oxygen maximum in the surface waters.

The second, or lower, region of dissolved oxygen concentration (Fig. 3) coincides with the hypolimnion and shows a steep decline in the oxygen concentration, levelling off to about 1 mg/L at around 12 m water depth. The decrease of the concentration of dissolved oxygen is most likely due to the oxygen consumption by bacteria in the water column or to the limitation of the flux of fresh oxygen from the surface through the thermocline. Analysis of the bottom sediments in the pit revealed small quantities of organic matter on the bottom of the pit. This finding indicates that the organic matter derived from the primary production in the surface waters is almost entirely mineralized before it reaches the hypolimnion. The increase in the concentration of dissolved oxygen at the heterograde is thus compensated by degradation further down in the surface waters in such a way that the compensation point for the primary production occurs at the start of the hypolimnion. Therefore it can be assumed that the only major source of oxygen for the hypolimnion comes from the surface and is not altered significantly by the

primary production. This assumption will be used as a starting hypothesis for the modelling of oxygen regime in the Crown Pillar pit.

The profile of pH in the Crown Pillar pit (Fig. 2) shows a profile similar to that of a hard water lake. The pH starts at around 8 in the surface water and drops to about 7.5 towards the bottom of the pit. The slight increase of pH at the surface of the pit is most likely due to the primary production which also creates the oxygen maximum (Fig. 2). The subsequent decrease of the pH at the bottom of the surface water layer should coincide with an increase in total inorganic carbon (not measured) that results from mineralization.

The oxygen model

The oxygen model is based on a simplifying assumption for the transfer of oxygen. During the winter, the pit is essentially closed by ice cover and oxygen source is negligible. The oxygen profile is low throughout the entire water column. In the spring when the ice melts and the entire pit is suddenly exposed to oxygen in the air diffusing from the surface water into the hypolimnion. Dissolved oxygen concentration in both the mixed surface water and the thermocline is deemed uniform because of mixing by wind. In addition, the primary production compensation depth is just above the hypolimnion. The problem can then be simplified to that of diffusion across an initially depleted semi-infinite hypolimnion

with oxygen concentration held constant at the boundary. This simplification thus requires that 1) the progression of oxygen in the hypolimnion be mainly limited by diffusion, which is a justifiable assumption since oxygen sinks for degradation are deemed small as explained above; and 2) the overlying waters act like an infinite supply of oxygen to the hypolimnion below; 3) there is no ice cover. The solution of such problem was already given by Crank (1975), and is as follows:

$$C - C_0 = \text{erfc} \left(\frac{z}{2 \sqrt{Dt}} \right) \quad (1)$$

where z is depth (m), D is diffusion coefficient (m^2/sec) and t is time (sec). The function erfc is the error function complement. Equation 1 is adjusted to the oxygen profile at station 3 in the Crown Pillar pit with D as the variable parameter (Fig. 4). With a diffusion time assumed to be 6 months since ice break, a best fit of the curve yields a value of $1.5 \times 10^{-7} \text{ m}^2/\text{sec}$. Such value compares favorably with the study of Quay *et al.* (1980) who determined a hypolimnetic advective coefficient of 1.7×10^{-7} . It is 2 orders of magnitude greater than the corresponding molecular diffusion of about $1 \times 10^{-9} \text{ m}^2/\text{sec}$. This shows that the transfer of oxygen is controlled by advective diffusion and that our initial assumptions are valid for the meromictic Crown Pillar pit. Since the concentration of dissolved oxygen in the surface water is known from solubility tables and temperature, the maximum consumption of oxygen from the tailings disposed on the bottom of the pit can be determined from the thickness of the hypolimnion. This is the steady state model.

The steady state model

This model examines what happens to the concentration profile of dissolved oxygen when the disposed tailings exert a steady oxygen demand at the bottom of the pit. We are only interested in the long-term solution when the oxygen profile becomes constant. At that time the total flow of oxygen at any depth is a constant, and is equal to the demand at the bottom. According to the above, we assume a constant diffusion coefficient of $1.7 \times 10^{-7} \text{ m}^2/\text{sec}$. Therefore at any depth the flux follows Fick's law:

$$F = -D \frac{dC}{dz} \quad (2)$$

However, at steady state, the flow is constant throughout and equals flux multiplied by surface area:

$$F(z) A(z) = C_{ste} - D A(z) \frac{dC}{dz} \quad (3)$$

Where $F(z)$ is flux at depth z ($\text{g} \cdot \text{m}^2 \cdot \text{sec}^{-1}$); $A(z)$, the area of the pit at depth z (m^2) and R_0 (g/sec) is the oxygen consumption resulting from the oxidation of some tailings at the bottom. Following the previous discussion the model assumes a uniform mixed layer with oxygen concentration of C_0 above the hypolimnion. The solution is:

$$-\frac{C_{ste}}{D} \int_{z_0}^z \frac{1}{A(z)} dz = C - C_0 \quad (4)$$

where z_0 is depth at the top of the hypolimnion (m). The function $A(z)$ is evaluated using a cubic interpolation of bathymetry readings (Fig.5). Surface area decrease in a quasi linear way to the bottom, probably a consequence of the excavating process in the pit since the earth-moving equipment could not operate past a certain slope. We can imagine that the amount of earth removed at each successive level is smaller than the previous one by a fixed amount, i.e. the amount of earth necessary to hold the equipment on the rim. If this assumption is true, the linearity between the surface area and depth can be expected for most man-made pits generated by the excavation equipment.

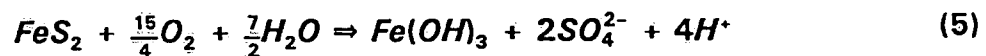
A numerical solution of equation 4 when oxygen flow (R_0) is arbitrarily fixed at $2 \times 10^{-4} \text{ g} \cdot \text{sec}^{-12}$ is shown in Fig. 6. The profile predicts a small variation in oxygen concentration up to 20 metres followed by a rapid decrease. The increase in oxygen gradient arises from the need to maintain a constant oxygen flow in spite of a decreasing surface area. A pit dug with straight and vertical walls would have a constant surface area with depth, and thus a linear decrease in O_2 concentration.

Discharging tailings at the bottom of the pit reduces the effective depth of the hypolimnion and increases the maximal flow of oxygen to that depth. We can calculate the maximum flow of oxygen in the pit by setting the oxygen

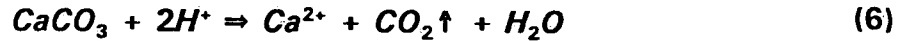
concentration to zero for that depth and solving for R_o in eq. 4. This is always true because any further consumption would result in a negative oxygen concentration at the bottom, which is impossible. If, for example, the pit was to be filled to a depth of 20 m with the tailings, the maximum oxygen flow would be about 0.001 g/sec. A maximum demand curve was calculated by numerical approximation using Mathcad (Mathsoft 1989) and yields a roughly log-linear curve with inflection at the top and bottom of the hypolimnion (Fig. 7).

