ACID GENERATION MODELLING - EQUITY SILVER WASTE ROCK DUMPS

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The Equity Silver mine near Houston B.C. is proposing to cease operations in 1992. The large open pit operation has produced more than 80 million tonnes of waste rock which for the most part has been placed into surface dumps. The waste contains about 4 percent sulphide minerals and is a strong acid generator. Since 1981 Equity Silver Mines Limited (Equity) have been intercepting and treating seepage during which time there has been a steadily increasing load of acidity.

Over the past several years Equity have developed their plans for decommissioning. The plan includes the control of acid release rates through the capping of the dumps with a low permeability cover. This plan was implemented over much of the dump in 1990/91. The preliminary indications is that the cover is functioning well.

The decommissioning plan for Equity calls for perpetual treatment of seepage and runoff from the dumps. This requires substantial operating costs for labour, power, chemicals and maintenance. In order to provide assurance that these funds would be available over the long-term, Equity have been requested to post a bond. A Technical Committee was formed with representation from Equity and several government agencies to review bonding requirements.

The committee met on 6 occasions and presented their best estimate of potential long-term costs and the net present value of a bond for several scenarios. The committees approach included empirical estimates of acid production for a series of assumptions. The concerns of the committee were that they did not have sound basis for determining peak acid production rates, the duration of peak rates and the decline in acid production over time or long-term acid production rates. As a result they applied a broad range to their assumptions.

Equity was comfortable with the Technical Committee reports but wanted to confirm the data by having a site specific ARD (Acid Rock Drainage) model developed for their site. The model development was completed in 1991 and calibrated to the historical data. Model runs were completed for till, uncompacted clay and compacted clay covers.

Model results confirm the shape of the ARD curve and suggest that the Technical Committee estimates were conservative but not unreasonable. The net present value of the bond based upon the ARD model results overlaps the committees estimates.

This paper presents information regarding the general structure of the ARD model, estimates of ARD production by the model for the various cover scenarios, and compares the model results with several empirical estimates.

INTRODUCTION

Mining commenced at Equity Silver mine in April 1980. The economically open-pit minable ore will be exhausted during 1992, by which time about 80 million tonnes of waste rock will have been excavated and placed into waste dumps. The tailings resulting from the ore processing have been submerged under water in an impoundment which will contain approximately 32 million tonnes of tailings at the time of closure. The waste rock, as well as the tailings, contains between 2 and 3% pyritic sulphide. When exposed to air and water, the sulphides oxidize and produce acid which leaches toxic metals and other deleterious substances from the waste rock. The resulting runoff is generally referred to as Acid Rock Drainage (ARD).

The Equity Silver mine will cease open-pit operations in 1992. To cover the cost of the perpetual treatment of the ARD and the cost of the long-term maintenance of the collection/treatment facility, the B.C. Government have required Equity to post a reclamation bond. The value of the bond has been established based upon the estimated long-term costs for power, labour, maintenance and treatment (lime).

The acid generation potential of the waste rock is estimated to be in excess of 100 kg $CaCO_3$ equivalent/tonne (Gormely, 1989). To alleviate the acid generation problem caused by the waste rock piles, Equity are installing a compacted till cover over the waste rock as a long-term control measure. Acid generation can only proceed in the presence of oxygen and water; therefore, the function of the continuous, compacted till cover is the reduction of oxygen and water transport through the waste rock dump.

SENES Consultants Limited were retained by Equity Silver Mines Limited to evaluate the potential effectiveness of the proposed till cover for reducing the long-term acid generation rates of the waste rock dumps and to estimate these acid generation rates through the application of steady-state and dynamic mathematical models. The results of this study are addressed in this paper.

PREVIOUS STUDIES OF SOIL COVER EFFECTIVENESS

Acid mine drainage is generally considered to be the greatest environmental problem facing the mining industry today. Consequently, considerable effort and resources have been, and continue to be, expended in the study of the subject and in the development of preventative and remedial technologies. Currently, soil covers are considered to be one of the most promising remedial technologies for the prevention or reduction of acid generation by sulphide bearing waste rock and tailings deposits. The effectiveness of such covers has been investigated both theoretically and experimentally by several workers (Yanful *el al,* 1990; Ramuson and Collin, 1988; Halbert *et al,* 1983; and Bennett and Ritchie, 1991).

