PREDICTION OF SEEPAGE EMANATING FROM A TSF IN AN ARID CLIMATE

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ABSTRACT

The quality of seepage emanating from a Tailings Storage Facility (TSF) is dictated by a dynamic equilibrium between kinetically controlled sulphide oxidation processes, rainfall recharge rates and mineral solubility constraints. A source term characterization study was completed on a closure design for a (TSF) containing predominantly magnetite, quartz, pyrite and pyrrhotite. The objectives of the study were to develop a source-term model for the TSF footprint during operational and closure phases. Static and kinetic geochemical tests and geotechnical tests were conducted on tailings samples collected from the beach, pool and wall sections of the TSF and were used to populate numerical models. A low, average and high case time series of mass loading per unit area was estimated for sections of the TSF and return water dam as a function of various assumptions.

The study concluded that seepage volumes are driven by saturated flows associated with the pool section of the TSF and the return water dam during the operational phase. Dry conditions were predicted for the wall section of the TSF during the operational and post-closure phases which could be attributed a high evaporation and low rainfall in the arid climate. The humidity cells provided an understanding of the acid rock drainage (ARD) reactions and indicated that acidic leachate will be produced soon after deposition from the course tailings, whilst the fine tailings material showed some signs of buffering. Modelling, however, indicated that tailings will oxidize relatively rapidly and that there is insufficient neutralization to buffer acid generation. Derived theoretical closure concentrations showed that salt accumulation will occur much faster through sulphide oxidation than secondary by-products will be flushed if solubility constraints are taken into account.

Key words: Tailings Storage Facility, source-term characterisation, geochemical modelling

1. INTRODUCTION

A source-term characterization study has been conducted in support of the Environmental Impact Assessment and closure design of an existing Tailing Storage facility situated in the Northern Cape Province in South Africa.

The key question that the source term study aimed to answer was:

- What are the likely seepage volumes that flow into the groundwater from the TSF?
- What are the likely seepage mass loads transported into the groundwater from the TSF?
- How will seepage change over time during post-closure with proposed cover?

The source-term model provided an input to the numerical groundwater model that was used to simulate groundwater impacts from the TSF. A preliminary cover design study assessed the performance of various covers to reduce seepage volume and quality from the TSF. The study concluded that a cover comprising of underflow material and rock-soil mixture would limit seepage to a range of 76 to 393 m^3 per annum. The source-term model simulated the effects of the proposed closure design on the seepage volume and mass loads from the TSF.

2. BACKROUND

Figure 1 provides the conceptual model of the TSF footprint area and return water dam (RWD). The sections of the TSF included the; pool, (wet and dry) beach and wall to take count of the spatial variability of seepage flow and geochemical processes. The climate at the study site is arid which is characterized by low rainfall, high evaporation and high daily temperatures. The mean annual evaporation recorded is 3 536 mm (A-pan equivalent). The mean annual rainfall determined from a rainfall record for a rain gauge located in the vicinity is 92 mm. The 95th percentile and 5th percentile of the annual precipitation was determined to be 190 mm and 37 mm respectively.