Acid-Base accounting for the tailings

The feasibility of storing tailings in a meromictic lake or a man-made reservoir depends on the rate of their oxidation. The main environmental consequence arising from the sulfuric acid generated by the oxidation of the sulphide-containing tailings is the lowering of pH in the leachate from the tailings with subsequent dissolution of different metals and trace elements in the tailings. For a given consumption of oxygen the release of the acid is best described by the oxidation of pyrite:



The tailings contain also a quantity of calcite that acts as a buffer against the generated acid:



However, the amount of carbonate in the tailings is usually not sufficient to neutralize all the generated acid. The goal here is estimating the amount of additional calcite required. The method of acid-base accounting (MEND, 1991a) examines two principal processes: 1) Acid generation and 2) Acid buffering. The term Maximum Potential Acidity (MPA) is used to describe acid generation arising from eq. 5 above. The term Neutralization Potential (NP) expresses the buffering action of calcite already present according to eq. 6. The difference between the two, i.e. the required addition of calcite, is Net Neutralization Potential (NNP).

$$\text{NNP} = \text{NP} - \frac{\text{MPA}}{\epsilon} \quad (7)$$

The equation is written in such way that a negative value for NNP indicates the potential to generate acid. We also introduces the term ϵ to account for the neutralization efficiency of calcite as given below. Although the problem was recognized in the MEND (1991b) report, it did not include ϵ in the treatment.

Acid-base accounting calculations are based on simplifying assumptions about the main processes involved. The model considers that:

- 1) Sulfide minerals are the only important source of acidity

- 2) All reactions proceed to completion
- 3) Oxygen is the only oxidant
- 4) Calcite is the only buffer

Biases are introduced when the composition of the tailings significantly depart from the above and also by the methods used during assays. For example, if Neutralization potential is determined by dissolved inorganic carbon (DIC), a significant amount of siderite (FeCO_3) will cause an overestimate of NP. Similarly, an overestimate of MPA occurs when total sulfur is taken as an estimate of pyrite because many neutral species like barite and gypsum do not generate acids. A similar problem arises from the presence of non-pyritic sulfides such as pyrrhotite, or non-iron bearing sulfides such as galena. A detailed analysis of the various biases imparted to determination of acid generation potential can be found in MEND (1991b). For our purpose we assumed that the acid generation in the Matabi tailings is mainly due to pyrite.

a) Maximum potential acidity

The fraction of pyritic sulfur in the tailings was obtained by using a variant of the McLachlin (1934) method, given in Appendix 1 and outlined in METHOD #1 of the MEND report (1991b). The approach is to selectively dissolve pyrrhotite by washing with hot HCl. The remaining sulfides are then decomposed with nitric

acid, evaporated to dryness, and redissolved in dilute HCl. The amount of dissolved Fe is taken as pyritic iron. The equivalent amount of sulfur is therefore:

$$M_S = M_{Fe} \left[2 \frac{AW_S}{AW_{Fe}} \right] \quad (8)$$

$$M_S = 1.143 M_{Fe}$$

The equivalent consumption of oxygen to oxidize this pyrite is obtained from equation 5:

$$M_{O_2} = M_{Fe} \left[\frac{15 FW_{O_2}}{4 AW_{Fe}} \right] \quad (9)$$

$$M_{O_2} = 2.14 M_{Fe}$$

In the above equations, M_x is the mass of compound x expressed in percent total mass; FW_{O_2} , formula weight of molecular oxygen (32 g/M); AW_{Fe} is atomic weight of Fe (56 g/M); AW_S , atomic weight of S (32 g/M). Table 1 shows that pyrite sulfur accounts for only 14.6 % of the total mass of the tested tailings collected in the vicinity of the Crown Pillar pit.

The complete oxidation of this pyrite requires an amount of oxygen equivalent to 27.1 % of total tailing mass.

It is the accepted norm to express MPA as equivalent tonnes of $CaCO_3$ per Kilotonne tailings. The maximum potential acidity is:

$$MPA = 31.25 M_s \quad (10)$$

b) Neutralization potential

The Neutralization Potential (NP) is a measure of the calcite present in the tailings before oxidation takes place. Calcite is determined by measuring the total inorganic carbon in a sample. In the procedure, the sample is mixed with HCl and the CO₂ is measured by an IR analyzer. In our measurements, we inserted a preweighed amount of the tested tailings in a small sealed container in line with an automated DIC analyzer. The acid was injected into the sample and the evolved gas carried directly to the calibrated analyzer. The NP is expressed in tonnes CaCO₃ per Kilotonne (Kt) tailings by the following:

$$NP = \frac{8.33 M_c}{W} \quad (11)$$

where M_c is the measured inorganic carbon (in mg); W is weight of sample (g)

Results of this analysis are expected to be obtain in the near future. However, a maximum value of NP can be obtained by using the results obtained by the x-ray fluorescence (Appendix 2). The concentration of total calcium in the tailings is 0.46%. Assuming that all calcium is derived from calcite, the concentration of inorganic carbon would be 1.15% or 11.5 mg/g. Neutralization potential is thus at most 95.8 tonns of calcite per one Kilotonne of tailings (eq.11).

It is important to note that the neutralization of acidity by the presence of calcite in the tailings does not affect the oxygen demand of the tailings. The addition of the calcite is only required to stabilize the pH at an acceptable value. Such pH has a direct impact on the real neutralization power of the added calcite because even if equation 6 states that one mole of CaCO_3 should neutralize one mole of SO_4 ($\epsilon = 1$), the actual neutralization efficiency is probably less (MEND 1991b, Brady and Hornberger 1990). The reason for this is the fact that dissolution of calcite in water forms three pH-dependent acids: H_2CO_3 , HCO_3^- , and CO_3^{2-} . Since each species neutralizes a different amount of acid, the overall neutralization efficiency of calcite is specific to the final pH of the solution and can be calculated as a titration of carbonates with a strong acid (SO_4^{2-}) in the presence of a solid (CaCO_3), which is well known (Stumm and Morgan 1981).

We wish to solve the charge balance:

$$2 C_a = C_t (2 - \alpha_1 - 2\alpha_2) + H^+ - \frac{K_w}{H} \quad (12)$$

where C_a is the concentration of acid (M/l); C_t is total calcite (M/l); H^+ , hydrogen ion (M/l); K_w , dissociation constant for water (10^{-14}); α_1 , speciation ratio for HCO_3^- ; α_2 , for CO_3^{2-} .