The major factors which have been shown to influence the rate of oxidation in reactive tailings and waste rock, and therefore the rate of subsequent acid generation, are: the availability of oxygen; the availability of water; bacterial catalysis; and the availability of carbonate material to buffer pore water.

Of these factors, the availability of oxygen is generally accepted to be of overriding importance in any reactive tailings management program (Ramuson and Collin, 1988). The oxygen concentration profile existing in a waste rock deposit determines the zone of active sulphide oxidation.

Several theoretical investigations have provided quantitative estimates of the benefit to be gained from the application of soil covers. For example, Yanful *et al.* (1990) have shown that the application of a 40 cm non-reactive cover with a effective diffusivity of 0.21 m^2/month will reduce oxygen diffusion into tailings by 78%, a situation which leads to a 78% reduction in acid production.

Ramuson and Collin (1988) have mathematically modelled the oxygen transport in layered soil covers for a pyritic tailings deposit. They concluded that the use of a clayey moraine cover may substantially reduce oxygen transport to the tailings. For example, (he application of a 1 m thick cover of such a material is expected to reduce the oxidation rate of the tailings from above 3,000 g pyrite/m^2.year (uncovered) to about 131 g pyrite/m^2.year. It

should be noted that although these results were determined using the characteristics of modern sand waste dumps, the same benefits are expected if the cover is applied to coarse waste rock deposits such as those found at the Equity Silver mine (Ramuson and Collin, 1988).

Another important study on the behaviour of soil covers is currently being conducted by Bennett and Ritchie (1991) at the abandoned Rum Jungle mine site in northern Australia. Between 1983 and 1986, two pyritic waste rock dumps, which were major sources of environmental pollution, underwent extensive rehabilitation. This included first reshaping of the dumps and then capping them with a three-layer cover incorporating a compacted clay cover. Oxygen concentrations in pore gases were monitored prior to, during, and after the remedial activities. An early observation was that the pore gas oxygen concentrations in the dumps fell to low levels soon after the covers were applied. Also, analysis of measured temperature profiles showed that the rehabilitation works had effectively stopped the oxidation of pyrite within the dumps (Harris and Ritchie, 1987). Subsequent measurements appear to show that the integrity of the cover with respect to oxygen transport is being maintained in one of the two dumps. The other dump exhibits a seasonal variation in pore gas oxygen concentrations. Further analysis of this variation is required before it can be determined if the cover's effectiveness has diminished since it was applied.

Another investigation involving the assessment of potential cover benefits has involved the development and use of a sophisticated mathematical/computer model. The Reactive Acid Tailings Assessment Program (RATAP) has been developed to analyze the effects of oxidation processes and variables on the rate and quantity of acid generated by the bacterial-assisted oxidation of sulphide minerals in mine tailings (Halbert *et al*, 1989). The model allows for evaluation of the effects of various close-out strategies on the flux of acidity from tailings deposits.

The validated RATAP model has been applied to several pyritic tailings deposits situated in Elliot Lake. It was used to evaluate potential benefits of applying a earthen cover to the surface of the tailings. The results of this investigation indicate that a 1 metre application of soil cover with the same physical characteristics as the tailings (hydraulic conductivity = 1×10^{-5} cm/s) could reduce acid generation rates by 50%. Low permeability covers of 10^{-6} cm/s or less, can reduce peak rates by more than 90%.

EXPERIMENTAL INVESTIGATIONS

Evaluation of the Oxygen Diffusion Coefficient

To determine how effective the proposed till cover will be in preventing oxygen diffusion into the waste rock dumps, the oxygen diffusivity of the till material under *in situ* conditions must be measured or estimated. Obviously, an *in situ* measurement is not possible; therefore, the diffusivity was determined experimentally. To determine the oxygen diffusivity of the material, a three compartment diffusion cell was fabricated at the University of Waterloo. The desired soil compaction was achieved by employing a calibrated hydraulic press.