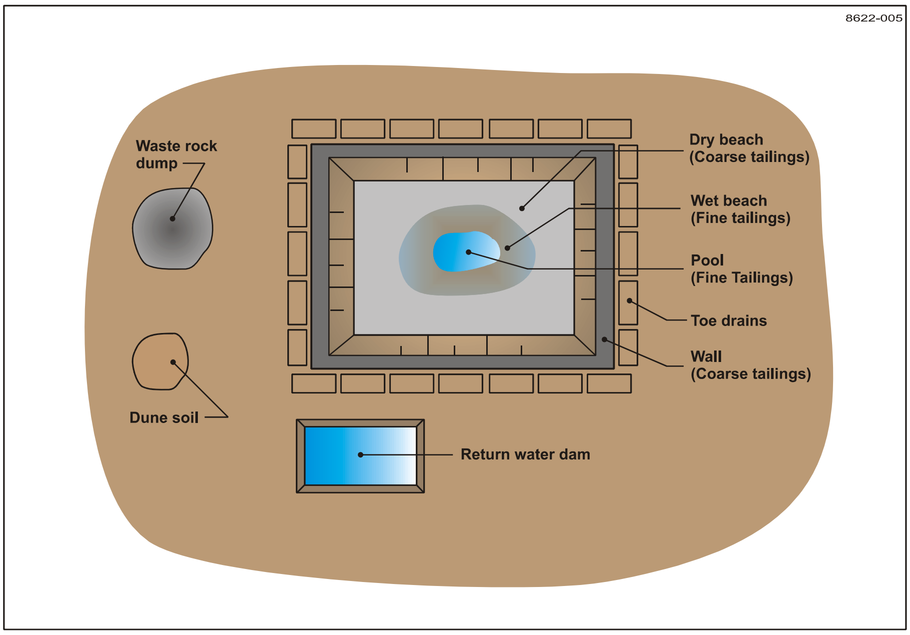


Figure 1. Study area with delineated seepage areas identified – operational phase

3. APPROACH AND METHODOLOGY

The sequential steps followed for the source-term model included: review of available information, field programme, analytical programme, conceptualisation of the TSF and seepage mass load modelling.

The modelling approach is indicated in Figure 2. The integrated mass load model consisted of two key components: a geochemical module and a flow module each supported by detailed specialist models. The modules considered 1-D profiles for: the pool and wet beach (fine tailings) and dry beach and wall (coarse tailings). The quality of seepage emanating from the TSF is dictated by a dynamic equilibrium between kinetically-controlled sulphide oxidation processes, rainfall recharge rates and mineral solubility constraints. Water and gas transport are the main processes affecting ARD and contaminant mobilization from tailings material.

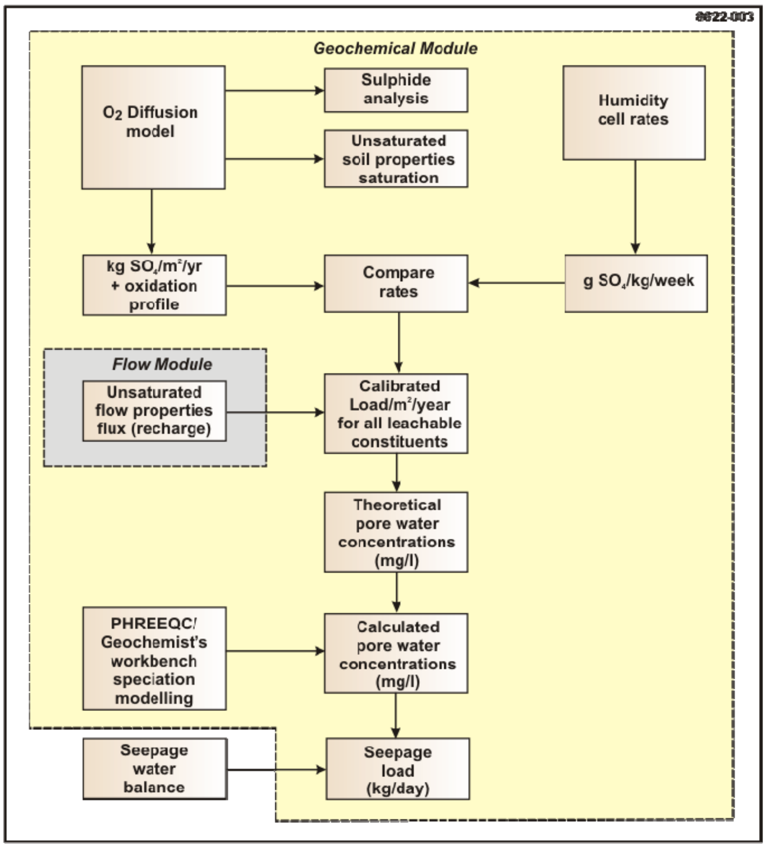


Figure 2. Modelling approach for integrated mass load model (post closure)

The specialist models used were Vadose/W (GeoSlope, 2004); 1D Oxygen diffusion model to model the average oxygen consumption; Phreeqc v 2.1 (Parkhurst and Appelo, 1999) and Geochemist's Workbench Ver. 6.0.5 for modelling of equilibrium reactions and identification of geochemical solubility controls on seepage quality.