Total carbon can be expressed as the solubility products ($K_s = 10^{-8.22}$) for CaCO_3 :

$$C_t = \left[\frac{K_s}{\alpha_2} \right]^5 \quad (13)$$

The speciation ratios are related to the dissociation constants for carbonates and pH:

$$\alpha_1 = \frac{H K_1}{H^2 + H K_1 + K_1 K_2} \quad (14)$$

$$\alpha_2 = \frac{K_1 K_2}{H^2 + H K_1 + K_1 K_2} \quad (15)$$

where K_1 is first dissociation constant for carbonates ($10^{-6.4}$) and K_2 , the second constant ($10^{-10.4}$). Finally, the neutralization efficiency is:

$$\epsilon = \frac{C_s}{C_t} \quad (16)$$

The result is plotted in Fig. 8 as ϵ against pH. Note that one mole of calcite can neutralize one mole of sulfuric acid only at pH 4.5 or lower. Release of leachates at such a low pH is probably unacceptable. In fact, a final pH near the natural water value of 6 requires a ratio of 0.6 to 0.8, and about 66% more calcite than at pH 4. Further, the ratio of 0.625 suggested by Brady and Hornberger (1990) would yield a pH near 6.8, which is quite acceptable.

Acid-Base accounting applied to a meromictic pit

The general equation for acid base accounting must be altered to reflect the conditions under which tailings oxidize at the bottom of a meromictic pit. Contrary to the usual calculations where the total amount of sulfide S is expected to react completely, oxidation in the pit is limited not by the amount of sulfur present, but by the limitation of oxygen consumed. It follows that the actual amount of tailings deposited is not immediately important. The amount of calcite required to neutralize the acid should therefore be solely a function of the oxygen flow, and should be expressed also as a rate.

There are two steps involved in the neutralization. At first, the tailings are deposited at the bottom and the calcite already present in the tailings neutralizes the acid until it is exhausted. In the following second step, calcite is added continuously in proportion to the acidity generated. We calculate the rate of calcite addition, R_{ca} (t/yr) directly from maximum oxygen flow R_o (g/sec):

$$R_{MPA} = \frac{R_{O_2} \cdot 8 \cdot FW_{CaCO_3} \cdot 31.56}{\epsilon \cdot 15 \cdot FW_{O_2}} \quad (17)$$

$$R_{MPA} = 52.6 \frac{R_{O_2}}{\epsilon}$$

Then from the calcite already present in the tailings (NP) and the total tailings impounded (Kt) we calculate the time required to consume the buffer and,

therefore, the period before any supplement is required. We define this period as the transition period, TP (yr)

$$TP = \frac{NP M_t}{R_{MPA}} \quad (18)$$

We can get an idea of the actual speed of processes occurring at the bottom of the pit. Suppose it is decided to cover the bottom of the pit up to a depth of about 21 m. Assuming the density of the tailings 2 and the known volume at that depth of 4340 m³, we calculate a load of 8.7 Kt tailings. According to Fig. 6, the maximum oxygen consumption at that depth is 0.001 g/sec. From eq. 17 the rate of calcite addition for an efficiency of 0.6 is 87 Kg/yr.

The tailings in the vicinity of the Crown Pillar pit have at most 96 t calcite/Kt. Therefore eq. 18 yields a transition period of more that 9000 years. This is to be expected since the oxygen consumption of the tailings depends solely on the meromictic character of the pit while the amount of buffer depends on the amount of the tailings. In fact, the tailings can be impounded indefinitely on its own provided the meromictic properties are always maintained. The amount of acid which would leak out of the tailings should be sufficiently buffered to be harmless.

Remarks and Conclusion

The model presented here is voluntarily simplistic. The approach is based on the presumption that acid generation is the sole problem and that oxygen sources other than the surface of the pit are not significant. Leaching of other toxic compounds present in the tailings can be important but is not addressed in this model. Some subjects remain to be examined.

First, for the convenience, in calculating the maximum oxygen flow, we have conservatively assumed that the process takes place at zero O_2 concentration. However, for a reaction to proceed there must be a small content of O_2 present. Therefore we need to know the stability and kinetic constants of submerged tailings to determine the relation between dissolved O_2 and their oxidation. Further, we did not consider the effect of seasonal cycles on the water column and processes occurring during the ice cover period. We expect a decrease of the oxygen available to the tailings during the winter. In addition, the tailings disposed on the bottom of the pit are treated in the model as a homogenous mass uniformly exposed to oxygen supplied from above. However, the oxidation of the tailings is further limited by the thickness of the layer of the deposited tailings which will further decrease acid generation as the top layers of the tailings protect the lower ones.

Second, we did not consider the process of the oxidation of the tailings mediated by bacteria. Therefore the conditions which govern the process and response of the bacterial community under prolonged anoxia need to be investigated.

However, the results obtained by the modelling show clearly that the disposal of the tailings into a meromictic lake or man-made reservoir is a stable method to confine tailings for long periods of time without interferences. The main assumption is that the hypolimnion layer remains undisturbed, and requires a permanent, stable density gradient during a long period of time. Infiltration of oxygen appears to be the most important concern.

In addition to the above considerations, there always remains the concern that confining contaminated material for long periods of time is only a temporary solution, and that the longer the material is kept confined the greater are the chances of accidents. Therefore we recommend to study the environment of meromictic lakes, pits, and other man-made reservoirs with disposed mine tailings under different conditions which would allow further oxidation of the disposed tailings. As a result of such studies, tailings and waste material produced by metal mining could be returned back to the environment under controlled and safe conditions.

REFERENCES

- Brady, K.B.C. and Hornberger, R.J. (1990). A manual for premining prediction of coal mine drainage quality - Draft. Unpubl. report for the Pennsylvania Dept. of Environmental Resources, Bureau of Mining and Reclamation.
- Cole, D. (1983). Textbook of Limnology, 3d edition. The Mosby Co., St. Louis.
- Crank, J. (1975). The mathematics of diffusion. Second edition, Oxford Science Publications, Oxford University Press.
- Dubay, C.I. and Simmons, G.M. (1979) Amer. Mid. Nat. 101:108-117.
- Eberly, W.R. (1964). Invest. Indiana Lakes Streams 6:103-139.
- Fry, B. (1986). Sources of carbon and sulfur nutrition for consumers in three meromictic lakes of New York State. Limnol. Oceanogr. 31(1):79-88.
- McLachlin, C.G. (1934). Increasing gold recovery from Noranda milling ore. Appendix 2 - Quantitative determination of pyrite and pyrrhotite in Noranda ore and mill products. Am. Inst. Min. Met. Eng. Trans. 112:593-596.