The till cover material occurs naturally with a moisture content of 19% (dry basis); or 87% saturation. It was considered that a cover would likely have levels of saturation at or below the measured values therefore testing was completed at moisture contents ranging from 0 to 19%. Moisture content was found to have a profound effect on the effective diffusion coefficient, resulting in measured effective diffusion coefficients ranging between 1.66×10^{-4} to 5.64×10^{-3} cm^2/sec for the moisture levels ranging from 0% to 19% by weight. An equation relating the effective diffusion coefficient to the moisture content was proposed.

Water and Air Permeability

The permeability of till soil to both water and air was also measured. The gaseous and liquid permeabilities of uncompacted and compacted till soils were determined from experimental data of mass flux versus the pressure drop through samples of various thickness. The liquid permeability varied from 0.22 mDa (0.2×10^{-9} m/s) for compacted soil, to 0.57 mDa (0.57×10^{-8} m/s) for uncompacted soil. As in the case of diffusion, the moisture content of soils had a strong effect on the gaseous permeability.

THE ARD MODEL

Overview

The model simulates ARD by considering the waste rock dump as an equivalent rectangle of specified depth and surface area. The depth is then subdivided into a number of layers, forming a series of interconnected modelling units. Water infiltrating the waste rock pile is assumed to flow downwards and exit as seepage at the base of the dump. The void space within the dump is assumed to contain a small amount of pore water associated with the surface of the rock particles. The model allows for the continuous deposition of waste rock onto the top of the dump as well as the installation of a cover after a specified time interval.

Acid generation is dependent on the rate of oxidation of pyrite. The chemical and biological oxidation of the pyrite within the dump is assumed to be function of the mass and surface area of pyrite, the temperature, the pH and the oxygen concentration. In addition to oxidation, chemical processes such as dissolution, complexation and precipitation are also considered. The pH of the pore water is determined by conducting a net ionic balance, and acidity is calculated as the difference between anions and cations (i.e. predominately sulphate, calcium and potassium) in the seepage flow. Note: acidity is calculated under anoxic conditions at the base of the waste pile, and is expressed as mg acidity (i.e. calcium carbonate equivalents) per litre of seepage, and as kg (calcium carbonate equivalents) per annum.

Mass and Surface Area of the Waste Rock

For the purpose of kinetic modelling, the waste rock is divided into two fractions: fine particles (fines) and coarse particles (rocks). The particle size demarking fines and rocks can be determined from particle size classification testwork. The size distribution (cumulative mass fractions) of the fine particles is an important input to the model. For the coarser fraction, only an estimate of the average diameter is a required input to model. The average pyrite content in each fraction (fines, rocks) can be estimated from field data.

The size distribution of the fines is described by a truncated Beta distribution, otherwise known as the Paretto distribution. Pyrite oxidation of the fines is modelled using "shrinking particle" kinetics. This kinetic model assumes that the radius of the pyrite particle decreases with oxidation; this is only valid for very small particles.

Pyrite oxidation of the larger rock particles is modelled using a combination of "shrinking core" kinetics and fracturing. Attrition (fracturing) is assumed to result in the formation of new surfaces, which, in turn, is directly proportion to the total mass of pyrite in coarse rock. These are particularly prevalent in massive pyrite.

Temperature

The temperature profile within the waste rock pile is determined as the seasonal background temperature (which is based on the annual average temperature in air) with correction for the additional heat generated by pyrite oxidation (which is highly exothermic). Within the dump, heat is assumed to be transported by conduction through the rock and convection by infiltrating water; convective heat transfer by air was not included as it is not a critical element at Equity. The thermal properties of the waste" rock were estimated from thermal characteristics for similar rocks, or for soil (fines). Field data (temperature profile) was utilized to set the maximum temperatures produced in the waste rock dump.

Transport of Oxygen

The diffusion of oxygen into the dump was determined by the physical characteristics (void space, moisture content, etc.) of both the waste rock and, if one is present, the cover. The model incorporates both oxygen diffusion through the pore space to the surface of the waste rock particle, and diffusion through the surface boundary layer (water) to the site of pyrite oxidation. The latter is important for oxidizing pyrite embedded in the host rock matrix. The oxygen concentration profile is recalculated as oxygen is consumed by the oxidation of pyrite.

