phelps dodge Tyrone, Inc. P. O. Drawer 571, Tyrone, New Mexico 88065 • (505) 538-5331

October 31, 2006

Certified Mail #70023150000565800000
Return Receipt Requested

Mr. Clint Marshall
Groundwater Quality Bureau
New Mexico Environment Department
1190 St. Francis Dr. P.O. Box 26110
Santa Fe, New Mexico 87502

CertifiedMail#70023150000565800017
Return Receipt Requested

Mr. David Ohori
Mining and Minerals Division
Mining Act Reclamation Program
1220 South St. Francis Drive
Santa Fe, New Mexico 87505

Dear Messrs Marshall and Ohori,

Re: Submittal of Revised Seepage Investigation Report for Leach Ore and Waste Rock Stockpiles, DP-1341 Condition 81, GR010RE Condition 1.6

Phelps Dodge Tyrone Inc. (PDTI) is pleased to submit the enclosed reports (3 copies each) entitled ***Revised Seepage Investigation Report for Leach Ore and Waste Rock Stockpiles.*** The report was prepared by Daniel B. Stephens and Associates on behalf of PDTI. Also included is the electronic version of the report.

Should you have any questions or comments regarding this submittal, please contact Mr. Greg Schoen at (505) 574 6359.

Very truly yours,

Thomas L. Shelley

Thomas L. Shelley, Manager
Environment, Land and Water

TLS:gs
Attachments
20061025-102

Revised Seepage Investigation of Leach Ore Stockpiles and Waste Rock Stockpiles

Final Report: DP-1341 Condition 81 Tyrone Mine

Volume 1: Report, Appendices A and B

Prepared for	**Phelps Dodge Tyrone Inc.** **Tyrone, New Mexico**

October 31, 2006

Daniel B. Stephens & Associates, Inc.

6020 Academy NE, Suite 100 • Albuquerque, New Mexico 87109

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List of Acronyms

ABA	acid base accounting
AGP	acid generating potential
ANP	acid neutralizing potential
ARD	acid rock drainage
CCP	closure/closeout plan
cm/s	centimeters per second
cm/yr	centimeters per year
CO_2	carbon dioxide
COC	contaminant of concern
DBS&A	Daniel B. Stephens & Associates, Inc.
DP	discharge permit
EC	electrical conductivity
GETS	*Geochemical Evaluation of Tailings and Stockpiles*
GIS	geographic information system
gpd	gallons per day
gpm	gallons per minute
GWB	Geochemists Work Bench
HCT	humidity cell test
K_{sat}	saturated hydraulic conductivity
MA	mineral assemblage
meq/L	milliequivalents per liter
mg/L	milligrams per liter
mmhos/cm	millimhos per centimeter
µmhos/cm	micromhos per centimeter
MWMP	meteoric water mobility procedure
NMED	New Mexico Environment Department
O_2	oxygen
PDTI	Phelps Dodge Tyrone Inc.
PLS	pregnant leach solution
PMC	*Preliminary Materials Characterization*
ppm	parts per million
SCS	U.S. Soil Conservation Service
SEM	scanning electron microscope
SMC	*Supplemental Material Characterization*
SPLP	synthetic precipitation leach procedure
SX/EW	solution extraction/electrowinning

List of Acronyms (continued)

TCaCO3/kT	tons $CaCO_3$ per kiloton of rock
TDS	total dissolved solids
wt pct	weight percent
XRD	X-ray diffraction
XRF	X-ray fluorescence

1. Introduction

Phelps Dodge Tyrone Inc. (PDTI) is submitting this document in order to fulfill its requirements as a mine operator in the state of New Mexico. The New Mexico Environment Department (NMED) issued *Supplemental Discharge Permit for Closure DP-1341* (April 8, 2003) to PDTI for the Tyrone Mine (Tyrone). Section III of the permit requires PDTI to conduct studies of Tyrone and implement mine closure and closeout actions as a condition of the permit. This study is being conducted to fulfill the requirements of Condition 81 of the permit. Condition 81 is written in the permit as follows:

> 81. Tyrone shall submit a revised seepage investigation report for the Leach Ore Stockpiles and Waste Rock Piles under closure conditions. In accordance with the schedule approved under Condition 74, Tyrone shall submit to NMED for approval a work plan, including an implementation schedule, for a revised seepage investigation for the Leach Ore Stockpiles and Waste Rock Piles. The study shall be designed to consider the data needs for Conditions 82, 83, and 89, and the results of the materials characterization study described in Condition 80. The purpose of this investigation is to predict, at a minimum, the quantity and quality of seepage from individual Leach Ore Stockpiles and Waste Rock Piles and potential associated impacts to groundwater and surface water following Cessation of Operation.

The revised seepage investigation work plan (Greystone, 2004a) describes PDTI's proposed supplemental study to fulfill the requirements of Condition 81 of the permit. This final report was identified in the work plan as being one of the requirements for Condition 81. The primary purposes of this report are to provide the results of stockpile material and seepage characterization investigations and the results of PDTI's seepage modeling. Certain mine facilities, including stockpiles, will be reclaimed prior to the next permit renewal in 2008. PDTI reserves the right to modify the conclusions of this report based on these reclamation activities.

The overall objectives, scope, and schedule of this study are stated in Sections 1.1, 1.2, and 1.3, respectively. Applicable background information on the Tyrone stockpiles, related reports on stockpile seepage and runoff, and other supporting studies conducted for closure and closeout planning are described in Section 1.4. Section 2 provides the methods used for this investigation of the stockpile's hydraulic properties and seepage and runoff quality. PDTI's modeling methods for simulating the stockpile seepage flow and quality during and after mine closure are also provided in this section. The alternatives analyzed for this study and coordination of this study with other closure studies is discussed in Section 3. Section 4 reports the results, and Section 5 provides a discussion of the seepage monitoring that is occurring at this site. Section 6 describes the potential impacts to groundwater and surface water and supporting analyses. The conclusions of the study are provided in Section 7, and a bibliography of relevant documents is provided in Section 8.

1.1 Objectives

There are four primary objectives of this study:

- Characterize the quality and quantity of seepage and runoff from the existing leach ore and waste rock stockpiles

- Estimate the quality and quantity of seepage and runoff from the leach ore and waste rock stockpiles during and after mine closure

- Estimate potential impacts to groundwater and surface water during and after mine closure

- Provide data and analyses to support conditions 80, 82, 83, and 89 of DP-1341

This study has incorporated additional objectives in order to support studies required by other conditions in Permit DP-1341 as they are implemented.

1.2 Scope

The scope of this study includes:

- Document review and database compilation
- Stockpile seepage and runoff characterization

- Stockpile hydraulic testing
- Stockpile seepage and runoff quantity and quality modeling
- Estimation of stockpile mass loading to ground and surface water
- Evaluate potential groundwater quality beneath stockpiles
- Evaluate the impacts of geochemical processes on slope stability

The last scope item will be undertaken to support the *Supplemental Slope Stability Analysis* (Golder, 2003).

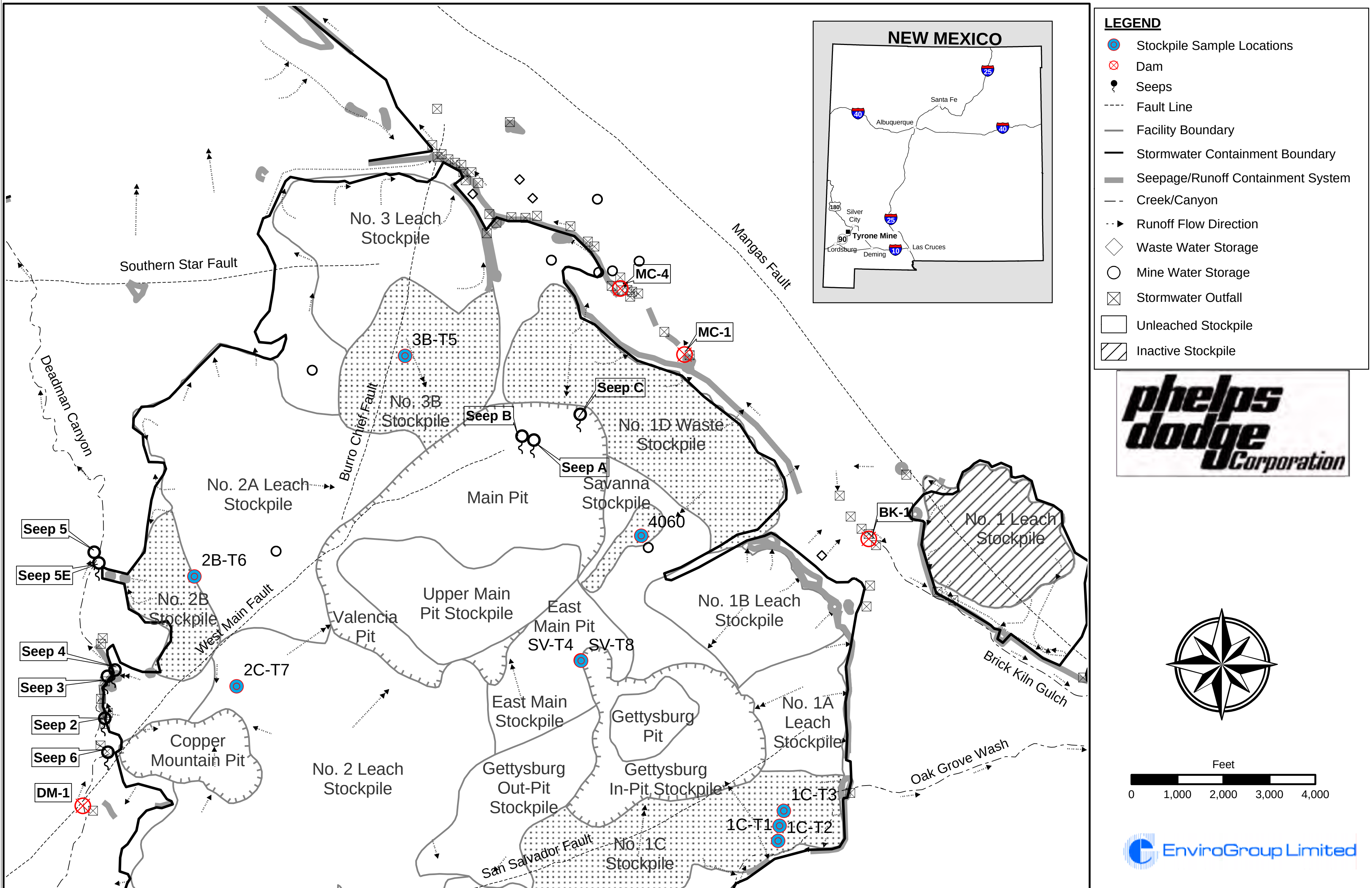
Seepage and runoff quantity and quality from all existing leach ore and waste rock stockpiles at Tyrone will be evaluated. The leach ore stockpiles that will be evaluated for closure and closeout planning are defined in DP-1341 (NMED, 2003) as follows:

- No. 1 stockpile (presently inactive)
- Nos. 1A and 1B stockpiles
- Nos. 2 and 2A stockpiles
- No. 3A stockpile
- East Main stockpile
- Gettysburg Out Pit stockpile
- Gettysburg In Pit stockpile

The waste rock stockpiles that will be considered in this study are:

- Nos. 1C and 1D stockpiles
- No. 3B stockpile
- Portions of the 2B, Savanna, and Upper Main stockpiles.