Mathsoft, Inc. (1989). MATHCAD version 2.5 User's guide. Mathsoft, Inc,
Cambridge, MA.

MEND (1991a). Acid rock drainage prediction manual. MEND Project 1.16.1b,
March 1991. CANMET (publ.), Ottawa, Ontario.

MEND (1991b). New methods for determination of key mineral species in acid
generation prediction by acid-base accounting. MEND Project 1.16.1c, April
1991. CANMET (publ.), Ottawa, Ontario.

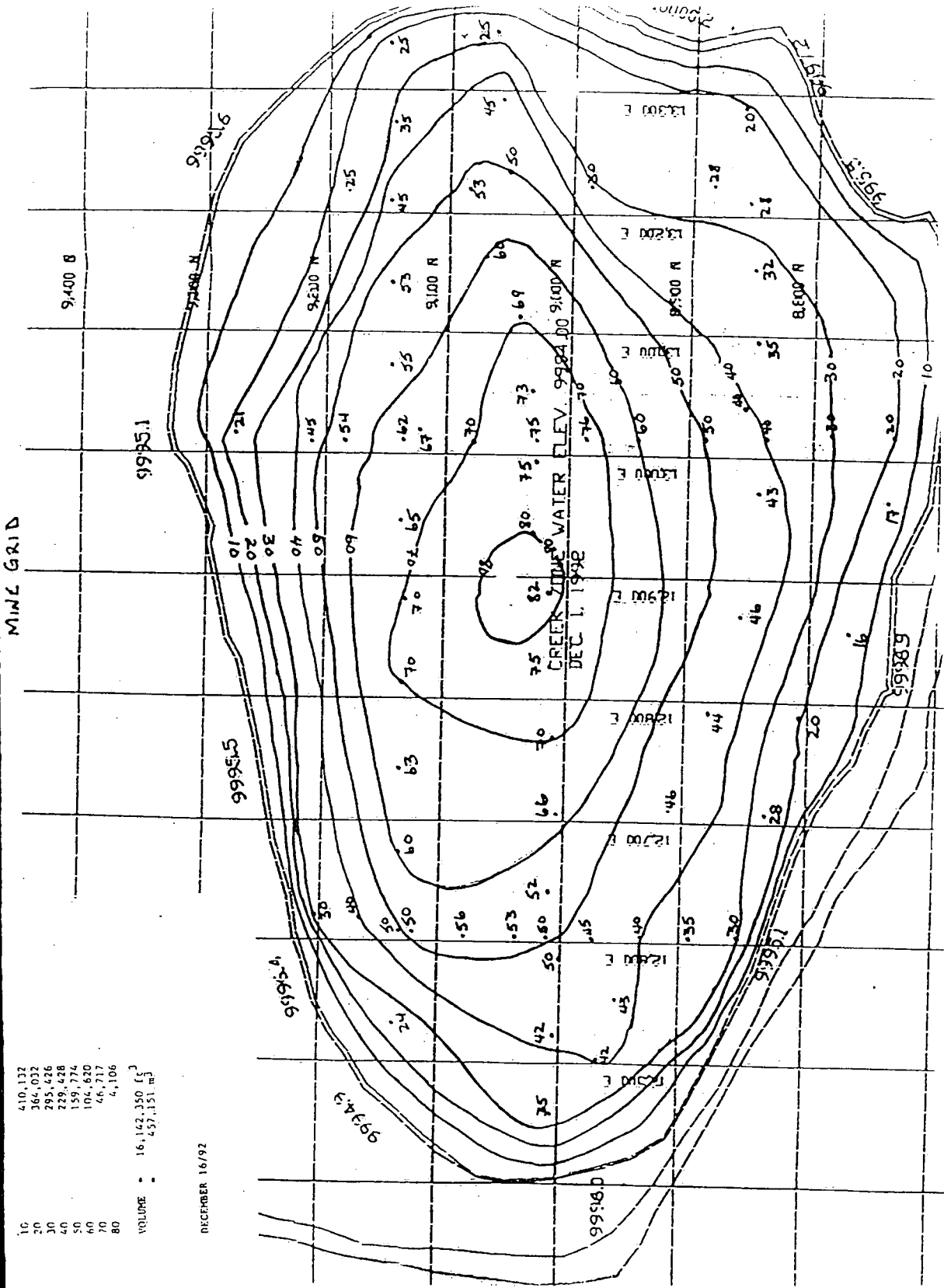
Stumm, W. and Morgan, J. (1981). Aquatic Chemistry. Wiley - Interscience (publ.),
New York, London, Sydney, Toronto.

Table 1. Total sulfur analysis of 1 g of tailings.

SAMPLE	Fe(Pyrite) ppm	Fe(Pyrite) %	S(Pyrite) %	total S %	Difference %
508	12.7	14.6	25.2	10.6	

Tailings

Note: The concentration of total sulfur obtained by x-ray fluorescence; pyrite by the method of McLachlin (1934). Dissolved Fe was determined by ICP-MS instead of atomic absorption spectrometry. Pyrrhotite does not contribute to acidity and is deemed to be the difference between the total sulfur and pyrite.



10	410.132
20	364.032
30	285.426
40	228.428
50	157.774
60	104.959
70	46.717
80	4.106