The Vadose/W software was used to model unsaturated flows as a function of project phases, operational rules during the operational phase, varying climatic conditions and the material properties. Seepages from areas under unsaturated flows were calculated by applying the Darcian equation. One dimensional flow profiles were constructed to simulate saturated flows and predict seepage rates and moisture conditions for the various TSF sections. The predicted seepage rates were combined with the areas of the TSF sections to translate the predicted rates into seepage volumes from the TSF.

The geochemical module simulated pore water qualities. For post closure a preliminary mass balance was developed to assess sulphide oxidation kinetics and the likely rainfall recharge rates. The results showed that salt accumulation in the tailings will occur much faster than flushing will be able to transport the available salts. The post-closure geochemical modelling therefore assumed that pore water concentrations are governed by solubility constraints and not salt availability. Geochemical speciation modelling for post- closure was conducted using Geochemist's Workbench Ver. 6.0.5., using the thermo.com.V8.R6+ and the thermo_phrqpitz thermodynamic database. Oxidizing conditions (pe 2-5) and gas equilibration were considered to be representative of the likely field conditions. The input water qualities were assumed to remain constant over time. Charge balance errors less than 20 % were considered acceptable.

4. RESULTS

Field Programme

Coarse and fine tailings were collected from the various sections of the TSF (Figure 1). Thirty tailings, eight soils, six rocks and five seepage samples (including QA/QC samples) were collected for the field program. The number of samples was based on the minimum samples (and analytical information) required to populate the specialist models.

Analytical Programme

Characterisation of the geohydraulic properties of the residue and gold tailings involved: water retention at seven suctions (-1, -5, -10, -50, -100, -500, -1500 kPa); moisture content determination; permeability tests; bulk density measurements; and particle size distribution analyses. Static tests included: Acid base accounting (ABA) with sulphur speciation, Mineralogical analyses (XRF and XRD); Distilled water shake flask test and quantification of vacuum pore water extracts from saturated samples. Two humidity cells were set up; one for course tailings and one for fine tailings.

Analytical Results

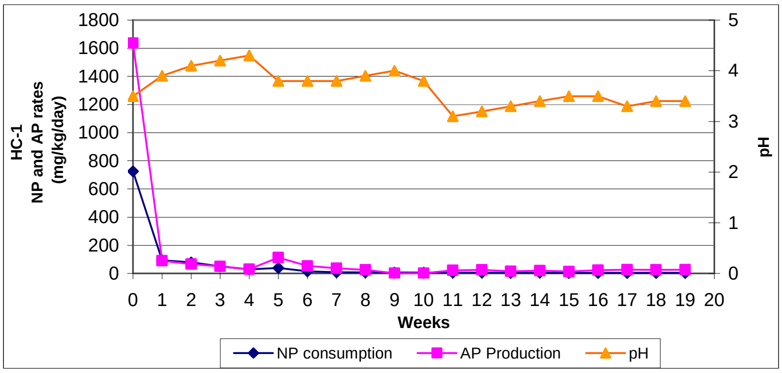
- The saturated hydraulic conductivity of the fine and coarse tailings is lower than the underlying soil and cover material. The underflow of the cycloned tailings and cover material has a high saturated hydraulic conductivity which decreases quickly under moist and dry conditions compared to the tailings materials. This is due to a low air entry value and a steep desaturation slope of the water retention function.
- The S^{2-} (sulphide) percentage for the tailings samples ranged from 0.89 - 3.8 %. XRD results indicated that the dominant sulphide bearing mineral is pyrrhotite. The tailings samples have a potential to generate acid as indicated the negative net neutralising potential (NNP) and neutralising potential ratio (NPR) <1 (Price, 1997).
- An increasing concentration gradient was observed for SO_4, Mn and Zn for the depth profile of the beach (coarse) tailing samples as a result of an oxidation front and or layering effects. No front is evident for Ca which is likely to be controlled by gypsum solubility constraints.