The locations of these facilities are shown in Figure 1-1. These stockpiles contain the majority of mine materials that will ultimately remain at the Tyrone Mine after closure. Hence, the potential impact to surface water and groundwater resulting from the construction and leaching of these stockpiles will be represented by evaluating current impacts from cumulative seepage and runoff discharges through time. In addition to the existing configurations of the stockpiles,



Source: Tyrone Mine Coverages, Bill Seibert, 2004.

phelps dodge Corporation

EnviroGroup Limited

TYRONE MINE

FIGURE 1
EXISTING STOCKPILE FACILITIES AND CONTAINMENTS

ANALYSIS AREA: Tyrone Mine, Grant County, New Mexico

Date: 4/22/04

Drawn By: JMR

File: R:\PD-0447(Phelps-Dodge)\EGL-TMP-Working\NewStockpiles2-egl.mxd the DP-1341 reclamation alternative will be evaluated in this study. The final alternatives will be selected based on the findings of the feasibility study described in DP-1341, Condition 89 (NMED, 2003).

1.3 Background

Tyrone is an open pit copper mine located adjacent to State Highway 90, approximately 10 miles southwest of Silver City in Grant County, New Mexico. The general layout of the existing stockpile facilities at the Tyrone Mine is shown on Figure 1-1. Background information for Tyrone is provided in the Tyrone closure/closeout plan (CCP) (M3, 2001), which was submitted pursuant to the New Mexico Mining Act and associated rules, the New Mexico Water Quality Act, and the New Mexico Water Quality Control Commission regulations. Baseline and future mine closure design studies were conducted in support of the CCP, including studies of leach ore and waste rock stockpiles. Additional closure studies are required by Condition 74 of Permit DP-1341. Section 1.3.1 describes the relevant stockpile facilities that have been studied for the revised seepage investigation, and Section 1.3.2 summarizes the relevant investigations previously conducted at Tyrone that support this Revised Seepage Investigation.

1.3.1 Leach Ore and Waste Rock Stockpile Facilities

Solution mining technology (Bartlett, 1992) is used to extract copper from the leach ore stockpiles at Tyrone. The waste rock stockpiles are used to dispose of excavated materials that have sub-economic copper values. Section 2 of the *Supplemental Materials Characterization Study Work Plan* (Greystone, 2003) presents updated descriptions of stockpile facility construction, operation, and closure methods employed at Tyrone and the stockpile materials characterization studies previously conducted at the mine. This section summarizes the current stockpile leaching, seepage, and runoff management systems at Tyrone.

As shown on Figure 1-1, the Tyrone Mine contains several stockpiles located near and within the Main and Gettysburg pit areas. Tyrone is permitted to discharge up to 98.3 million gallons per day (gpd) of acidic leach solution (raffinate) on top of the leach ore stockpiles (NMED, 2003); however, the typical flow rate is substantially lower and averages approximately half of the allowed maximum rate. The raffinate flows through the leach ore stockpile material and dissolves copper from copper-bearing minerals. The copper-bearing pregnant leach solution (PLS) then flows to the base of the stockpile and reports to PLS surface collection impoundments located at the toe of the stockpiles within pre-mining drainage systems, to subsurface seepage interceptor systems, or to mine pits. The PLS collection impoundments consist of synthetically lined, clay-lined, and unlined impoundments and stainless steel tanks. The seepage containment systems consist of constructed trenches that collect PLS and wells that pump the PLS to the solution extraction/electrowinning (SX/EW) plant for copper recovery as copper cathode. Seepage interception systems are located near the No. 3 stockpile, along Deadman Canyon, in Oak Grove Wash, and in Brick Kiln Gulch (Figure 1-1).

The waste rock stockpiles are not subject to leaching, and the seepage from these stockpiles is a result of natural infiltration of meteoric water that falls on the stockpile surfaces and flows to the base of the stockpile. The interceptor systems also collect and pump perched groundwater affected by PLS and seepage from waste stockpiles. Stormwater runoff flows directly into the pits or is routed through diversions to impoundments located near the toes of the stockpiles in the Deadman Canyon area, below the No. 1C stockpile, and in Oak Grove Wash (Figure 1-1).

1.3.2 Summary of Relevant Studies

The completed mine closure and closeout supporting studies (M3, 2001) that were used to support this investigation and the types of data and information provided in these studies are listed in Table 1-1.

This study utilized information from the *Stockpile and Tailing Pond Seepage Investigation* (Daniel B. Stephens & Associates, Inc. [DBS&A], 1999b), *Geochemical Evaluation of Tailings and Stockpiles* (GETS) (SARB, 1999), *Stockpile Outslope Evaluation Mass Loading Results for the Tyrone Mine* (DBS&A, 2001), *Supplemental Materials Characterization of the Leached Ore Stockpiles* and *Waste Rock Stockpiles,* preliminary and final reports (EnviroGroup, 2005b, 2005c), and other references cited in these documents. The sections in these reports that are relevant to the stockpiles are summarized in Sections 1.3.2.1 through 1.3.2.4, because these reports provided the most relevant data that were used in this investigation. In addition, relevant

Table 1-1. Reports, Documents and Data

Report	Reference	Data Available									
		Site Background	Hydrogeology	Hydraulic Parameters	Stockpile Configurations	Stockpile Compositions	Geochemical Parameters	Physical Parameters	Predictive Modeling (Hydrology/ Geochemistry)	Existing Impacts	Containment Measures
Supplemental Materials Characterization of the Leached Ore Stockpiles and Waste Rock Stockpiles, Preliminary Report	EnviroGroup, 2005b	X			X	X	X	X			
Supplemental Materials Characterization of the Leached Ore Stockpiles and Waste Rock Stockpiles, Final Report	EnviroGroup, 2005c	X			X	X	X	X			
End-of-Year 2001 through 2006 Closure/Closeout Plan	M3, 2001	X	X		X				X	X	X
Stockpile Outslope Evaluation Mass Loading Results for the Tyrone Mine	DBS&A, 2001				X	X	X		X		
Summary of Long-Term Stability Analyses for Stockpiles and Tailing Ponds at the Tyrone Mine	Golder, 2001	X			X	X		X			
Prediction of Impact on Water Quality	DBS&A, 2000a		X	X					X	X	X
Cover Design Study Status Report	DBS&A, 1999a			X			X	X	X		
Stockpile and Tailing Pond Seepage Investigation	DBS&A, 1999b		X		X	X	X		X		
Geochemical Evaluation of Tailings and Stockpiles	SARB, 1999				X	X	X		X		
Preliminary Materials Characterization	DBS&A, 1997a				X	X	X				
Supplemental Materials Characterization Study	DBS&A, 1997c				X	X	X				
Borrow Materials Investigation	DBS&A, 1997e	X			X	X					

data and analyses were used from other studies compiled in the CCP (M3, 2001) and non-closure/closeout-related reports commissioned by PDTI for mine compliance, planning, and operations purposes.

1.3.2.1 Stockpile and Tailing Pond Seepage Investigation Report

The *Stockpile and Tailing Pond Seepage Investigation* report was prepared by DBS&A (1999b) primarily to (1) evaluate the quantity and quality of present and future stockpile and tailing pond seepage and (2) assess the hydraulic connectivity between stockpiles and adjacent surface water or groundwater areas that are or could be affected by releases of contaminants of concern (COCs). The stockpile seepage investigation focused primarily on determining the response of seepage flow and quality to individual precipitation and snowfall events, evaluating the major flow components associated with the stockpiles, and measuring hydrologic and other physical parameters of the stockpiles and underlying native materials. Please note that the western edge of the No. 2A stockpile discussed in the *Stockpile and Tailing Pond Seepage Investigation* report is labeled as the No. 2B Stockpile in Figure 1-1.

1.3.2.1.1 Seep Monitoring. Seepage monitoring was conducted with automated seep monitoring systems at Seep 5E located along the western edge of the No. 2A stockpile between September 16, 1998 and May 5, 1999, and at the collection point of the South Rim seeps located south of the No. 1C stockpile between August 11 and November 2, 1998. Precipitation was also monitored during seep monitoring periods at the Tyrone Mine General Office weather station. Manual flow measurement data were collected at Seep 5E as part of the weekly mine inspections through the period of September 16, 1998 through June 11, 1999.

Average flow at Seep 5E for the period of monitoring varied between 13 gallons per minute (gpm) from September through December 1998 to approximately 6 gpm between January and June of 1999. The variability in flow observed at Seep 5E appeared to be directly related to the amount of precipitation observed during these two periods. Response in flow to precipitation was hours to days. Variability observed in precipitation-related flow events were attributed to the localized nature of the storm events.

The pH of the Seep 5E water ranged between 3.3 and 4.3 during the monitoring period. The pH tended to decrease after precipitation events and rise during dry spells. The electrical conductivity (EC) of the Seep 5E water ranged between 3,750 and 6,700 micromhos per centimeter (µmhos/cm) during the monitoring period. However, fluctuations in EC did not appear to be related to precipitation events.

Manual seep flow data indicated that the average flow at the collection point for the South Rim Seeps for the period of monitoring varied between approximately 4.6 gpm from August through November 1998 to approximately 1.3 gpm between December and June of 1999. The variability in flow observed at the collection point for the South Rim Seeps was directly related to the amount of precipitation observed during these two periods. For the August through November period approximately 7.6 inches of precipitation fell at the mine, and during the period of December 1998 through June 11, 1999 only 1.9 inches of precipitation fell.

The pH of the South Rim Seep water fluctuated dramatically during the monitoring period, from 1.8 to 5.8. A general increase in pH was observed when climatic conditions were relatively dry. There was a rapid decrease in pH after significant rainfall events. The EC of the water at the collection point for the South Rim Seeps ranged between approximately 3,100 and 5,300 µmhos/cm for the monitoring period. The EC fluctuated dramatically following rainfall events.

1.3.2.1.2 Physical and Hydraulic Parameters. In general, field observations indicated that four general types of materials could be found in almost all stockpile lifts. These included a compacted zone near the stockpile surface in which the physical and hydraulic characteristics of the materials have been altered by mine traffic. In addition, three general types of dump materials exist within each lift and lie at angle of repose: (1) a clastic unit consisting of cobbles/boulders, (2) a matrix-supported unit consisting of coarse sands and gravels, and (3) a matrix-supported unit consisting of sands and gravels mixed with clay.