In the upper section of the waste pile, when fresh reactive surfaces are available, pyrite oxidation will be reaction rate controlled. As the oxidation moves further into the waste pile, diffusion of oxygen becomes increasingly important and is ultimately rate limiting. Under diffusion control, the distinction between biochemical and chemical oxidation becomes irrelevant. The rate of sulphide mineral oxidation, hence sulphate production, is related to the oxygen flux by reaction stoichiometry.

The placement of a cover limits the diffusion of oxygen into the dump. This cover effect is simulated by specifying an appropriate value for the effective diffusion coefficient, which depends on both the type of cover material (till, clay) and the method of placement (compacted, loose). Diffusion coefficients can be estimated from field data (oxygen penetration profile) or determined experimentally (laboratory testwork), as carried out for this study at the University of Waterloo.

Calculation of pH

The pH of the pore water was calculated from the net ionic balance of the chemical species present. The pH balance is dominated by sulphate (SO_4^{2-}), iron (Fe^{2+}, Fe^{3+}), calcium (Ca^{2+}) and aluminum (Al^{3+}) ions, which are usually present in significant quantities. The ionic balance also includes dissolved magnesium, copper, and zinc and their complexes. The pH can be buffered due to the presence of minerals such as calcite and gypsum which are sources of Ca^{2+}, SO_4^{2-} and CO_3^{2-}.

Reactions and Chemical Processes

The Equity model considers only the oxidation of pyrite and chemical processes such as dissolution, complexation and precipitation. The pore water containing the dissolved chemical species is assumed to infiltrate vertically through the waste rock. Mass balance equations are used to keep track of the movement of chemical species through the waste dump. The concentrations in solution are determined from mass balance and solubility constraints.

Calculation of Acidity

The acidity is presented as a running annual average, expressed as Kg calcium carbonate equivalents per year, and as mg calcium carbonate equivalents per litre of seepage, where the seepage volume is the total volume of infiltrating water passing through the dump per year. Acidity is calculated as the difference (in molar equivalents), between the major anions contributing hydrogen (H^+) ions (e.g. sulphate) and the cations able to accept hydroxyl (OH') ions (e.g. calcium, potassium).

MODEL RESULTS

The ARD model was run for several cover scenarios including a base case which provided for application of: a pervious till cover; a compacted clay cover with the properties measured for the *in situ* clay cover; a semi-compacted clay cover; and a non-compacted clay cover. These model runs were considered to assess the sensitivity of the results to degradation of the cover due to natural processes.

The key properties of (he covers are indicated below:

	Apparent Diffusion Coefficient m^2/a	Infiltration m^3/a
Base Case (no cover)	73	330,000
Loose Till Cover (1.4 m)	30.4	220.000
Non-Compacted Clay Cover (0.7 m)	17.8	123,000
Semi-Compacted Clay Cover (0.7 m)	9.15	75,000
Compacted Clay Cover (0.7 m)	0.52	5,600

The ARD model results for the till cover which represents the active field conditions for the Main Dump are shown in Figure 1. The model agrees well with the field data but underestimates the peak. The reason for underestimating the peak is likely a combination of factors including: 1) the fines content of the dump is likely higher than measured in the field samples; 2) convection may play a minor role in increasing oxidation rates; and 3) a limit was imposed on the peak temperature.

The Main Dump and Bessemer Dump were modelled separately and the two ARD prediction curves were combined. Figure 2 illustrates the total acid generated for the Main Dump and Bessemer Dump for the model results versus field data.

The benefits achieved through the use of the various covers on the Main Dump are illustrated in Figure 3.

SUMMARY AND DISCUSSION OF RESULTS AND ARD ESTIMATES

Key Input Factors Controlling ARD

The key factors from this modelling exercise have proven to be the gaseous diffusivity through cover, and waste rock, the infiltration rates, the quantity of fines, and the crumbling or weathering rate of the waste rock and energy transport within the pile. The diffusivity through the cover and the waste rock can be determined experimentally. Where oxygen penetration is a limiting factor to ARD production, the rate of acid production is proportional to the diffusivity.