The course humidity cell had an acidic start pH and the fine humidity cell (HC-1) turned acidic after 5 weeks. The primary and secondary oxidation rates were calculated (method based on Morin and Hutt, 1997) and are presented in Table 1. Figure 2 shows the calculated Acid Generation Rates (AGR) and Neutralisation Consumption Rates (NCR) based the humidity cell tests results.

Table 1. Calculated primary and secondary oxidation rates from humidity cell data

Acid Generation Rate	Primary Oxidation Rate ($gFeS_2/t/week$)	Secondary Oxidation Rate ($gFeS_2/t/week$)	Time to total pyrite oxidation (years)[1]	
			TAP[2]	**SAP[3]**
HC 1 (Course tailing)	4 300	246	9.4	1.95
HC 2 (Fine tailing)	1 903	63	22	12
Neutralisation Consumption Rate	**Primary Neutralisation Consumption Rate (g/t/week)**	**Secondary Neutralisation Consumption Rate (g/t/week)**	**Time to total NP consumption (years)**	
HC 1 (Course tailing)	2 214	81	0.00	
HC 2 (Fine tailing)	1 917	53	0.90	

Note: [1] *Based on secondary oxidation rate from humidity cell*
[2] *TAP –Total Acid Production based on Total %S AP calculated for HC1 and HC2*
[3] *SAP –Sulphide Acid Production based on the highest % S^{2-} obtained for the HC composites.*



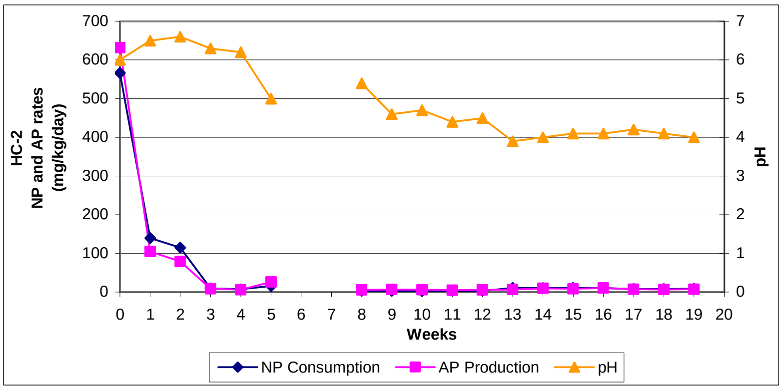


Figure 3. Acid generation and neutralization consumption rates humidity cells

From Figure 3 (and Table 1) it is evident that the initial NP consumption rate for course tailings (HC 1) is almost half the initial AP production rate calculated. This indicates that there is insufficient acid neutralizing minerals. The initial AP and NP generation rate of HC 2 (fine tailings) are almost equal indicating the dissolution of fast reacting neutralising minerals until complete depletion.

Modelling Results

Flow Modelling

Moisture conditions were modelled for steady state conditions which represents a condition where the flows through the TSF are in equilibrium with the climatic conditions. The moisture conditions were predicted for the cases where the flows are in equilibrium with a wet, average rainfall and dry year. Table 3 indicates the modelled moisture content (average case only) seepage volumes with a sand /soil cover considered for post-closure.

Table 3**.** Summary of predicted seepage volumes for operational and post-closure phases

Project Phase	**Section**	**Moisture (average)**	**Seepage volume (m^3/day)**		
			Low Case	**Average Case**	**High Case**
Operational	Pool		2	26	310
	Beach	15 (20)	3.9	5.2	8.2
	Wall	0.65 (6)	0.14	0.2	0.28
	Return Water Dam		6.6	74	821
Total			**15**	**95**	***1 142***
Post-Closure	Intermittent ponding	6.6	0.011	0.029	0.052
	Free runoff	2.6	0.078	0.21	0.37
	Wall	1.2	0.14	0.36	0.62
Total			**0.23**	**0.60**	**1.1**

Notes: Value in brackets indicates measured values

The model results indicate that the cover layer is mostly dry due to high evaporation and low rainfall. The surface of the cover layer is occasionally saturated during rain events, but desaturates quickly thereafter. Dry conditions were modelled for the material underlying the cover layer. The intermittent ponding region has higher moisture content than the free runoff and wall regions due to the occasional ponding and the higher water retention capability of the fine tailings at the intermittent ponding section