Field hydrologic testing of stockpile top surfaces was conducted as part of the Tyrone cover design study (DBS&A, 1999a). Results from small scale tests conducted with ponded or tension infiltrometers showed that hydraulic conductivities ranged between 10^{-4} and 10^{-5} centimeters per second (cm/s). The large-scale falling head tests yielded top surface saturated hydraulic conductivity estimates that were an order of magnitude higher than those of the smaller-scale ponded infiltrometer tests. The estimated saturated hydraulic conductivity from these tests ranged between 1.5 x 10^{-4} and 1.2 x 10^{-2} cm/s.

The physical and hydraulic parameters affecting the movement of water within the native materials below the stockpiles were measured on two core samples collected during the stockpile seepage investigation. These samples represented both compacted and uncompacted colluvium. The core sample results indicated that the physical and hydraulic properties of the compacted and uncompacted colluvium are markedly different. The measured saturated hydraulic conductivity of the two samples varied by approximately three orders of magnitude. The measured saturated hydraulic conductivity of the uncompacted colluvium was 2.4 x 10^{-3} cm/s while the measured saturated hydraulic conductivity of the compacted colluvium was 1.9 x 10^{-6} cm/s.

The results of the particle size analyses of stockpile grab samples showed large variations in the texture of the stockpile materials. The material making up the stockpile samples varied from cobble size rock to clay-sized particles. The uniformity coefficient of the materials was between 330 and 1,500, and the coefficient of curvature ranged between 1.9 and 6.7.

1.3.2.1.3 Stockpile Modeling. DBS&A developed a numerical model to simulate seepage flow through the Tyrone Mine stockpiles. The numerical model was applied to the western portion of the No. 2A stockpile and calibrated through seepage flow measurements taken at the toe of the stockpile at Seep 5E. Flow within the stockpiles was separated into two types based on anticipated water movement patterns within the stockpiles: macropore and matrix flow. The macropore flow component represented the rapid but short-duration flow (i.e., preferential flow) of water infiltrating from the top surfaces of stockpiles generally in response to intense precipitation events, and the matrix flow component represented base flow conditions within the stockpile system.

Macropore flow simulations. The occurrence and magnitude of preferential flow through the stockpiles were analyzed by evaluating variations in seep flow at the base of the western portion of the No. 2A Stockpile (Seep 5E) following individual precipitation events. The kinematic wave theory was applied to model the preferential flow of seep water through the stockpile. Three precipitation-related flow events were evaluated as part of the kinematic wave calculation of macropore flow. Results of these three separate storm-related flow events indicate that between approximately 0.9 and 3.6 percent of the precipitation that occurred during these storm events resulted in preferential flow through the western portion of the No. 2A stockpile. The peak flow of the Seep 5E hydrograph was adequately simulated by the kinematic wave model. However, the late time tailing of the hydrograph was not captured well because this portion of the hydrograph included matrix flow contributions that were not accounted for by the kinematic model.

Although the results of the kinematic wave analysis were not conclusive, they suggested that for precipitation events between approximately 0.3 and 2.3 inches, most of the water that would infiltrate the stockpile does not migrate as macropore flow. The observed variations were most likely attributable to the varying intensities and durations of individual precipitation events.

Matrix flow simulations. Eight matrix flow simulations were run representing a range of bedrock, colluvium, and infiltration conditions for the western portion of the No. 2A stockpile. The finite-element code SWMS-2D was selected to simulate seepage flow within and beneath the western portion of the No. 2A stockpile. The watershed boundary area for Seep 5E was the perimeter boundary of the No. 2A stockpile, a waste stockpile located within the Seep 5E watershed that abuts and is continuous with the No. 2A West leach system.

Eight different material types were applied to the numerical model including (1) three materials within the main body of the stockpile, (2) upper and lower compacted zones at the top of each stockpile lift, (3) a thin layer of colluvium at the base of the stockpiles, (4) a bedrock unit beneath the colluvium, and (5) alluvium within the drainage emanating from the toe of the stockpile.

A layered system was applied to the stockpile materials in each lift that results from the end-dump process used to construct the No. 2A stockpile. Each lift was formed by repeating the three material types. These material types include (1) a clast-supported clastic unit consisting of cobbles/boulders, (2) a matrix-supported unit consisting of coarse sands and gravels, and (3) a matrix-supported unit consisting of sands and gravels mixed with clay. The individual layers varied between approximately 3.3 and 13 feet.

Summary of Matrix Flow Simulations. Based on the modeling results, the available quantitative and qualitative field data for the stockpiles, and their field experience at Tyrone, the authors of the report believe that model runs 1 and 3 were most realistic. Therefore, they estimated that the infiltration at the top surface of the stockpile (combined macropore and matrix flow) is between 15 and 20 percent of the average annual precipitation at the Tyrone Mine. Simulation results from model runs 1 and 3 show that, of the total amount of precipitation infiltration into the stockpile, between approximately 67 and 70 percent flows into the Seep 5E collection system. The remaining 30 to 33 percent infiltrates into the bedrock unit underlying the stockpile. These amounts equate to between 10.1 and 10.5 percent of average annual precipitation flowing to the Seep 5E collection system and between 4.5 and 4.9 percent of average annual precipitation infiltrating into the underlying bedrock unit.

Estimation of Seepage from Ancestral Drainages into the Underlying Bedrock. Water seeping from the western portion of the No. 2A stockpile ultimately exits the system by one of two pathways. Either it drains directly downward into the underlying bedrock unit (and ultimately into the regional groundwater system), or it flows laterally within the ancestral drainages underlying the stockpile and into the Seep 5E collection system. A small portion of the water flowing within these drainages may also infiltrate into the bedrock unit underlying these drainages. Conservative estimates of water seepage from the ancestral drainages into the underlying bedrock unit were obtained using the Green Ampt infiltration model. The Green-Ampt model was applied for large times, which reduced the model to Darcy’s law with a unit hydraulic gradient (gravity drainage).

For the analysis, the drainages were assumed to be 4 meters wide. The drainage area beneath the western portion of the No. 2A stockpile was then digitized, which produced an estimated area of approximately 5,101 square meters (equivalent to approximately 2 percent of the total area of the watershed covered by the No. 2A stockpile). With a vertical saturated hydraulic conductivity of 7.9×10^{-8} cm/s for the bedrock unit, the estimated infiltration into the bedrock unit from the drainage bottoms was negligible (less that 0.5 percent of the total seepage from the base of the stockpile).

Summary. Numerical model simulation results indicated that between approximately 15 and 20 percent of the average annual precipitation at the Tyrone Mine infiltrates into the stockpiles in an uncovered condition. At the western portion of the No. 2A Stockpile and the South Rim Seep area the simulations indicated that between approximately 60 and 70 percent of the water that infiltrates into the stockpiles ultimately flows to the toe (seep) collection systems. Field results show that there was a noticeable response in flow at the toe collection systems following individual precipitation events. Macropore flow within the stockpile is relatively minor compared to matrix flow, and water quality decreased briefly in response to the precipitation events.

1.3.2.2 Geochemical Evaluation of Tailings and Stockpiles Report

The GETS report was prepared by SARB (1999) to (1) present a geochemical evaluation of the tailings dams and stockpiles at the Tyrone Mine, (2) determine the potential for acid rock drainage (ARD), and (3) evaluate the processes controlling the quality of water exiting the stockpiles and tailings. The following data collection and analyses were completed for GETS:

- Surface trend mapping of stockpiles
- Mineralogical, chemical and acid base accounting (ABA) analysis of selected stockpiles at depths
- Kinetic tests on weathered stockpile material

As part of the *Supplemental Materials Characterization* (SMC) (DBS&A, 1997c), ten kinetic tests were performed on mineral assemblage samples taken from drill cores collected from the bedrock during Tyrone's exploration drilling. These samples were selected by the DBS&A staff to be representative of the main mineral assemblages (MAs) found at the Tyrone Mine. These samples represent materials that have not undergone weathering and oxidation since mining operations began. The first 18 weeks of these tests were reported in previous studies, and in the GETS these tests were continued for a total of 35 to 50 weeks.

The kinetic tests of leach capping, oxide ore, and oxide-chalcocite mineral assemblages (MA-1, MA-2, and MA-3, respectively) indicated an alkalinity production of 1 milligram per liter (mg/L) of

$CaCO_3$ per week and sulfate production of less than 1 mg/L per week throughout the 35 to 50 weeks of testing. The pH was stable at around 6 to 7.

Four of the five kinetic tests of the sulfide mineral assemblages (MA-4, MA-5, and MA-6) indicated a drop in pH, which was initially 7.5 to 8 in the rinsates and then stabilized in the range of 5.5 to 6.5. The alkalinity production was slightly higher in the beginning of the tests than at the end of the tests, but was less that 1 mg/L $CaCO_3$ per week throughout the test period. The sulfate production tailored off (slight drop at the end for three of the samples) at an average of approximately 13 mg/L per week.

ABA (53 samples), solid element concentrations (53 samples), and mineralogical (64 samples) analyses were performed on the No. 1C and Upper Main stockpiles. In addition, 10 samples were collected from the No. 2A stockpile for ABA, for mineralogical analysis, and kinetic tests. These samples were collected after solid element concentration analysis results were obtained for the other two stockpiles investigated. It was deemed not useful to analyze these samples for element concentrations since there is no visible movement of elements through the unleached No. 1C and Upper Main stockpiles.

The 10 samples that were mineralogically analyzed were also analyzed for ABA. The non-extractable sulfur, also called residual sulfur, is primarily pyrite. The acid generating potential (AGP), in the recalculated numbers, was based on the sum of pyritic sulfur and non extractable sulfur. The AGP is 10 to 20 percent higher than the laboratory-reported AGP numbers. All AGP values for the analyzed samples from No. 2A stockpile were within the range 2 to 16.5 tons $CaCO_3$ per kiloton of rock (T $CaCO_3$/kT). Acid neutralizing potential (ANP) was zero for all analyzed samples. As a comparison, the AGP reported for surface samples had a range of 5 to 70 T $CaCO_3$/kT and were much higher than the samples selected from the drill holes.

The elements that are easily affected by acid generation (copper, zinc, and silver) did not show any distinct remobilization. The drill holes Q-110+100, M+100-07 and P-08+100 showed relatively constant copper concentration with depth, while R-010 and S+100-110+100 showed increasing concentration with depth.

Another 10 samples from the No. 2A stockpile, collected during the stockpile drilling performed during 1997 and 1998, were selected together with two samples that had undergone laboratory leach tests at the Tyrone Mine for additional kinetic tests run at the University of New Mexico Engineering Department. This second set of kinetic tests was of stockpile material representing mixtures of materials collected from reverse circulation drilling. The samples were analyzed for grain size distribution prior to kinetic testing. These tests indicated that 30 to 70 percent of the particles in these samples had a grain size of less than 1 millimeter. This resulted in a much higher surface area exposed in the tests than in the stockpiles.