VOLUME : 16,162.350 [m³]
 457,151 m³

DECEMBER 16/92

Figure 1. Morphometry of Crown Pillar pit

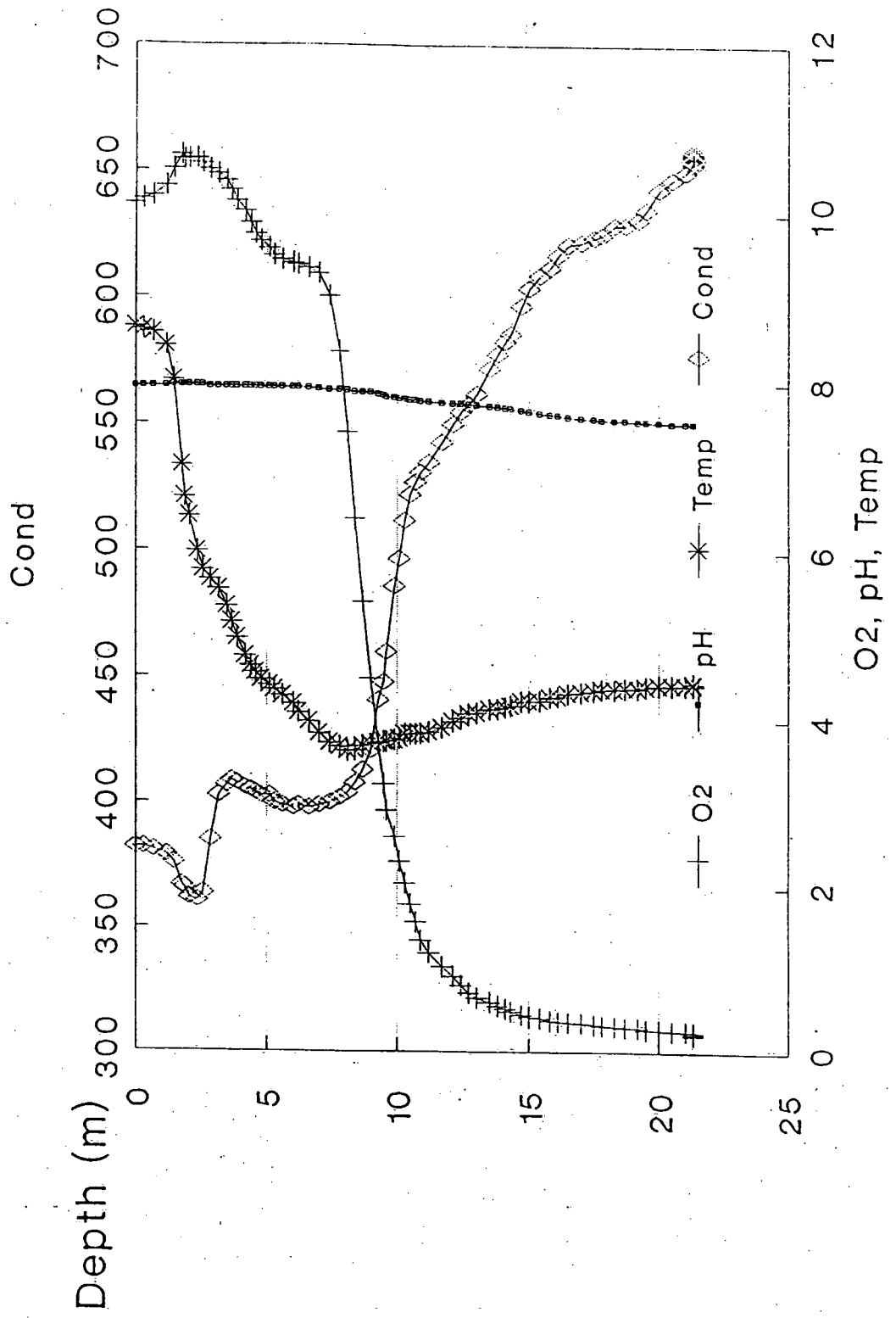


Figure 2. Conductivity, dissolved oxygen, pH and temperature profiles in Crown Pillar pit