Geochemical Modelling

Oxygen is consumed in the ARD processes associated with sulphide wastes and will cause a gradient in oxygen concentration in the TSF. Measured humidity cell rates were moderated by applying diffusion rate limitations based on the material properties and field conditions. The relevant material properties (obtained from laboratory analyses and or unsaturated flow modelling) and rates applied are listed in Table 4. The tailings thickness was assumed to be 50 m and rock/soil cladding was assumed to be 0.5 m. The O_2 diffusion model indicated that interstitial oxygen is rapidly consumed for the primary oxidation rate resulting in low oxygen concentrations below 2 m depth. The resultant flux of oxygen across the surface of the coarse and fine tailings material is 2.96×10^{-9} kg $O_2/m^2/s$ and 1.97×10^{-9} kg $O_2/m^2/s$ respectively.

Table 4**.** Input parameters used for O_2-diff modelling

Underflow wall					
Parameters/TSF Sections	**Units**	**Rock/soil cladding**	**Beach fines**	**Wall**	**Underflow wall**
Porosity	%	0.28	0.54	0.51	0.49
Near surface saturation	%	2.5	21	10	5
Bulk Density	kg/m3	1 850	1 700	1 800	1 970
Primary rate	kg/FeS/kg tailings/week		1 900	4 300	4 300
Secondary rate	kg/FeS/kg tailings/week		60	250	250

Seepage Quality

The seepage qualities for the operational and post-closure phases are indicated in Table 5 and Table 6.

Table 5. Seepage quality (in mg/l) predicted during operational phase

Section/ Parameter	Pool			Beach			Wall		
	Low case	Average Case	High Case	Low Case	Average Case	High Case	Low Case	Average Case	High Case
pH	7.1	6.2	3.8	6.4	6.0	4.0	4.6	4.4	3.2
Alkalinity	14	35	0.00	2.2	2.1	3.0	0.00	0.00	0.00
Cl	80	90	250	24	73	110	580	590	1 335
SO_4	2 000	2 000	2 400	4 600	8 600	10 900	166 000	273 500	371 200
As	0.5	0.5	0.01	0.06	0.07	1.0	3.3	4.8	4.9
Al	0.00	0.00	6.8	0.00	0.35	330	680	4 200	7 900
Ca	580	560	590	455	510	520	245	250	260
Cd	0.00	0.03	0.03	0.70	3.9	7.4	90	100	300
Cu	0.03	1.4	0.00	0.05	0.20	0.00	0.00	0.00	45
Fe	0.01	3.2	160	0.60	0.70	500	700	1 700	4 200
Mg	60	60	65	380	400	580	9 400	10 000	11 200
Mn	40	60	100	8.3	1 800	2 500	52 200	52 600	56 900
Zn	1.7	3.6	5.9	20	40	3 100	22 900	30 800	102 000

Table 6**.** Seepage quality predicted during post-closure (with proposed cover)

Material / Parameter	Fine tailings pore water quality		Coarse tailings pore water quality	
	Low case (mg/l)	High Case (mg/l)	Low case (mg/l)	High Case (mg/l)
SO_4	>195 300	>327 800*	>239 100	>408 500*
Mn	>46 100	>94 600*	4 800	> 189 200*
Zn	>30	>16	2 000	>25 600
Fe	<0.001	>178*	<0.026	>45 500*
Mg	>24 100	26 100	>6 300	17 800*
Na	>14 400	28 100	7 700*	>15 800
Al	<0.001	>50	<0.001	>3 060
Cu	>2.2	>22	<0.43	>460
Ca	<185	571	<2.9*	520
Cd	>50	>25	>751	>100
As	>80	>42	>150	>20

Notes: **Values determined using the pitzer database > and < sign indicates parameter with increasing and decreasing modeled concentration respectively i.e no geochemical controls found for parameters with increasing concentration. Maximum evaporative concentration are indicated as modelled concentrations e.g. Ca*

5. DISCUSSION

Static and Kinetic Test

- The kinetic tests indicate that ARD processes will start immediately after deposition. The coarser material is much more susceptible to oxidation and will produce an acidic leach soon after deposition. The fine tailings material show more diffusion limitations than the course tailings. The acidification over time does show that the fine tailings will oxidise relatively rapidly and there is insufficient neutralisation to buffer acid generation.
- There is low availability of neutralising minerals in the tailings as indicated by mineralogical, ABA and humidity cell results. The low Neutralising Potential implies that the post-closure water qualities will trend to the high case in the long term.