The pH was relatively stable for all samples tested. However, the pH level was higher for the samples with leach cap (3.5 to 5.5) or copper oxide mineralization than for samples of sulfide mineral assemblages (2 to 4.5), while the two copper leach samples stabilized around pH 3. The sulfate concentration in these samples was several thousand mg/L in the first few rinses, and then dropped rapidly one-half to one order of magnitude. The two highest recorded sulfate concentrations in these tests were approximately 80,000 mg/L and 33,000 mg/L for Mix 7 and Mix 8, respectively, for the first week’s rinse. The sulfate increased for most of the samples after 3 to 4 rinse periods, then dropped again. The sulfate increase coincided with the pH increase.

Even after 25 weeks of rinsing the samples, the sulfate concentration of sulfate production was one-half to one order of magnitude higher than for the kinetic tests of the unmined material. This could have been because there were more sulfate minerals left in the stockpile material and/or ferric iron was available for sulfide oxidation, resulting in a much higher sulfide oxidization rate than for the unmined material.

The stockpile flow modeling involved modeling the macropore flow using the kinematic wave theory applied to stockpiles. Using this method, the macropore flow was modeled as channels through the stockpiles. The matrix flow was assumed to be the rock matrix, everything outside the macropore flow.

In order to predict the water quality of seepage exiting a stockpile having a variable grain size composition (clay size to boulder size), it was necessary to know the flow system and reactions within (1) the stockpile void spaces and (2) the stockpile matrix. Reaction time can be quite different in these two systems. DBS&A has modeled the flow system in the No. 2A stockpile based on field observations, rainfall measurements, evaporation measurements, stockpile toe flow measurements, water content of stockpile material, and a conceptual model of the structure of the stockpile. These input data were then used to perform reactive transport modeling of water going through the macropores and the matrix.

The geochemical modeling has attempted to model these two systems separately. The modeling indicated that the matrix flow water quality can be modeled as a whole with oxygen being transported through the system by convection. If modeling the matrix separately, the water quality will stabilize at an almost neutral pH within a few years. However, as long as there is still oxidation in the matrix, the matrix reactions will control the macropore quality.

As the water flows through the matrix it moves through the oxidizing front, increasing in sulfate, ferrous iron, and copper content and becoming lower in pH. On the way out of the matrix toward the macropore channel walls, it goes through the oxidizing zone and into oxidized material, picking up more sulfate and copper. Ferrous iron oxidizes and possibly precipitates as goethite or ferrihydrite.

The deeper parts of the stockpile will have less influx of oxygen and there will be little or no pyrite oxidation. The pH is therefore controlled by the K-feldspar-muscovite mineralogy as seen in the 20-year, 100-year, and 300-year modeling, in which a pH of 5.5 to 6 with low metals content results. There is a sufficient amount of reactive silicate minerals to neutralize all acid generated from the small amount of pyrite within the stockpile as long as the flow is through the matrix.

The stockpile reactive transport simulations, therefore, indicated that if most of the flow through the stockpiles was matrix flow, the water quality leaving the stockpile as seeps and possibly infiltrating to the groundwater will be of better quality than presently observed at the Seep 5E collection, since this present day seep is a mix of matrix and macropore flow waters. As long as the matrix is weathering (pyrite oxidation and silicate mineral alteration), the matrix flow water quality is well represented by modeling the matrix flow as a whole.

1.3.2.3 Stockpile Outslope Evaluation Mass Loading Modeling Results for the Tyrone Mine

The stockpile outslope evaluation report was developed by DBS&A (2001) to compare the stockpile mass loading performance of selected outslope reclamation alternatives in support of the CCP. The three alternatives considered for reclaiming stockpiles that would ultimately reside permanently at the Tyrone Mine after closure were:

- A base case alternative consisted of the planned ultimate (February 2008) stockpile configurations at the mine with angle of repose slopes. Top surfaces were to be covered with a 24-inch soil and borrow material layer and revegetated and outslopes were to be left uncovered.

- A push-down stockpile regrading alternative with 4 to 1 slopes. Both top and outslope surfaces were to be covered with a 24-inch soil and borrow material layer and revegetated.

- A pull-back stockpile regrading alternative with 4 to 1 slopes. The top and outslope surfaces, as well as any excess stockpile material that cannot be regraded within the original footprint area were to be covered with a 24-inch soil and borrow material layer and revegetated.

The primary purpose of this modeling study was to evaluate the relative mass loading modeling results for the three alternatives, as compared to the reference design, and to report the accompanying information on simulated infiltration rates and reactions of stockpile materials with descending meteoric water.

1.3.2.3.1 Site-Specific Modeling Inputs. The compositional and physical models representing the three-dimensional distribution of materials in the proposed 2008 stockpile facilities were reconstructed from geologic resource models and historical mine development records and mine planning sheets. Existing stockpiles have slopes that are at angle of repose, typically 2 to 1 or steeper. Initially, a terrain model of present-day topography was built in the Geographic Information System (GIS) using existing AutoCAD data provided by the mines. Each stockpile was then conceptually regraded to a 4 to 1 slope, and the resulting topography was generated.

The stockpiles were conceptually regraded by balancing cut and fill such that material mass balance was maintained. The area covered by the new footprints of the regraded stockpiles was also calculated using the GIS information.

1.3.2.3.2 Infiltration Modeling Inputs. Infiltration rate estimates for the individual stockpiles and stockpile complexes at the Tyrone Mine and associated outslope alternatives were obtained from UNSAT-H modeling of the interactions that occur in plant, soil, water, and atmosphere systems. These systems were assumed to be mature and well established on the covered surface of closed stockpiles. For uncovered stockpile surfaces, the model did not consider plants interactions, although some plants will likely volunteer on uncovered stockpile surfaces.

Based upon discussions with the NMED and the Mining and Minerals Division (MMD) at the February 1999 technical meetings, the 10-year (1977 through 1986) precipitation and temperature record from Fort Bayard was used for the UNSAT-H modeling. Climatically, the simulation period (1977 through 1986) represented a wet interval in the historical records for this region, including extremely wet winters and summers.

In consideration of written (O'Kane, 2000) and oral comments made by the third party reviewer, runoff was accounted for in the model by adjusting the input precipitation data entered into the UNSAT-H model. Runoff calculations were performed for each outslope alternative by using the precipitation data described above and the U.S. Soil Conservation Service (SCS) curve number procedure.

Daily calculations of runoff were performed for the simulation period (1977 through 1986). The corresponding runoff estimates were then subtracted from the daily precipitation data to obtain equivalent precipitation input files for the UNSAT-H model simulations. Curve numbers were determined for the four different scenarios: covered top, covered outslope (regraded slope, 4 to 1), uncovered top, and uncovered outslope (angle of repose slope, less than 2.5 to 1).

The cover material properties were determined from a sample collected from the No. 1D stockpile and are representative of Gila Conglomerate from the area. The covered stockpile hydraulic conductivity value selected was the geometric mean of the matrix component of the falling head test data, while the uncovered stockpile value selected was the geometric mean of the aggregate falling head test data (DBS&A 1999a, Table 4). Different hydraulic conductivity parameters were used for the covered and uncovered stockpile because it was assumed that the stockpile material would be homogenized during regrading and compacted prior to cover installation, whereas the uncovered outslopes would remain heterogeneous and relatively loose. As a result, the hydraulic conductivity would be, in all likelihood, lower for the covered stockpile material.

1.3.2.3.3 Mass Loading Model Inputs. A stockpile mass loading model was constructed and used to assess the performance of the selected reclamation alternatives. Mass loading performance was tracked because it is a weighted measure of both seepage quantity (i.e., volume) and quality (i.e., constituent concentrations). Therefore, mass loading was used an indicator of which of the three alternative slope configurations minimized the overall potential for impact on groundwater quality relative to no reclamation of the stockpiles.

Data from static and kinetic tests and seepage monitoring were used in the mass loading model. Kinetic tests (i.e., humidity cell test [HCT] modified after the method of Sobek et al., 1978) were performed on sulfide-bearing materials that may produce acidic seepage (DBS&A, 1997c; SARB, 1999). The HCTs were performed on representative samples of Tyrone Mine waste rock (SARB, 1999). The dissolution rates, derived for each waste rock type by interpolation of HCT data, were weighted and multiplied by scaling constants in a master spreadsheet model. This data set contained the results of selected chemical analyses of leachate samples collected weekly. Data for three samples representing mineral assemblages MA-3 (sample BG 32 558’-577’), MA-4 (sample D-36 289’-303’), and MA-5 (sample C+100-19+100 494’-514’) were used for the calculation. These samples were selected because the compositional models of the stockpile facilities presented in the *Preliminary Materials Characterization* (PMC) and SMC show that the primary sulfide-bearing materials (i.e., Group A) in the Tyrone stockpiles were mineral assemblages MA-3, MA-4, and MA-5 (DBS&A, 1997a; 1997c). The last weekly leachate samples analyzed from each HCT were used to derive the steady-state dissolution rate. Measured concentrations were multiplied by four to generate monthly dissolution rates for each constituent.

The composition of a seepage sample collected at Seep 5E from the toe of the No. 2A stockpile was assumed to be similar to leachate from MA-1 (leached cap) materials. MA-1 is the predominant Group B mineral assemblage type. The proportion of each sulfide-bearing material (MA-3, MA-4, and MA-5) in each stockpile spreadsheet model was based on the stockpile compositions presented in the PMC and SMC. Mineral assemblage MA-6 was not considered because it was a minor component of the stockpiles. Therefore, the proportion of each mineral assemblage in each stockpile was normalized to the three primary sulfide-bearing material groups. For facilities that contained MA-1 materials, the ratio of sulfide-bearing material (MA-3, MA-4, and MA-5) to MA-1 was estimated. This ratio was used to simulate the mixture of these leachate components through geochemical mixing modeling. The seepage from stockpiles that do not have a significant contribution of MA-1 materials was assumed to contain a 9 percent component of residual stockpile leachate that is compositionally similar to the Seep 5E composition.

The annual infiltration rates for selected years (1980, 1982, 1984, and 1986) that span the range of annual precipitation amounts represented in the climate record were used in the mass loading model as a steady-state seepage rate. The GIS database and software were used to calculate thickness isopachs of each stockpile by subtracting pre-mining topography from regraded topography. The infiltration and thickness distributions were then fed into the master spreadsheet model to calculate travel times through thickness intervals with 25-foot increments. Integral dissolved loads from waste rock dissolution over the estimated travel time were then calculated within the master spreadsheet.

Geochemical reactions within the stockpile may limit the concentrations of dissolved constituents in solution. The geochemical modeling code EQ3/6 (Wolery, 1992) was used to correct the rate-based loadings calculated by the spreadsheet model for attenuation (chemical speciation and precipitation reactions). The geochemical model also calculated constituent concentrations and a pH for the basal seepage. In addition, by adjusting the amount of sulfide reactant (calculated by the spreadsheet as a mixture of composite HCT leachates) added during the EQ3/6 geochemical mixing simulations, the target proportions of the MA-1 (i.e., Seep 5E) leachate in the stockpiles could be matched approximately.