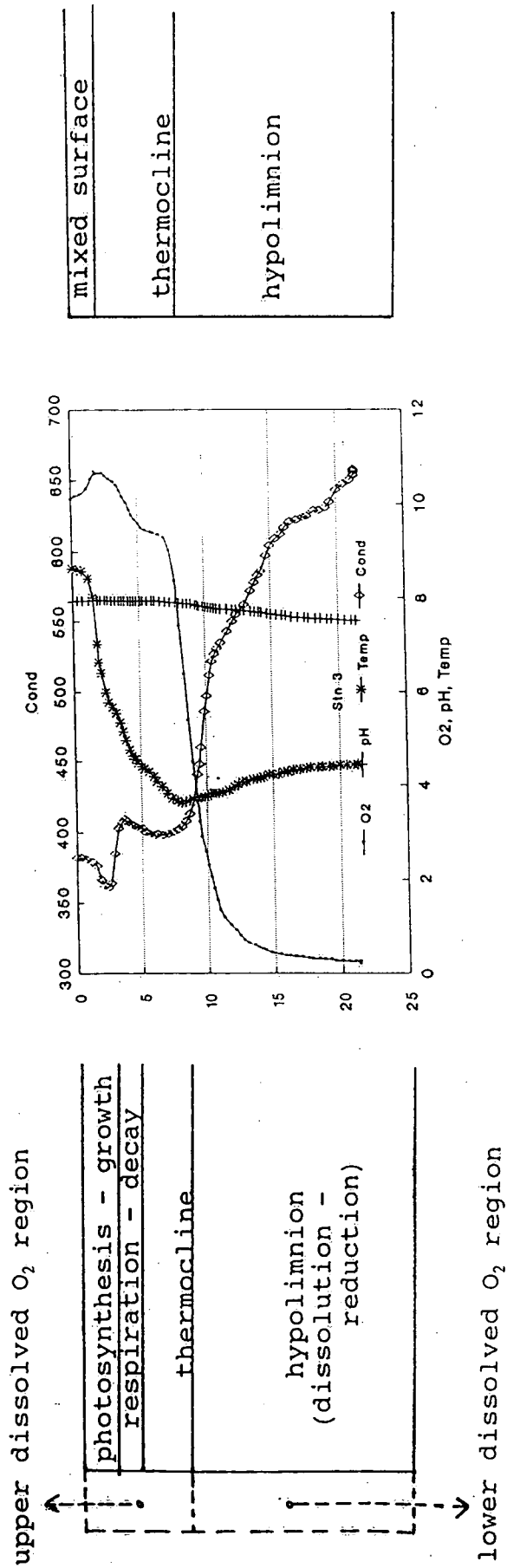


Figure 3. Water layers in Crown Pillar pit

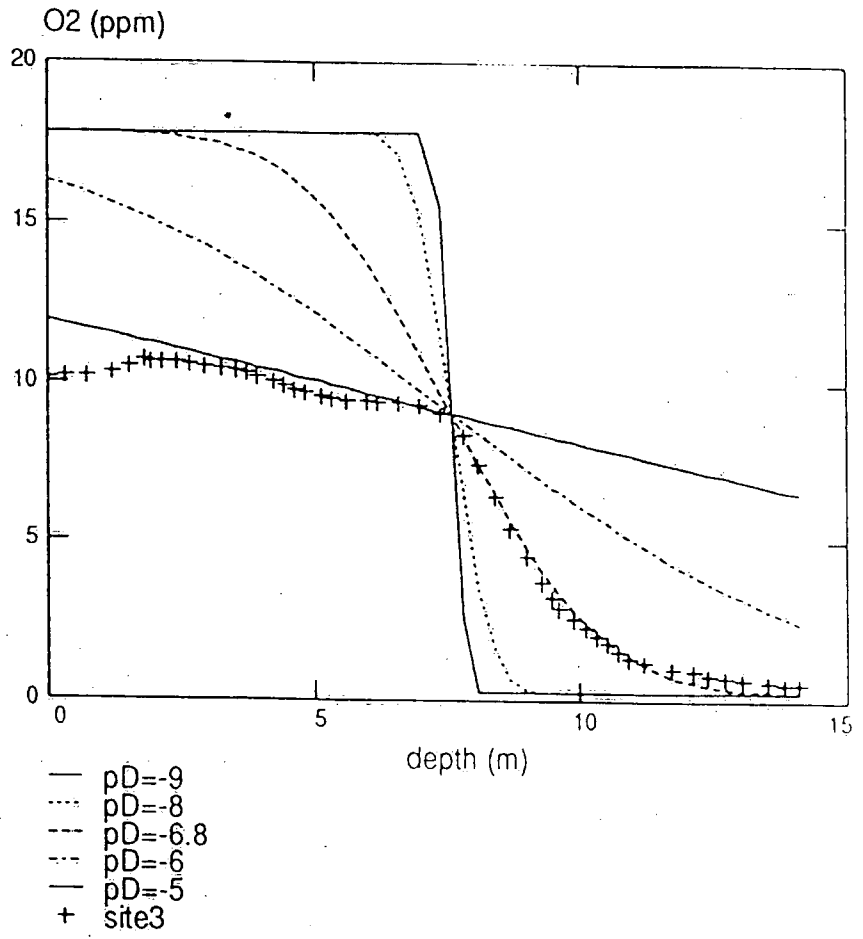


Figure 4. Diffusion coefficient of oxygen for Crown Pillar pit

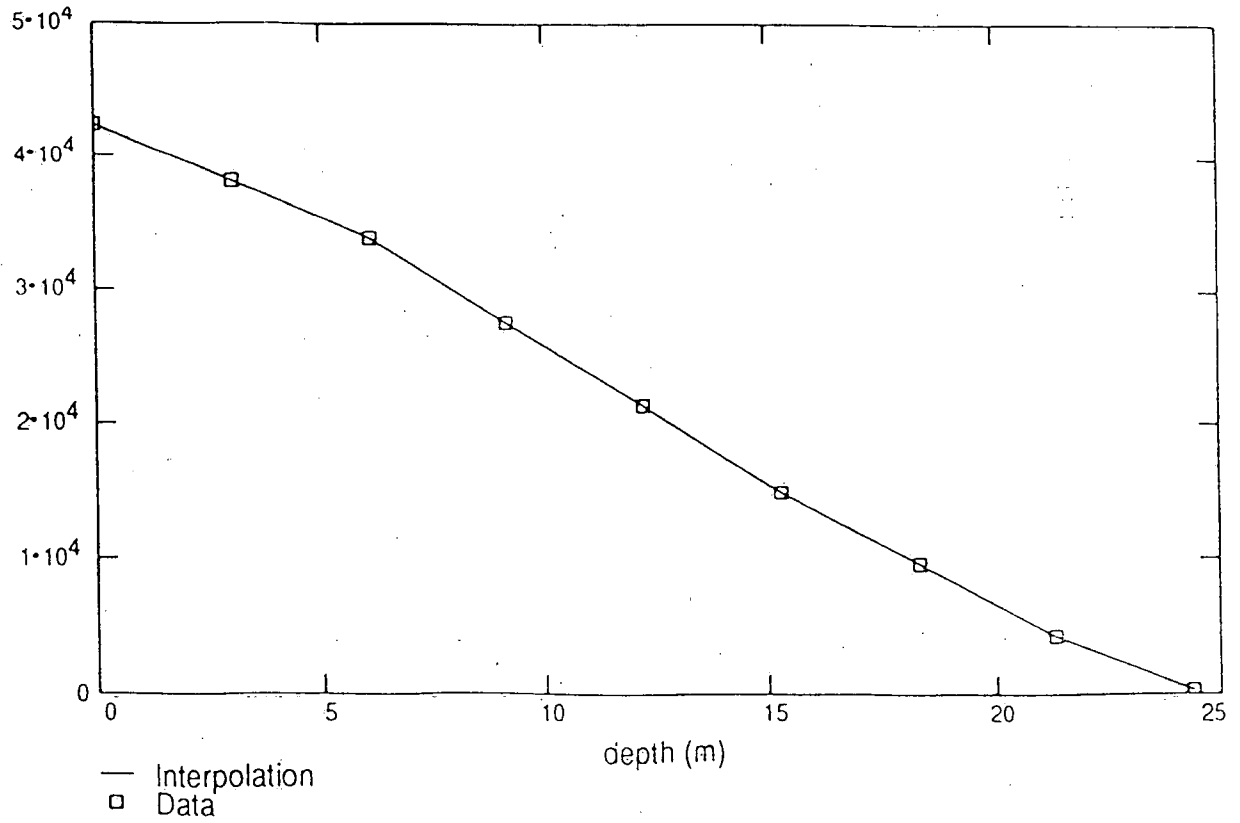


Figure 5. Area distribution function

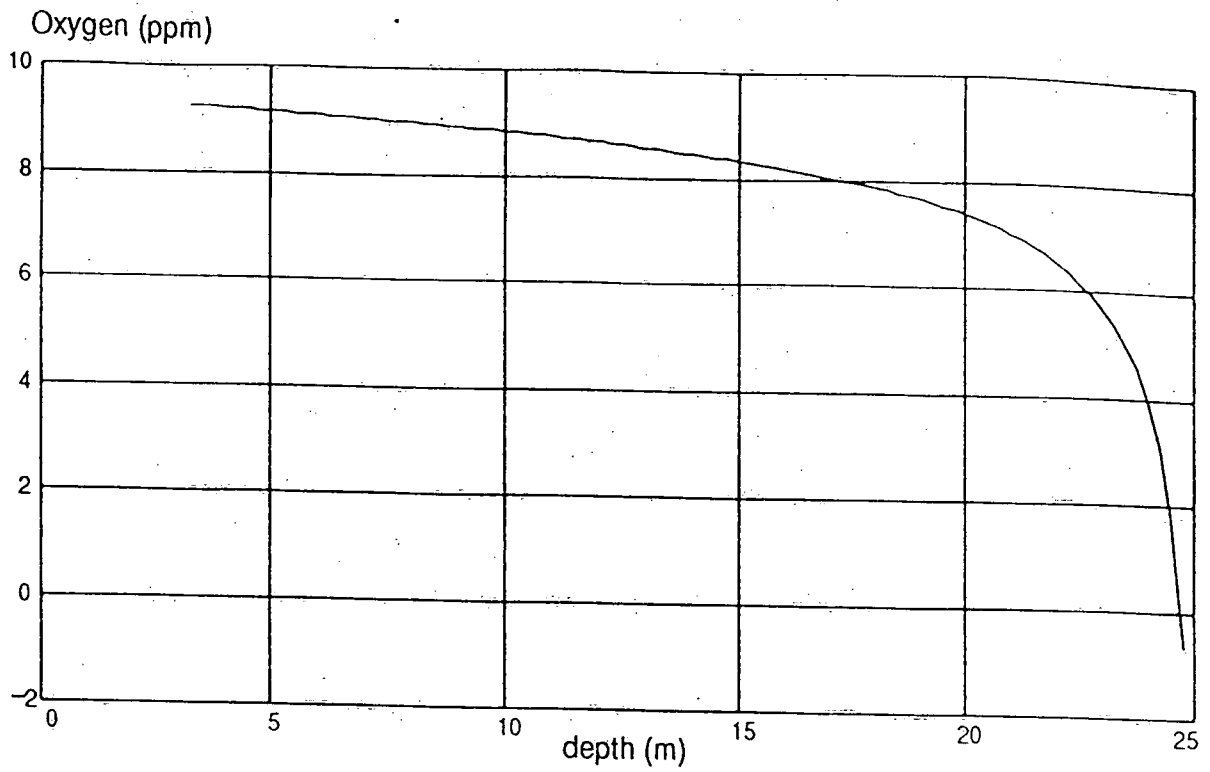


Figure 6. Oxygen profile at a steady state

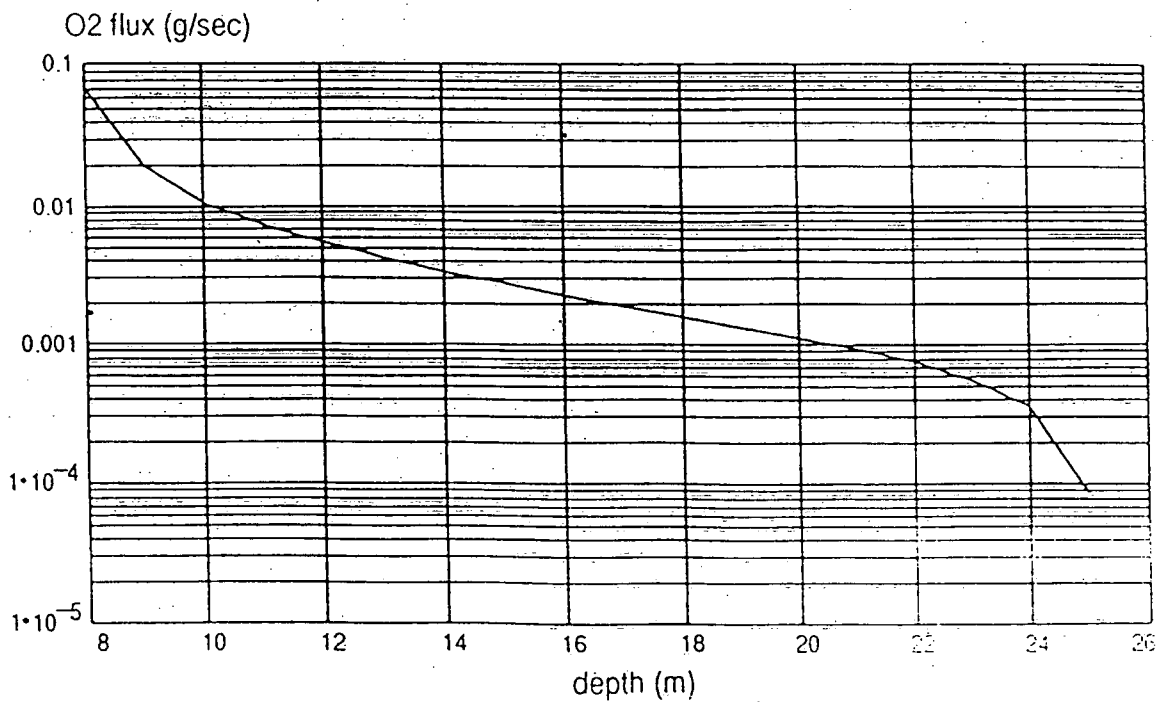


Figure 7. Oxygen flux in Crown Pillar pit

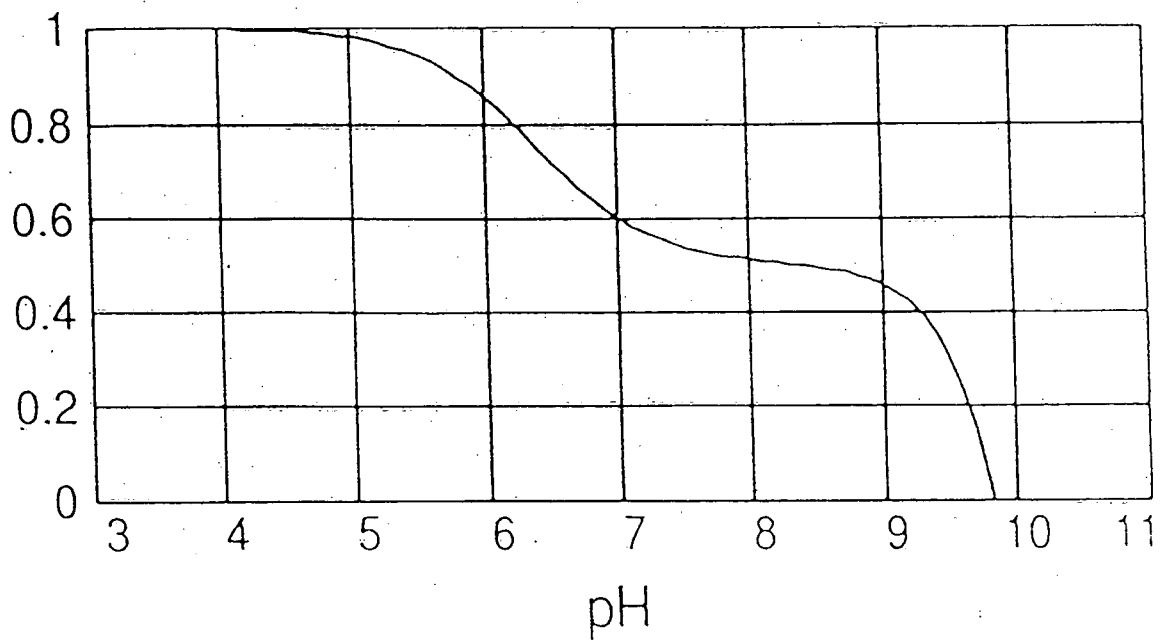


Figure 8. Neutralization efficiency of CaCO₃

APPENDIX 1

DETERMINATION OF PYRITE AND PYRRHOTITE FORMS OF SULPHUR

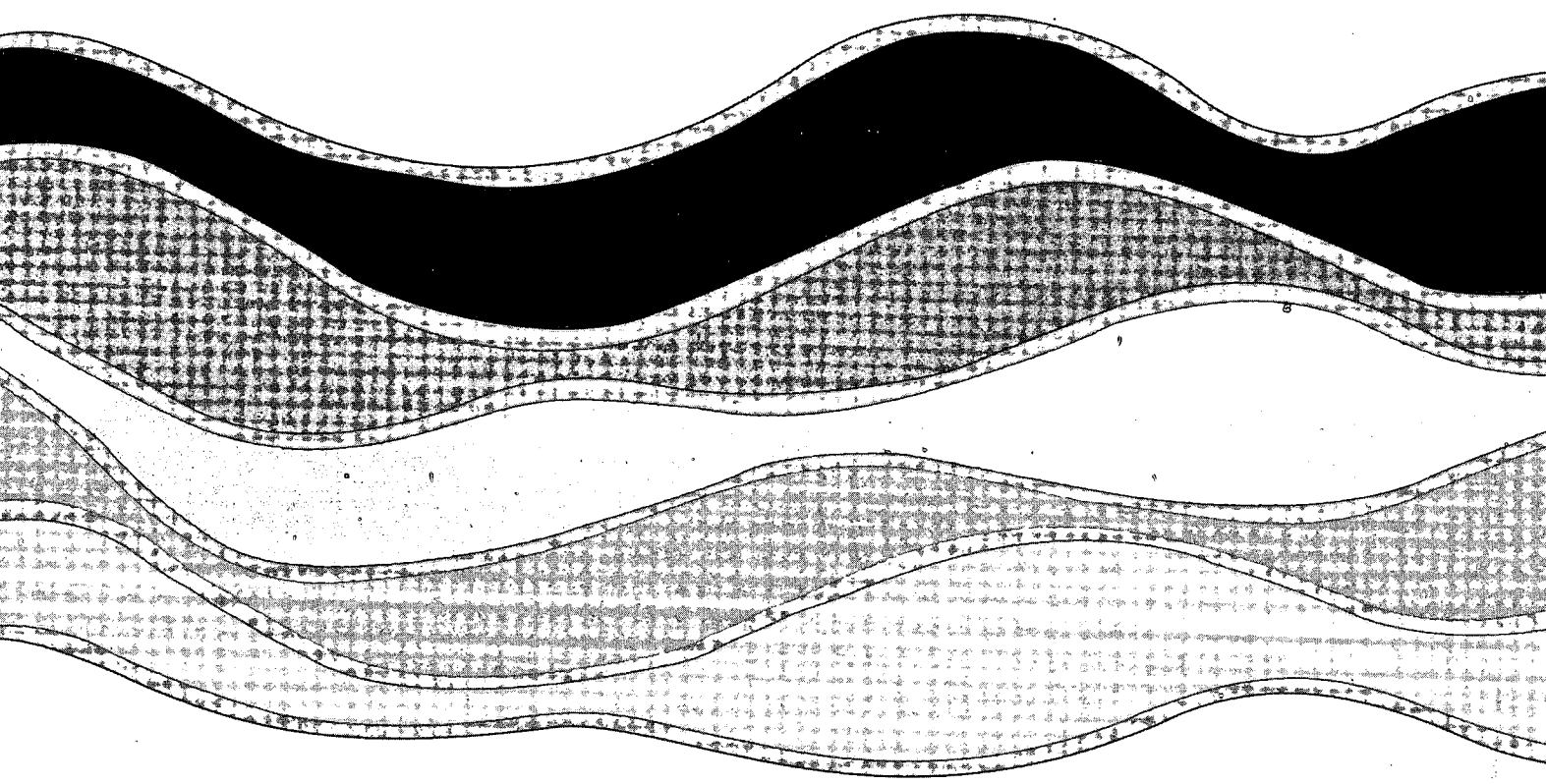
1. Determine total sulphur of sample using appropriate method.
2. Weigh into a 300 cm³ beaker: 1 g of ground sample if pyrite content is in excess of 10%; or 3 g sample if pyrite is less than 10%.
3. Add 50 cm³ of solution containing 2 parts of water and 1 part HCl (by volume)