Empirical estimates based upon moisture content and permeability agree well with the measured diffusivity of the cover material. Therefore the effect of oxygen diffusivity into the Equity waste rock dumps is well understood and the model predictions can be considered reasonable. However, it is uncertain what the actual cover diffusivity will be, as variations in compaction, weathering, settling, defects etc. will control the actual diffusivity into the dump.

Similarly, empirical estimates of infiltration agree well with measured flow data for total discharge from the Equity waste rock dumps. Again, model predictions for infiltration are expected to be reasonable for the cover conditions modelled. Infiltration rates have a moderate effect on ARD production. As infiltration reduces, contaminant levels in pore water increase to a point where ARD is contained by inhibition resulting from low pH, high salt content, etc. At very low infiltration rates, ARD may well be a direct function of infiltration as pore waters will reach maximum concentrations which are equilibrium controlled.

The fines content and the pyrite content of the fines (i.e. surface area of exposed pyrite that can be easily oxidized) is a key factor in ARD production. As the fines content increases, peak production rates increase and can be sustained for a longer duration before decline of acid production to long term rates. Three samples of waste rock were collected and screened to estimate the content of fines. The fines content of the Main Dump (two samples)

ranged from 5.0 to 6.6% of the rock mass and also exhibited the same concentration of sulphide. Increasing the average fines content (model input) by 32% (from 5% to 6.6%) increased the peak acid production by about 11%. This strategy suggests peak ARD rates are limited by other factors and although the fines content is a key factor for many waste dumps, it is not a major factor in controlling peak ARD rates for Equity's Main Dump.

The one factor for which there is no information is the weathering rate of rocks. Weathering serves to replace the fines which are consumed as acid generation proceeds. A modest weathering rate has been used for the Equity dump and as such is not a key factor. Increasing the weathering rate of the rock will reduce the rate of decline and marginally increase the long term ARD rate.

Model Results vs. Empirical Estimates

Peak acid production rates were calculated by modelling and by the use of empirical estimates. These estimates are compared in Table 1.

The model estimates peak acid generation rates of 7,800 t/a. These levels are increased to approximately 8,200 t/a if the fines levels is increased in the Main Dump. The model results compare favourably with all empirical estimates and calculations from measured field data for 1990.

A review of the estimates suggests that the Technical Committee report was conservative and may well have underestimated the benefits of cover. However, the fact that all estimates are within a factor of 2 is remarkable and suggests that, overall, there is a good understanding of the scope of the ARD problem in the present case.

The 100 year average ARD levels from the ARD model and from the Technical Committee report are compared on Table 1. Again there is very good agreement between the various estimates.

Present Value of Options

The acid production from the Main Dump and Bessemer Dump for the various cover options is illustrated in Figure 4. The net present values for 1993 to 2093 were calculated using the acid generation data obtained from the model.

The net present value (NPV) calculations assume a fixed cost of $406,000/a plus a variable cost for lime depending upon the annual lime demand. The costs are discounted at 3%/a beyond 1993 using a cost of lime at $138/t. The Technical Committee further added a variable cost for pumping at $0.13/m^3.

The net present value (1993) for the base case is $26,700,000. For the non compacted and semi compacted clay cover, the NPV reduces to approximately $23,700,000 and $20,400,000, respectively. Compacted clay cover reduces the NPV to approximately $14,800,000.

It is doubtful that a clay cover can be installed that will retain all its properties for 100 years; therefore, the NPV is likely between the base case estimate and the compacted clay cover estimate. A NPV of about $20,000,000 would appear to be reasonable.

The Technical Committee estimates varied widely however the most likely estimate with clay cover was $25,900,000 and without cover was $42,500,000. The upper value is well in excess of the estimates from this study, however, the compacted clay cover estimate of $25,900,000 falls within the range of NPV ($14,800,000 to $26,700,000) predicted from this study.

Summary

A preliminary ARD model specific to the characteristics of the Equity waste rock dump was developed. The model predicts acid production very well; however, although predicted concentrations (e.g. sulphate) were not unreasonable, they were not consistently in good agreement with measured field data. The major objectives of the

model were to assess cover effectiveness, to evaluate where potential peaks occur with respect to the ARD production curve and to determine the long term shape of the ARD curve.