It was assumed that gypsum and amorphous silica control the concentration of Ca and SiO_2, respectively, in the basal seepage. The solubility of amorphous silica was fixed at 100 mg/L based on numerous observations of such geochemical systems (Nordstrom and Alpers, 1999). Therefore, the predicted basal seepage composition always approached or reached equilibrium with respect to these minerals. For the purpose of the reaction path simulations, several mineral species (quartz, trydimite, coesite, α-, and β-cristobalite, Ca-, H-, K-, Mg-, and Na-nontronites, pyrophillite, illite, hematite, goethite, delafossite, Cu-ferrite, muscovite, microcline, anhydrite, and $CoFe_2O_4$) were suppressed from precipitating because they are not known to precipitate directly from solution in weathering environments. The selection of suppressed minerals was based on scoping geochemical model runs, professional evaluation, and the findings of Nordstrom and Alpers (1999).

The model was calibrated, to the extent possible, to the observed secondary mineral assemblages observed in the stockpiles (SARB, 1999) and in past test examinations of HCT samples (DBS&A, 1998), and to stockpile seepage quality by comparison with the results of sensitivity runs. Seepage quality information from perched zone wells 1-5 and 1-6 located at the toe of the No. 1 stockpile (DP-896) were used for this purpose.

1.3.2.3.4 Infiltration Modeling Results. Infiltration modeling was performed using the UNSAT-H model with runoff-adjusted rainfall for four different stockpile closure cases (covered top, covered outslope, uncovered top, uncovered outslope) at the Tyrone mine. In addition, different curve numbers and soils profiles were used in the model, resulting in a total of 16 sensitivity runs. For the purposes of clarity in this presentation of the model results, infiltration means the water ingress into the top surface of the model domain, which was either bare stockpile or cover material (DBS&A, 2001, Appendix B, Figure B-1). Drainage means the water flux at the 60.25-cm depth below the top surface into the covered stockpile beneath the cover material (covered stockpile runs) or beneath the uncovered stockpile material (uncovered stockpile runs). Once meteoric water entered the model domain as infiltration, it was redistributed among the nodes by evaporation, transpiration, or drainage. Water and water vapor could move upward and be lost out the top surface by evaporation and transpiration. Water could also move downward and eventually out of the model domain by drainage.

An array of drainage values resulted, and four key years of the ten-year simulation period were defined as dry, typical, average, and wet years to delineate the range. The driest year (1980) had the least amount of precipitation (21.3 cm), and likewise the wettest (1986) had the largest amount (65.7 cm). The average year (1984) had total precipitation (45.1 cm) that was slightly above the mean (41.4 cm) for the 10-year period from 1977 through 1986. Finally, 1982 was chosen as typical since the precipitation pattern closely resembled that of southwestern New Mexico (Trauger, 1972), with nearly half of the precipitation (taken from the annual total of 33.2 cm) occurring in the monsoon months (July, August, and September) and a relatively dry spring and fall.

UNSAT-H treated any precipitation that cannot infiltrate into the surface material—based on the hydraulic conductivity of the surface material—as runoff that was lost to the system. The UNSAT-H model predicted no additional runoff after the daily input precipitation totals were modified by subtraction of the runoff previously estimated by the SCS curve number method.

The drainage rates of 0.07, 0.23, 0.66 and 2.26 centimeters per year (cm/yr) through the covered top represent flow out the bottom of the 60-cm cover for the years of interest. Initially the drainage rates were very slow because of the relatively dry climate conditions at the beginning of the simulation, but they increased as the simulation progressed toward higher precipitation years.

The drainage rates of 0.11, 0.25, 0.80, and 3.37 cm/yr were simulated for the covered outslope, and these rates were very close to those for the covered top for the four successive years of interest. The increasing drainage pattern for the uncovered top had drainage rates of 0.28, 1.39, 3.85 and 11.19 cm/yr for the four years of interest. The drainage rates for the uncovered outslope also increased with increasing precipitation with simulated rates of 0.27, 1.38, 3.74 and 10.53 cm/yr for the four years of interest.

1.3.2.3.5 Results of Mass Loadings. The sulfate loading results generated by selected sensitivity runs provided the proportional mass loadings that may occur directly below the top surface and outslope areas of each Tyrone stockpile. In all of the individual mass loading runs, the area underneath the stockpile outslope was significantly wider and the projected mass loading was greater than the mass loading that was simulated beneath the smaller top surface area. The total sulfate loadings for the dry years were smallest, and the wet year totals were the largest.

The total mine sulfate loading patterns were similar to those for each individual stockpile area except for the No. 1 complex and the No. 3B stockpile, both of which showed somewhat higher mass loading for the pull-back alternative (including the pull-back cone) than for the push-down alternatives for all the climate scenarios. For the No. 3B stockpile, this result was attributed to the assumption that materials from the Nos. 3A and 3B stockpiles would be commingled in one pull-back cone volume after regrading the No. 3 stockpile. In some of the sensitivity runs, the No. 1 stockpile, the No. 1 complex, and the No. 3A stockpile also had slightly higher sulfate loadings for the regraded alternatives (push-down and/or pull-back) than for the reference design and base case.

1.3.2.3.6 Equivalent Concentrations. The mass loading model runs also generated equivalent concentrations for seepage below each stockpile outslope and top surfaces based on the simulated annual mass loadings and seepage volumes. The average sulfate concentration in basal seepage for each mass loading model scenario for all Tyrone stockpile areas were weighted according to each stockpile’s seepage volume.

The dry year, typical year, average year, and wet year scenarios have equivalent sulfate concentrations that were progressively lower for the same alternative and scale factor because of the dilution effect. Similarly, for the same climate scenario, the equivalent sulfate concentration increased or diminished as the scale factor or proportion of Group A to Group B materials was increased or lowered. This trend was confirmed by comparison of the dry year results for the mid-scale (0.004) factor to those from dry scenario runs using the low scaling (0.0004) factor, and by comparing the mid-scale and high-scale (0.04) wet year results. The scale factors represent the specific surface areas used in the kinetic models. Stockpile models having the thickest sequences, greatest reactivity, and lowest flows produced the highest average equivalent concentrations. Hence, the top of the No. 3A stockpile, which is composed predominantly of Group A materials and is one of the thickest stockpiles at Tyrone (ultimate thickness of approximately 500 feet), has the highest simulated equivalent concentrations among the base case results for equivalent climate and scale factor scenarios. Similarly, the top surface reference design for the No 3B stockpile mass loading simulations tallied most of the lowest equivalent concentrations among the stockpile models because it had a very high proportion of Group B materials relative to the other stockpiles. It should also be noted that under each stockpile, the simulated sulfate concentration varied above and below the average values because the thicker material sequences yield higher concentrations and thinner sequences yield lower concentrations of sulfate in basal seepage.

The reaction path (EQ6 runs) output files track the composition of the leach solution as it passed through and reacted with the composite stockpile materials. The most consistent trend for the simulated seepage quality was that the concentrations of sulfate, iron, and manganese were attenuated by precipitation of jarosite and pyrolusite, which decreased the mass loading for these constituents. However, the precipitated minerals could also act as sources of dissolved constituents when chemical conditions change along the reaction path such that the solubility of these minerals increases.

1.3.2.3.7 Model Calibration. Accurate prediction of mineral solubility is an important goal of geochemical model calibration under equilibrium conditions. The reaction path (EQ3/6) model predicted the formation of jarosite in all stockpile mass loading simulations, and this mineral species was found in cuttings from the No. 2A stockpile reverse circulation drill holes (SARB, 1999). In addition, a potassium- and iron-bearing sulfate precipitate, which was believed to be secondary jarosite, was detected in several of the HCT samples during scanning electron microscope (SEM) analyses of the reacted materials after the test was completed (DBS&A, 1998). This indicates that active sulfide oxidation and relatively acidic conditions were locally present in the HCT columns even though the leachate samples were only mildly acidic. Such conditions account for the release of sulfate and other constituents during the tests. Gypsum, syngenite (a sulfate mineral species in the same family as gypsum), alunite, pyrolusite, and chalcanthite also precipitated from the simulated leachate during the runs. Many of these mineral species were observed during the SEM analyses, and all of these phases are consistent with those observed in sulfide mineral deposits that are undergoing rapid oxidation and weathering (Alpers and Nordstrom, 1999). Several fluoride species, such as fluorite, also precipitated during the simulations, and fluorite precipitation was believed to control fluoride concentrations in low-temperature, aqueous systems (Jacks et al., 1993).

According to O’Kane's (2000) review comments “Seepage quality predictions will depend on the pile compositional model (based on mine records), humidity cell data, and the geochemical model. Predictions of pH and dissolved COCs should roughly correspond to observed seepage water quality.”

Long travel times (tens to hundreds of years under natural conditions) make model calibration problematic as waste stockpiles are being built faster than water flows through them. Therefore, the models were calibrated, with respect to residence times and scale factors, to seepage quality originating from the No. 1 stockpile by comparison to the equivalent concentrations generated by wet year (1986) sensitivity runs. As explained below, the high-flow runs were not representative of the actual post-closure seepage rates, but they did generate a simulated seepage quality that could be compared to chemical analyses of field samples.

The wet year results from the No. 1 stockpile model were compared to seep monitoring data collected from wells 1-5 and 1-6, which are located at the toe of the No. 1 stockpile. This comparison was valid because the configuration modeled was nearly identical to that of the existing stockpile. The concentration of sulfate in the simulated leachate was somewhat lower in the high scale factor wet year scenario than that observed in the monitor wells. However, the simulated stockpile leachate composition did not account for the addition of ferrous sulfate during the precipitation plant operation. Ferrous iron is brought into solution as a result of scrap iron oxidation, and the sulfuric acid must be added in order to restore acid consumed in the same reaction (Murr, 1980). The addition of ferrous sulfate brings the adjusted sulfate and total dissolved solids (TDS) concentrations in the simulated leachate very close to those observed in the stockpiles toe seepage. After addition of ferrous sulfate, the pH of the simulated leachate also fell within the range of the seepage samples due to the oxidation and hydrolysis of the added iron. Overall, the comparison indicated that the simulated seepage qualities from high scale factor simulations roughly correlated to the actual seepage quality emanating from existing stockpiles.

1.3.2.3.8 Evaluation. The primary metric for this component of Tyrone’s environmental evaluation of stockpile outslope reclamation alternatives was the annualized mass loading. This parameter was more indicative of the potential for groundwater impacts than the infiltration rate or estimated concentrations of constituents in basal seepage taken alone. The annualized mass loading of a dissolved constituent transported (advectively) per unit time was obtained by multiplying the linear infiltration per year by the footprint area of the stockpile (divided into top and outslope sections) times the concentration of constituents in the basal seepage. Therefore, the mass loading parameter was a facility-specific measure of the combined environmental impact from meteoric water flow and geochemical reactions in the stockpiles.