Flow Modelling

- The seepage volume from the TSF during the operational phase is predominantly driven by saturated flow associated with the pool.
- Dry conditions were predicted for the TSF for the post-closure phase and the wall section during the operational phase. This could be attributed to the arid climate with high potential evaporation and low rainfall.
- The predicted seepage volumes under post-closure steady state conditions are significantly lower than during operational phase since seepage is driven by unsaturated flow process which is an order of magnitude lower compared to saturated flow occurring during operational phase.

Geochemical Modelling

A fundamental assumption of the seepage quality modelling is that the interaction of the TSF seepage and underlying calcrete does not change the seepage quality that is reporting to the groundwater. This is a conservative assumption based on the initial interaction of the seepage with calcrete which results in an interface and reduced metal mobility. This interaction is rapid and the interface or "armouring" forms rapidly and once present remains in equilibrium with the seepage during transport to the groundwater. Hence it is expected that the seepage quality from the TSF will be unchanged on flowing through the calcrete once the armouring is formed.

Operational Phase

- The average and high case pool seepage quality (operational phase) was predicted to be near neutral (pH 6.2) and acidic (pH 4.0) respectively. The high case pool quality is conservative and indicates the penstock water quality after flushing of historically oxidized tailing material. The (operational) beach area seepage pH is expected to range from 4.0 -6.4 pH units and can be attributed to the degree of oxidation occurring in the wet beach and dry beach areas of the tailings facility.
- A field scaling up factor of one thousand times was applied to the humidity cell rates based on the difference of the O_2 flux; calculated from the humidity cell results and as predicted by O_2 diffusion modelling. Hence the time required for the sulphide materials to be consumed ranges from 2000 to 12 000 years based on sulphide AP. The low availability of neutralizing minerals present in the tailings is insufficient to neutralize acid generation.
- Gypsum ($CaSO_4.2H2O$) was predicted to control the Ca and SO_4 concentrations at pH 3.2 to 7.1 during operational phase. The SO_4 concentrations for the beach (high case) and wall seepage quality was predicted to be 11 000 mg/l and 166 000 – 371 000 mg/l respectively. The higher concentrations relate to concentration in the pore space as a result of evaporative losses.
- Elevated metal concentrations were predicted in the wall section for Mn and Zn (52 000 – 57 000 mg/l and 23 000 – 102 000 mg/l respectively) due to limited mineralogical control predicted. Several other minerals (Diaspore, Cuprite and Barite, Cuprous ferrite) were predicted to control the dissolved concentration of metals under oxidizing conditions.

Post-Closure Phase

- For the post-closure seepage quality the low case calculations were conducted using solutions with pH values of 7, indicating an unacidified system. High case concentrations were modelled using similar pore water chemistry, but assuming that sufficient sulphuric acid will be produced to result in a pore water pH of < 2. These two scenarios take account of the possibility that metals may be immobilised at neutral pH, until all neutralizing potential is consumed in the tailings. This is expected to occur for a limited period if any neutralizing minerals are present. Likely long-term and high case concentrations will occur under acidic conditions.
- Derived theoretical post-closure concentrations showed that salt accumulation will occur much faster than flushing will be able to transport available salts. Geochemical modelling thus assumes that pore water concentrations are governed by solubility constraints and not salt availability. The long term pore water concentrations are likely to resemble the maxima predicted as sufficient sulphur is present to achieve the predicted concentrations as calculated with Vadose/W.