The model is believed to be an effective tool to assess the benefits a of cover. The results clearly demonstrate that covers are effective for controlling long term ARD and that the relative effectiveness is a strong function of the characteristics and integrity of the cover material. For the uncovered base case, the model predicts that acid generation will peak in 1990/91 at a level of approximately 8,000 t/a followed by a relatively constant decline in acidity releases to 3,000 t/a by the year 2000. Model runs extended for a 200 year period indicate a slow decline in ARD rates to approximately 65% of the year 2000 levels. This indicates ARD will last for well beyond 100 years, but at levels that are about 20% of those which were predicted for 1990/91.

The short term effectiveness of cover is not totally evident as the Equity waste dumps are believed to have already reached peak ARD rates. Therefore the dump contains large inventories of acid waste that must be drained before the true effectiveness of the cover is apparent. The placement of a clay cover will increase the rate of decline of ARD by reducing infiltration into the dump and it is predicted that by 1995, ARD rates should reduce to approximately one third or less of the peak values. Should the compacted clay cover be totally competent and retain its low permeability, ARD can be essentially eliminated. If the cover is not totally competent but has characteristics of what was modelled for the semi-compacted or non-compacted covers, the ARD rates can be expected to decline to approximately 25 to 30% of the peak values predicted for 1990/91.

In summary we believe the ARD model:

- reasonably reflects ARD production for the Equity waste rock dump;
- is an effective tool for assessing the benefits of a cover on waste rock dumps;
- confirms the predicted shape for the ARD curve;
- predicts that ARD rates peaked in 1991 for the Equity waste rock dump;
- predicts that placement of a continuous, clay cover on the Equity waste rock dump will cause the ARD rates to decline to 33% or less of peak levels by the year 2000; and
- predicts that ARD at the Equity waste rock dump will remain a concern for well beyond 100 years.

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Table 1

ESTIMATES OF PEAK ARD RATES (t/a)
FOR MAIN DUMP AND BESSEMER DUMP

	Model Results	Empirical Estimates		Technical Committee	Peak Measured (1990)
		Oxygen Diffusion	Infiltration		
No Cover		30,000	16,500		
Loose Till Cover (1.4 m)	7,800	12,500	11,000	17,100	8,900[3]
Non-Compacted Clay (0.7 m)		14,575	6,150		
Semi-Compacted Clay (0.7 m)		7,600	3,750	12,100[2]	
Compacted Clay (0.7 m)	430	280			

ESTIMATES OF 100 YR. AVERAGE ACIDITY (t/a)

	Model Results [4]	Technical Committee [5]
No Cover		
Loose Till Cover (1.4 m)	~2,800	5,400
Non-Compacted Clay (0.7 m)	~2,000	
Semi-Compacted Clay (0.7 m)	~2,000	2,100[6]
Compacted Clay (0.7 m)	~130	

Notes:

(1)   peak occurs before placement of cover
(2)   most likely estimate for clay covered option
(3)   not all Bessemer Dump was covered
(4)   extrapolated from model results
(5)   most likely estimates
(6)   most likely estimate for covered option
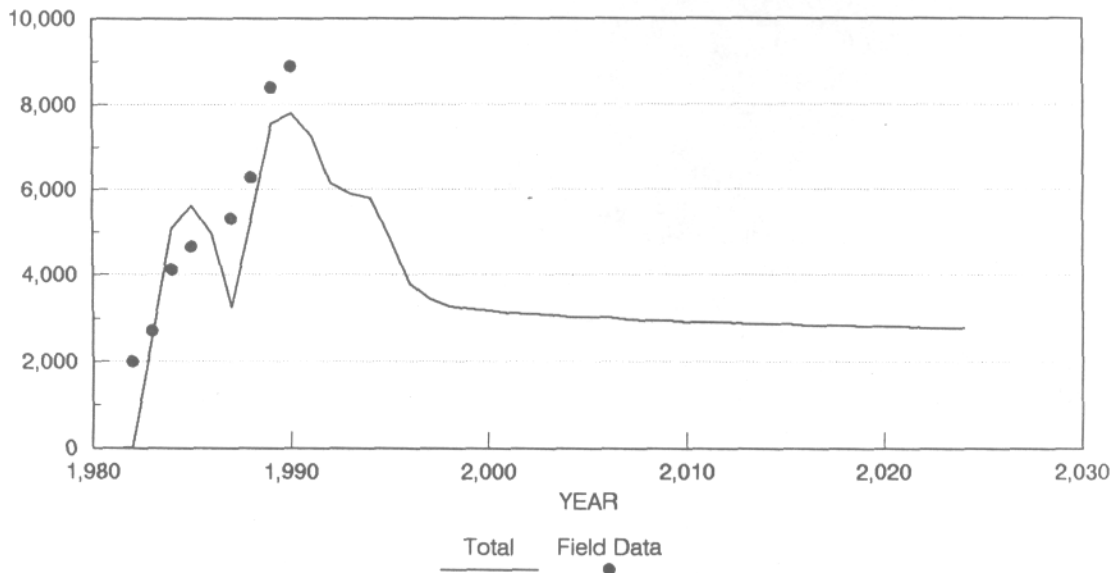
Figure 1
ACID GENERATED
Main Dump

Acid Generated (Thousand Kg CaCO3)

Simulation Field Data
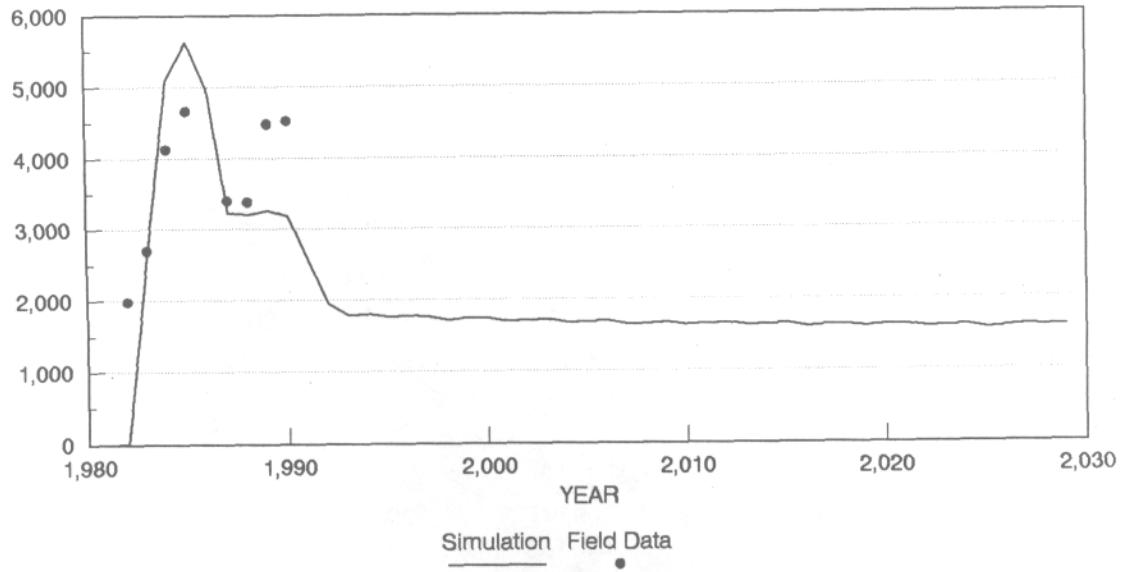
1 m of loose till placed in 1986

Figure 2
ACID GENERATED
Main Dump and Bessemer Dump

Acid Generated (Thousand Kg CaCO3)

Total Field Data

Till and Base Case added

Figure 3

COMPARISON OF COVER EFFECTIVENESS

Main Dump - Acid Generation

Acid Generated (Thousand Kg CaCO3)

Base Case   Till Only   Clay 1   Clay 2   Clay 3

Figure 4

COMPARISON OF COVER EFFECTIVENESS

Main Dump and Bessemer Dump - Acid Generated

Acid Generated (Thousand Kg CaCO3)

Base Case   Clay 1   Clay 2   Clay 3

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