The mass loading results for the reference design were compared to the base case, push-down, and pull-back alternatives to assess their relative environmental performances. Throughout the remainder of this discussion, the term pull-back includes the excess pull-back cone volumes unless explicitly called out. The relative differences were emphasized rather than the absolute values because many of the modeling uncertainties cancel when individual simulation results were normalized to the same reference condition. However, the model calibration indicated that the model was generally accurate with respect to predicting secondary mineral formation and leach solution quality for existing stockpile conditions when the high (0.04) scale factor was applied.

The mass loading model's sensitivity to variable infiltration was tested by running the model with selected infiltration results from the UNSAT-H runs. The model runs included covered and uncovered stockpile scenarios, and a uniform 60-cm cover thickness was applied in the covered scenarios. The sensitivity runs and the cover design study for the Tyrone Mine (DBS&A, 1999a) showed that variable runoff and cover thickness have a much smaller effect on stockpile infiltration than variability in precipitation does. For example, the UNSAT-H model runs conducted in the cover design study showed that the difference in infiltration between a 60- and 75-cm cover for a high-conductivity low-storage cover was relatively small (less than or equal to 1.1 cm/yr) for 1980 (dry year), 1982 (typical year), and 1984 (average year), and for 1986 (wet year) the difference in cover thickness translates into only 2.3 cm/yr of infiltration between the two simulations. This value was less than one-third of the difference in infiltration between the covered and uncovered outslope configurations modeled in the cover design study. Moreover, even the largest difference between the 60- and 75-cm cover results presented in the cover design study (DBS&A, 1999a) was much smaller than the range of infiltration values derived from different annual climate scenarios for the uncovered stockpile surfaces.

The years selected to evaluate the model's sensitivity to variable infiltration spanned the range of the precipitation input values, including the minimum, typical, average, and maximum precipitation years in the decade-long simulation period. Mass loading forecasts were less sensitive (i.e., have smaller variances) with respect to variable climate parameters than the simulated seepage qualities. Uncertainties associated with the scale factor corrections of the HCT dissolution rates were also evaluated and compared to the relative differences for each alternative. The scale factor was varied by one order of magnitude above and below the central estimate of the true scale factor in order to test the model's sensitivity to this key parameter. In all, 389 sensitivity runs were conducted in order to provide a basis for determining the significance of the relative mass loading results for each alternative. Additionally, 12 runs were conducted for the purpose of model calibration to seep monitoring data.

1.3.2.3.9 Comparison of Model Results. The modeling results showed that reductions in seepage quantity achieved through outslope regrading and cover application do not necessarily translate into proportional reductions in mass loading. The wet year, high-scale factor simulations always showed the highest absolute sulfate loadings for a set of sensitivity runs for a given stockpile, whereas the dry year, low-scale factor simulations always showed the lowest absolute sulfate loadings. The sulfate loading for the base case was close to that for the reference design for these particular runs among the individual stockpile results as well as for the total mine results. Furthermore, in the total mine sulfate mass loading comparisons, the bounding conditions high-flow, high-scale factor and low-flow, low-scale factor showed no significant difference among the reclamation alternatives (base case, push-down, and pull-back). This was also generally true for the individual stockpile sulfate loadings.

The mid-scale wet year model runs showed the greatest improvement in performance for the regraded alternatives as compared to the reference design. The base case showed a more modest reduction in sulfate loading for this scenario. However, the wet year had about a 50-year recurrence period, and it is highly unlikely that the wet year infiltration rates would have a significant impact on long-term seepage rates. Mid-scale factor model runs for the stockpile regrading alternatives only showed a modest reduction in total mine sulfate mass loading for the typical climate scenario over the base case alternative and reference design.

The performance of the regrading alternatives (push-down and pull-back alternatives) increased over that of the base case alternative and reference design with increasing infiltration and decreasing scale factor. Conversely, the relative performance of the regrading alternatives decreased with decreasing infiltration and higher scale factors. The results of model calibration indicated that the high-scale factor runs were more representative of actual stockpile mass loading than the mid- and low-scale factor runs. The relative difference in mass loadings among the reclamation alternatives for the scenario that exhibited the best calibration to existing conditions (wet year, high-scale factor) were very small and mostly within 20 to 25 percent of each other based on the total mine sulfate loadings.

In all of the alternatives considered, the relative water quality of basal seepage degrades as the infiltration rate was reduced and the scale factor was increased. Assuming similar material reactivities for the stockpile alternatives, the slower infiltration through the cover on regraded outslopes has the potential to generate seepage that has worse water quality than uncovered outslopes that have relatively higher infiltration rates, although the total flow from the covered outslopes would be less.

1.3.2.3.10 Qualitative Analyses. Thicker sequences of waste material are located closest to the Main Pit, and these interior stockpile areas produced the highest equivalent sulfate concentrations and mass loadings. Across the top surface, mass loadings were reduced by the cover, which reduced infiltration into these thick sequences where it derived the most benefit. The effect of push-down regrading was to redistribute the material away from the pit facilities and toward and/or over alluvial channels. This increased the potential for sulfate loading because of the increased seepage area and because this seepage could potentially recharge groundwater that is outside the capture zones of the Main Pit.

A lack of air flow in the deeper portion of the stockpiles may limit sulfide oxidation and decrease the effective rate of constituent dissolution (Morin and Hutt, 1997). Therefore, the most significant improvement in the seepage quality may occur where air and water infiltration rates are reduced over the thickest sequences, as in the base case alternative. The base case alternative had the greatest depths of materials, and the cover was emplaced on top of the thickest sequences. The push-down regrading option resulted in thinner, more spread-out sequences of materials. The pull-back scenario had the greatest depth of material for the original footprint, but any excess cut material (pull-back cone) stockpiles may have thinner, more spread-out profiles.

Reductions in mass loading from leach solutions and seepage are currently achieved through toe controls on existing stockpiles, which can be used for the post-closure reference design and base case alternatives. The basal seepage results generated by the mass loading model did not partition seepage between the toe collection systems and the underlying regional groundwater aquifers. Results of the stockpile seepage investigation at the Tyrone Mine (DBS&A, 1999b) indicated that the majority of seepage at the base of the No. 2A stockpile (approximately 70 percent) presently flows into underlying alluvial channels and ultimately to the existing toe (seep) collection systems located along the perimeter of the stockpiles (DBS&A, 1999a). However, these controls may not be effective after outslope regrading because the simulated infiltration rates through covered outslopes are lower than the hydraulic conductivities of most bedrock units beneath most stockpiles (DBS&A, 1997d, Table 1) at the Tyrone Mine. Hence, under the regraded scenarios, a greater proportion of basal seepage and its dissolved load would tend to flow into the underlying bedrock units rather than preferentially along the bedrock contact and ultimately to the toe control systems as occurs under current conditions. This effect may offset any potential gains in mass loading performance that were indicated by the modeling for the outslope regrading alternatives.

1.3.2.4 Supplemental Materials Characterization of the Leached Ore Stockpiles and Waste Rock Stockpiles, Final Report

The supplemental materials characterization (Condition 80 final report) was submitted by EnviroGroup in December 2005 to fulfill the requirements of DP-1341, Condition 80 (EnviroGroup, 2005c). The purpose of the report was to provide an analysis of the stockpile material data gathered for Condition 80 and to compare the information with materials data collected under previous studies.

A materials characterization database was compiled from the CCP studies and the studies performed for DP-1341, Condition 80. The database contained approximately 740 samples of fresh rock and stockpile materials that were characterized through field and laboratory analyses.

The stockpile materials characterization database was used to determine material reactivity and the effects of leaching and weathering.

Stockpile surface samples were collected as part of the SMC (DBS&A, 1997c) and selected stockpile borehole assay pulp samples were characterized in the GETS report (SARB, 1999). As part of the Condition 80 study, additional assay pulps from the Tyrone archives were retrieved from 15 stockpile boreholes to perform geochemical characterization analyses. In addition, supplemental stockpile borehole sampling was conducted for Condition 80, and a total of eight stockpile boreholes were completed using percussion hammer drilling to collect material samples for geochemical characterization. Four boreholes were completed using sonic coring drilling to collect material samples for geotechnical characterization samples for the Condition 78 stability study (Golder, 2003).

1.3.2.4.1 Borehole Logging and Monitoring. Geologic logging included descriptions of the texture, lithology, mineralization, and color and degree of alteration based on macroscopic observation. In addition, blow counts from the hammer percussion drilling were recorded as a relative indicator of material consolidation density and toughness. The geophysical and geochemical logging included elemental capture spectroscopy sonde, lithodensity, compensated neutron, and natural gamma ray spectrometry. These techniques provided information on the chemical composition, bulk density, moisture content, and clay content of the stockpile materials, respectively.

Stockpile monitoring wells were installed into the geochemical characterization boreholes during the Condition 80 drilling campaign. Thermistor strings and gas sampling tubes were installed in the monitoring wells to monitor temperature and oxygen (O_2) and carbon dioxide (CO_2) concentrations, respectively, in the stockpiles. Details of the monitoring well installations and measurements were provided in the Condition 80 preliminary report (EnviroGroup. 2005b).

Stockpile samples collected from borehole and open cut samples were analyzed for paste pH, paste EC, modified ABA, meteoric water mobility procedure (MWMP), mineralogy by x-ray diffraction (XRD), reflectance spectroscopy, and bulk composition by x-ray fluorescence (XRF). These methods are summarized in Table 1-2. The laboratory ABA, MWMP, XRD and XRF reports were contained in the Condition 80 interim and preliminary reports (Greystone, 2004b; EnviroGroup, 2005b).

Table 1-2. Analytical Method Descriptions

Test	Method	Description
Paste pH and paste electrical conductivity (EC)	Sobek et al. (1978)	Effective indicator tests of acid generation and soluble salt content.
Acid base accounting (ABA)	Sobek et al. (1978)	Static test evaluating acid generating potential of mine materials
X-ray diffraction (XRD)	PMET (2004)	Quantifies relative abundance of major and minor mineralogical components.
Reflectance spectroscopy	SII (2003)	Characterizes mineralogical properties of alteration and weathering products.
X-ray fluorescence (XRF)	Rollinson (1993), Crock et al. (1999)	Characterizes the whole rock chemical composition of the sample.
Meteoric water mobility procedure (MWMP)	ASTM E 2242-02 (2003)	Static leach test designed to assess the mobility of chemical constituents during leaching and weathering of mined materials.

The results of geologic and downhole geophysical logging were presented in the Condition 80 preliminary report (EnviroGroup, 2005b). In summary, geologic and downhole logging activities revealed that the stockpiles are variable and are made up of distinct and mixed layers of material. These layers were comprised of Tertiary quartz monzonite porphyry and Precambrian granite host rocks. The rocks were further classified in the geologic logs on the basis of mineralization according to the MA classification system used at Tyrone. The predominant MA types in the stockpiles were MA-1, MA-2, and MA-4.