Mass Loads

The major constituents comprising the seepage to groundwater are: SO_4, Cl, Ca, K, Mg, Mn Na and Zn. The likely SO_4 load emanating from TSF during the operational phase was estimated to be 33 kg/day to 55 kg/day. High salt concentrations were predicted in the post-closure pore water implying a significant contaminant load may be released below the tailings system in the long-term (post-closure). Due to the dry climatic conditions it is likely that the seepage during post-closure could be transported upwards resulting in deposition of salts on the surface. It is thus possible that this may become the predominant fate of the salts generated. However, unsaturated flow can still occur in slightly wet material.

6. CONCLUSIONS

The following conclusions can be drawn from the study:

- Sample representivity was assessed based on statistical variance of the analytical results from the samples collected. The maximum statistical error in analysis of 22% can be anticipated as one of the many factors which contribute to model uncertainty for the geochemical model. The variance related to these effects was taken into account when defining uncertainty ranges for the various input parameters;
- The tailings samples have a potential to generate acid as indicated the negative nett neutralising potential (NNP) and neutralising potential ratio (NPR) <1. The waste rock material has possible and or uncertain acid generation potential;
- The kinetic tests indicate that ARD processes will immediately start after deposition. The coarser material is much more susceptible (as indicated from kinetic tests) and will produce an acidic leach soon after deposition. The fine tailings material show some signs of buffering, however the acidification over time does show that this material will oxidise relatively rapidly and there is insufficient neutralisation to buffer acid generation;
- O_2 diffusion model predicted that the site specific oxidation rates will be 215 times slower compared to the secondary humidity cell rates and 1 014 times slower when compared with primary humidity cell rates. Therefore a maximum scaling factor of about a thousand times slower than the humidity cell rates was predicted by the O_2 diffusion model. The predicted time required for the sulphide materials to be consumed ranges from 1200 to 12 000 years;
- Modelled concentrations are based on the assumption that ionic ratios generated through weathering in the field will be similar to those measured in the humidity cells. This assumption is likely to be valid for an indefinite period after closure. In the long term differences in kinetics and preferential leaching of mobile elements may result in changes in calculated pore water concentrations over time due to associated changes in expected ionic ratios.
- There is low availability of neutralising minerals in the tailings as indicated by mineralogical, ABA and humidity cell results. The low Neutralising Potential implies that the post closure water qualities will trend to the high case in the long term;
- The seepage volumes during the operational phase are driven by saturated flows associated with the pool section of the TSF and the return water dam; and
- Dry conditions were predicted for the wall section of the TSF during the operational phase. Dry conditions were also predicted for the TSF during the post-closure phase. This could be attributed to the arid climate which has a high evaporation and low rainfall.

The following recommendation can be made from the source-term study:

- Increased confidence in the predicted seepage volumes could be attained by improved data on the saturated hydraulic conductivity of the underlying calcrete. The effects of the calcrete interaction with the seepage quality also needs to be considered in order to improves the predicted mass loads to groundwater;
- Conduct field scale lysimeter tests during operational and closure to asses the seepage behaviour under field conditions. The field data can be used to calibrate and refine the modelling results; and
- Calibrate modelled values against monitoring data during and after the operational and closure phase of the mine. This may be available and can be used to update the source term model alternatively monitoring protocols need to be implemented.

7. REFERENCES

Van Neikerk, A.M., 1997. Generic Simulation Model for Opencast Mine Water Systems, WRC Report NO. 528/1/97.

ASTM D 5744-96, 200. Standard Test Method for Accelerated Weathering of Solid Material Using a modified Humidity Cell, America Society for Testing and Materials (ASTM), United States.

Geoslope, 2004. Vadose/W software, Geo-Slope International Ltd, Calgary, Canada.

Morin, K.A and Hutt,N.M 1997, Environmental Geochemistry of Minesite Drainage, Canada, ISBN 0-9682039-0-6.

Price,W., 1997 “Guidelines and Recommended Methods for the Prediction of Metal Leaching and Acid Rock Drainage at Minesites in British Columbia, April 1997”.

Parkhurst, D., and Appello, C.A.J., 1999. Phreeqc version 2.0.

Usher, B.H., Cruywagen, L.M., de Necker, E. and Hodgson, F.D.I. 2001. On–site and Laboratory Investigations of Spoil in Opencast Collieries and the Development of Acid Base Accounting procedures, WRC Report.