4. Heat the mixture on hot plate for about 10 minutes until evolution of H₂S fumes is finished as denoted by testing with lead acetate paper.
5. Vacuum-filter through a Gooch crucible lined with an asbestos pad.
6. Wash the residue on the crucible thoroughly with hot water.
7. Transfer crucible with contents to 500 cm³ beaker, add a pinch of potassium chlorate to the residue in the crucible, then add a sufficient quantity of concentrated nitric acid to decompose sulphides.
8. Evaporate to dryness on hot plate, and heat the residue for 25 minutes.
9. Add 50 cm³ dilute (5 to 10%) hydrochloric acid.
10. Dilute to 300 cm³ with distilled water.
11. Determine Fe-content in the solution using atomic absorption spectrometer.
12. Report results calculated as sulphur content in pyrite in the sample.
13. Determine sulphur as pyrrhotite by difference.

APPENDIX 2

CONCENTRATIONS OF MAJOR AND TRACE ELEMENTS IN TAILINGS

Element	% Dry wt.	Std. Error
F	0.41	0.4
Na	0.09	0.02
Mg	0.47	0.02
Al	4.6	0.1
Si	18.2	0.1
P	0.014	0.001
S	25.2	0.2
K	0.29	0.02
Ca	0.45	0.02
Ti	0.22	0.01
Cr	0.007	0.001
Mn	0.081	0.007
Fe	23.3	0.2
Co	0.016	0.006
Cu	0.087	0.009
Zn	0.30	0.02
As	0.088	0.007
Sr	0.0062	0.0008
Zr	0.031	0.003
Sb	0.0070	0.002
Pb	0.38	0.02

Elements in concentrations < 50 $\mu\text{g/g}$ (dry weight):
 Ni, Cl, V, Se, Rb, Mo, Ag, Cd, Sn, Ba, Hg, Bi, Th, U



NATIONAL WATER RESEARCH INSTITUTE
P.O. BOX 5050, BURLINGTON, ONTARIO L7R 4A6

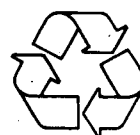


Environment Canada Environnement Canada

Canada

INSTITUT NATIONAL DE RECHERCHE SUR LES EAUX
C.P. 5050, BURLINGTON (ONTARIO) L7R 4A6

Think Recycling!



Pensez à recycler!

1st Impression™ Covers Item No. 03531 1/8 for 16 to 30 sheets
Avery Dennison 1-800-DENNISON

Environment Canada Library, Burlington



3 9055 1017 7977 4