Munsell colors of stockpile materials ranged from pink to red, reddish brown to reddish yellow, yellowish brown to brown, and greenish gray to gray. Grain size differences between layers were observed ranging from coarse cobble- and gravel-dominated layers, to fine layers where voids between coarser particles were filled with up to 85 percent clay-, silt-, and sand-sized particles. Coarse boulder zones and compacted materials were encountered at the base of the stockpiles, most likely due to gravity sorting during pile construction. This zone was identified by a high number of blow counts as the depth of the hammer drill bit neared the bottom of the stockpile.

The 2-inch size fractions were determined as part of the MWMP. The maximum particle size sampled by the percussion hammer drill rig was 5.5 inches. In general, the proportion of particles greater than 2 inches was less than 20 percent in most borehole intervals. In boreholes TBGC-1 and TBGC-5 there was a significant decrease in the greater than 2-inch size fraction particles deeper in the borehole. This indicated that fine material might be accumulating at the bottom of the waste rock stockpiles. Fine material can sift downward through the stockpiles and accumulate in the larger voids between boulders that were deposited preferentially at the base as a result of end dumping and gravity sorting. In the leach ore stockpiles the amount of oversize material was limited because the blasting pattern in the pits is denser for leach ore material in order to generate finer particles for more efficient leaching. Therefore, the distribution of particle sizes was expected to be more uniform within the leach ore stockpiles. However, there was a weak trend toward materials less than 2 inches at the base of the leach ore stockpiles.

Geophysical logging indicated that moisture contents in the stockpiles were relatively low, between 5 and 15 percent by volume. The gravimetric moisture measurements performed on stockpile borehole samples also indicated dry conditions. Examination of these gravimetric moisture profiles showed that the gravimetric moisture contents were generally lower than those measured by the neutron logging device. This was expected, as some drying occurred during sampling even though the samples were sealed in plastic buckets prior to analysis. Some of the borehole sequences (i.e., TBGC-1, TBGC-3, TBGC-5, and TBGC-7) became significantly drier at depth.

Retained moisture values for borehole profiles were also derived during the MWMP. Most of the retained moisture values varied between 7 and 30 percent by weight. Intervals with higher retained moisture contents have higher proportions of clay- and silt-size material, whereas low moisture contents were generally dominated by sands, gravels, and cobbles. In general, the retained moisture values in TBGC-6 track in situ measured moisture contents determined by neutron logging, indicating that the bulk of the stockpile materials were in a fully drained condition.

1.3.2.4.2 Paste pH and Paste Electrical Conductivity. The paste pH profiles showed acidic conditions in nearly all borehole intervals and generally ranged between 3 and 7 in the Tyrone waste rock stockpile boreholes TBGC-1 and TBGC-5. The borehole profiles for leach ore stockpiles showed that the paste pH was close to 4 over the depth ranges sampled in TBGC-2, -3, -4, -6, -7, and -7A. However, the assay pulp borehole samples from leach ore stockpiles showed a wider range of pH values.

As anticipated, the paste EC was generally higher in the leach ore stockpiles than in the waste rock stockpiles. The paste EC ranged approximately between 1 and 5 millimhos per centimeter (mmhos/cm) in the waste rock stockpile boreholes and between 2 and 10 mmhos/cm in the leach ore stockpiles. In general, the paste EC values increased as the paste pH values decreased.

1.3.2.4.3 Acid Base Accounting. The ABP of a sample is equal to the ANP minus the AGP. The negative ABPs in a majority of the stockpile borehole samples tested and the negative mean ABPs calculated for each stockpile indicated a net potential to generate acid. The stockpiles have low mean AGPs that were equal to or less than 41 T $CaCO_3$/kT owing to the relatively low sulfide content in the waste rock piles. The ABP values indicated near-neutral AGP for waste rock stockpiles containing a high proportion of leached cap (e.g., No. 3B and No. 1C stockpiles) and low to moderate AGP for the sulfide-bearing leach ore stockpiles (e.g., No. 2A stockpile). Therefore, the typical sulfide contents and AGPs of the leached ore stockpile samples were significantly higher than for the waste rock stockpile samples.

Overall, the mean ABPs calculated for the stockpiles based on borehole analyses were lower than the mean ABP (ABA) calculated for Group A (acid generating) materials for the SMC. The reported average ABP (ABA) for Group A was –43.3 T $CaCO_3$/kT. The average ABP for Group B (neutral) materials was 6.7 T $CaCO_3$/kT. Very few stockpile samples had positive ABPs. Figures 3-5 through 3-8 in the Condition 80 final report compared stockpile ABA results with the fresh rock materials analyzed in the PMC and SMC (DBS&A, 1997a, 1997c). Figure 3-5 of that report showed the majority of the fresh rock and stockpile samples fell into the acid generating category with an AGP to NP ratio of 1 to 1 or greater (Brodie et al., 1991; Morin and Hutt, 1994). Figures 3-5 and 3-6 in the Condition 80 final report showed that the ANP for most stockpile samples was at or below the detection limit (0.3 T $CaCO_3$/kT). In addition, the range in pyritic AGP and ANP values was smaller for the stockpile samples than for the fresh rock samples characterized for the PMC and SMC reports.

Figures 3-7 and 3-8 in the Condition 80 final report showed that the sulfate content for the stockpile samples tended to be higher than that of the core samples for equivalent AGP values, although the highest sulfate values were measured in the fresh rock samples. The ABA and sulfate trends suggested that acid generation was occurring in the stockpiles owing to sulfide oxidation and that the neutralizing potential present in the as-mined ore and waste was consumed in the process. As noted in Figure 3-5 of the Condition 80 final report, this reduced the range of AGP and ANP values for the stockpile samples as compared to the mined rock samples. Sulfate minerals were being produced as a result of the sulfide oxidation reactions, which increased the sulfate content in the stockpile samples as compared to the fresh rock samples analyzed in the PMC and SMC.

1.3.2.4.4 Meteoric Water Mobility Procedure. A summary of selected MWMP results for each geochemical borehole is provided in Section 4.2.2 of this report and therefore not included here. The summary includes a discussion of analysis results for the COCs at Tyrone (i.e., pH, sulfate, EC, fluoride, and the metals aluminum, copper, iron, manganese, zinc, cadmium, cobalt, chromium, nickel, and lead).

1.3.2.4.5 X-Ray Diffraction Mineralogy. Quartz, muscovite (illite), potassium feldspar (K-feldspar) and plagioclase feldspar were the predominant minerals in the stockpile samples and occurred in abundances greater than 1 weight percent (wt pct). Geophysical logging and reflectance spectroscopy also confirmed that illite was the predominant clay mineral. After illite, kaolinite was the second most common clay mineral reported in these samples and its average abundance ranged from 1 to 19 percent. The minerals pyrite and jarosite were detected in most samples at average concentrations that ranged between 0.1 and 3.1 percent. The presence of these minerals is an indicator of acid generation within the stockpiles.

Selected borehole mineralogical profiles of the geochemical characterization boreholes were presented in Appendix C of the Condition 80 final report along with a complete tabulation of the XRD data. The depth trends with respect to K-feldspar, plagioclase, muscovite (illite), and kaolinite were shown in these profiles. The amount of total feldspar was highly variable and ranged between 5 and 65 percent (K-feldspar and plagioclase). There was no overarching trend with depth in these profiles. In some profiles feldspars diminished with depth and in others the amount did not change or it increased with depth. This indicated that the feldspar content was controlled by the character of the material as it was emplaced on the stockpiles and not by post-depositional alteration of feldspars to clay. Similarly there was no systematic increase or decrease in the amount of muscovite and kaolinite with depth. There was a weak trend for muscovite and kaolinite to increase as feldspars decreased. The abundance of these minerals appeared to be controlled by the degree of hydrothermal alteration that occurred during the time of mineralization. Muscovite (illite) is formed under conditions of hydrothermal alteration and is not a product of stockpile weathering and leaching. Kaolinite can form under weathering conditions, but the downhole trends that were seen in these boreholes did not appear to be related to progressive weathering of stockpile material.

The depth trends with respect to amorphous clay, goethite, jarosite, and pyrite were contained in Appendix C of the Condition 80 final report. The amorphous clay contents in the boreholes range from 0 to 20 percent, and these profiles did not indicate that the amount of amorphous clay in the stockpile samples was correlated to depth (material age). There was also no evidence for a correlation of amorphous clay abundance with pyrite or jarosite contents. Furthermore, the amorphous content in the waste rock stockpile samples (TBGC-1 and TBGC-5) ranged as high as those found in leach ore stockpiles. This suggested that acidic conditions and leaching reactions were not the result of breakdown of the rock to amorphous clay components.

1.3.2.4.6 X-Ray Fluorescence Bulk Composition. Based on the quantitative XRF bulk composition results from the stockpile geochemical characterization boreholes, the major components (greater than 1 wt pct) in the stockpile materials were SiO_2, Al_2O_3, K_2O, and Fe_2O_3. Sulfur was also a major component in some stockpile intervals. Minor components (generally between 0.1 and 1.0 wt pct) include Na_2O, MgO, TiO_2, P_2O_5, CaO, BaO, and MnO in some intervals. Other constituents occur in trace amounts (generally less than 0.1 wt pct). The observed concentrations of major and minor elements were consistent with intermediate igneous rock types that have been subject to hypogene and supergene alteration and porphyry copper mineralization.

Al_2O_3 was a major component of the aluminosilicate minerals such as feldspars and illite that make up the host rock matrix. The concentration of Al_2O_3 was fairly consistent with depth in each stockpile profile and ranged between 10 and 20 wt pct. No significant trends in enrichment or depletion of Al_2O_3 were detected from examination of the profiles. This indicated that aluminum-rich clays were not forming preferentially at depth in the stockpiles owing to progressive weathering and leaching reactions.

Fe_2O_3 occurred in abundances between 3 and 10 wt pct, and MnO occurred at concentrations between 0.01 and 0.35 wt pct. The concentration of S occurred in abundances between 0.2 and 4 wt pct. There was no distinct correlation of the Fe_2O_3, MnO, and S concentrations in these profiles. There was also no distinct trend with depth, which indicates that these constituents were not being heavily mobilized and accumulating preferentially within the stockpile.

Most metals were present in the stockpile materials in concentrations that are similar to unmineralized igneous rocks. In general, most metal concentrations were less than 100 parts per million (ppm). The most important trace metal COCs that were detected in these rocks at high levels are copper, zinc, and lead. The profiles show that the concentrations of these base metals were variable and range from several hundred to several thousand ppm. There was no distinct correlation of these metals with the sulfur concentration in the rock. In addition, there were no significant trends with respect to depth, which indicated that these metals were not being mobilized and concentrated at lower levels within the stockpiles. Stockpile whole rock compositions were also analyzed as part of the GETS report and showed no evidence for preferential metal concentration within stockpile profiles.

1.3.2.4.7 Stockpile Monitoring. Average borehole temperatures ranged between approximately 15 and 40 degrees Celsius (°C). The mean maximum air temperature was approximately 30°C (DBS&A, 1999a), and average stockpile temperatures at or above that value were attributed to internal heating from the exothermic sulfide oxidation reaction. Elevated temperatures occurred in the lower intervals of TBGC-1 and in the upper to mid-range intervals of TBGC-7 and TBGC-7A. The higher temperature intervals in TBGC-1 and TBGC-7A, where temperatures exceed 30°C, were associated with relatively low ABP materials that were below –40

T $CaCO_3$/kT. This indicated that the oxidation of sulfides was generating heat that raised the internal temperatures of these stockpiles.

The average oxygen concentrations in pore gas were generally between 4 and 21 percent by volume in most intervals, although concentrations fell below detection in some intervals. Oxygen-depleted zones occurred in TBGC-5, TBGC-7 and TBGC-7A. These zones may correspond with relatively stagnant areas in the stockpile where air flow was reduced. However, in most borehole intervals the oxygen content was relatively high and will support pyrite oxidation.

Carbon dioxide concentrations were generally lower than 1 percent in most intervals. However, in some intervals the levels of CO_2 climbed to several percent and as high as 12 percent near the base of the stockpiles.

1.3.2.4.8 Stockpile Weathering and Leaching. The effects of stockpile weathering and leaching were investigated by examining material characteristic trends as a function of stockpile age. The age of the stockpile materials was determined from the stockpile depositional sequences provided in the form of stockpile cross sections in Appendix A of the Condition 80 preliminary report (EnviroGroup, 2005b). The No. 1 Stockpile sequences were not shown but that stockpile material was deposited between 1967 and 1975.

The charts provided in Appendix G of the Condition 80 final report showed the paste pH, ABP, pyritic sulfur fraction, sulfate fraction, and MWMP extract parameters acidity, EC, aluminum, copper, iron and sulfate, plotted as a function of stockpile material age. The maximum pyritic sulfur fraction diminished with age of the stockpile material, indicating that pyrite was reacting in the stockpiles and was being depleted as they age. No other distinct trends in these parameters could be discerned as a function of age. In other words, the apparent variability of a particular age group can be almost as high as the variability of the entire span of samples. Therefore, the variability among different material types probably accounted for the variability in the sample population across the age distributions.

1.3.2.4.9 Summary and Discussion. The results of paste pH and ABA testing showed that all of the stockpiles and stockpile complexes sampled have the potential to generate acidity and are generating acidity. However, the levels of acidity generated are low because of the relatively low sulfide contents. The ABA and sulfate trends suggest that acid generation is occurring in the stockpiles owing to sulfide oxidation and that the ANP present in the as-mined ore and waste is consumed in the process. Sulfate minerals are being produced as a result of the sulfide oxidation reactions, which increase the sulfate content in the stockpile samples as compared to the freshly mined materials. HCT results reported in the GETS report show that the sulfate production from the Tyrone materials is low and ranges from less than 1 to 16 milligrams per kilogram per week. The pH of rinsates from all tests remained above 5 for the duration of the tests, which indicates that the rate of acid production is relatively low owing to the relatively low sulfide contents in the rocks.

Stockpile temperature and pore gas composition monitoring has been conducted for approximately one year at the Tyrone Mine. Borehole temperatures are elevated in sulfide-rich zones due to the heat of reaction generated by sulfide oxidation. Oxygen concentrations measured within the stockpiles are generally sufficient to support pyrite oxidation, which appears to be occurring at a rate such that pyrite is partially depleted in the stockpiles as they age.

2. Investigation Procedures

This section describes the methods used to characterize stockpile seepage (Section 2.1) and describes the models and modeling methods that PDTI used to simulate stockpile seepage flow and seepage quality after mine closure (Section 2.2).

2.1 Seepage Characterization

Stockpile seepage is being characterized through field and laboratory investigations as described in Sections 2.1.1 and 2.1.2, respectively.

2.1.1 Field Procedures

Eight infiltration (percolation) tests were conducted on the Tyrone stockpiles. The infiltration tests were conducted from March 9 through March 16, 2005 on various stockpile bench surfaces throughout the mine site. Most of the benches were cut into existing stockpiles during remining activities and the test sites had been buried by one or more lifts of material prior to excavation, but one test was conducted on a stockpile top surface that has never been buried. The infiltration tests consisted of seven falling head tests and one constant head test, which are described in greater detail in Appendix A of the *Revised Seepage Investigation of Leach Ore Stockpiles and Waste Rock Stockpiles Interim Report* (EnviroGroup, 2005a).

2.1.2 Laboratory Procedures

Two types of laboratory tests were used to evaluate stockpile seepage. They included hydraulic testing and meteoric water mobility testing. A brief description of these lab tests is provided in the following subsections.

2.1.2.1 Hydraulic Testing

Laboratory hydraulic testing was conducted on stockpile samples collected from the same bench materials subjected to the field infiltration tests. The method used for collection of stockpile samples and the laboratory testing procedures conducted are described in Appendices A and B of the *Revised Seepage Investigation of Leach Ore Stockpiles and Waste Rock*

Stockpiles Interim Report (EnviroGroup, 2005a). Twenty-four stockpile samples were tested at the DBS&A Hydrologic Testing Laboratory to determine moisture content, bulk density, porosity, saturated and unsaturated hydraulic conductivities, particle-size distributions, and soil-water characteristic curves (EnviroGroup, 2005a, Appendix B). These samples were collected for laboratory testing to characterize the unsaturated as well as saturated hydraulic properties of the matrix materials in the stockpiles for the purpose of seepage modeling. Water percolation through the stockpiles occurs predominantly through the finer-grained matrix, as the oversize materials have relatively low intrinsic hydraulic conductivity (DBS&A, 1999a, 1999b).

2.1.2.2 Meteoric Water Mobility Procedure Testing

In 2004, regrading of the No. 1C stockpile was conducted in accordance with DP-1341 requirements. Stockpile samples were collected from the No. 1C stockpile bench cuts for the purposes of the DP-1341 Condition 80 and 78 studies. Splits of these samples along with the geochemical borehole samples described in the *Supplemental Materials Characterization of the Leached Ore Stockpiles and Waste Rock Stockpiles Final Report* (EnviroGroup, 2005c) were subjected to a laboratory static leach test using the MWMP according to ASTM E2242-02.

The MWMP was developed by the Nevada Department of Environmental Protection (NDEP) (1990) to determine the mobility of chemical constituents from soluble salts generated by leaching and weathering in mined materials. These tests are conducted at a water-to-rock ratio (by weight) of 1 to 1 to simulate the interaction between natural meteoric precipitation and the stockpile material. The leach extracts and any pore waters collected from the boreholes were measured for the following parameters or constituents: pH, EC, TDS, total alkalinity, bicarbonate, carbonate, acidity, sulfate, and other COCs specified in DP-1341 Condition 56 (a through c). As such, these results are used in geochemical models to provide a preliminary indication of seep water quality from the waste rock stockpiles and supplement data from water quality monitoring occurring at toe collection facilities.

2.2 Seepage Modeling

This section describes PDTI's modeling approach to simulate stockpile seepage quantity and quality. Computer modeling of reactive transport in waste rock piles is a complex subject, and a comprehensive review of the subject matter is beyond the scope of this document. The intent of this section is to provide a brief overview of the approach taken by PDTI in the application of computer modeling to mine stockpile and ARD systems. Modeling is necessary to evaluate post-closure seepage from the leach ore and waste rock stockpiles because the future state of these systems is expected to be different from the current state. However, the models were calibrated using seepage quality measurements.

2.2.1 Modeling Objectives

The most important part of any modeling study is to formulate well-defined objectives and scope (Alpers and Nordstrom, 1999). PDTI pursued the following modeling objectives:

1. Simulate leaching and weathering reactions in stockpiles
2. Simulate leachate and seepage quantity at existing collection systems
3. Simulate post-closure leachate and seepage quality at seepage collection systems
4. Calibrate model to observed seepage quantity and quality
5. Estimate post-closure stockpile mass loading to groundwater
6. Estimate the existing and post-closure distribution of mass loading
7. Evaluate the potential groundwater impacts for alternative closure designs

The first objective also will support the supplemental stability study (Golder, 2003), which will be used to determine the effects, if any, of rock alteration on stockpile outslope stability. Objectives 2 through 6 are requirements of DP-1341, Condition 81. The last objective will be conducted in support of Condition 89, the feasibility study (Golder, 2004).

2.2.2 Modeling Scope

All existing waste rock and leach stockpiles at Tyrone were evaluated in the modeling study. However, some of these stockpiles will be reclaimed prior to the next permit renewal. The existing boundaries of these facilities are shown on Figure 1-1. In addition to the existing configurations of the stockpiles, the DP-1341 closure plan was evaluated in this study. Three distinct post-closure periods were simulated:

- Mine closure drain-down period (approximately 10 years)

- Transition period (approximately 100 years)
- Steady-state period (greater than 100 years)

The attainment of steady-state conditions was based upon the observed concentration versus time curves. The greatest change in concentrations of constituents in seepage occurred during the first 100 years whereas concentrations changed relatively slowly after that time. The constituents to be simulated include those stipulated in Condition 56 (a, b, and c) of DP-1341 provided that sufficient data exist for model calibration.

2.2.3 Model Selection

PDTI's selection with regard to runoff and seepage flow modeling is presented in Section 2.2.3.1 and its selection with regard to geochemical modeling is presented in Section 2.2.3.2.

2.2.3.1 Runoff and Seepage Flow Modeling

Runoff and seepage flow modeling was used to determine the water mass balance and the seepage flow paths in stockpile systems given the following site-specific input parameters:

- Stormwater flow data and weather data
- Post-closure infiltration rates through alternative stockpile covers
- Alternative post-closure stockpile configurations
- Internal temperature, oxygen, and moisture monitoring results

Constituent mass transfer by runoff and downstream surface and groundwater quality impacts will be mitigated by the cover and stormwater containment systems. However, the runoff quantity must be estimated in order to estimate infiltration. Runoff will be determined as part of the cover design and test plot studies (Conditions 75 and 76). In addition, runoff quantity and quality estimates based upon field measurements will be used for base case modeling and seepage flow calibration for uncovered stockpiles.

Heat transfer and gas flow are also important processes for determining seepage water quantity and flow directions in some sulfide-bearing stockpiles. However, based upon observations of relatively low temperature gradients within most of the leach ore and waste rock stockpiles at Tyrone, heat transfer and gas convection are likely to be minor processes in the water balance equations and will not be considered in the modeling analysis.

The two primary constituent transport mechanisms are fluid flow (advection) and diffusion. In many subsurface systems in the near earth surface, advective transport dominates diffusive transport because of precipitation-induced recharge. However, the cover studies will evaluate the feasibility of reducing the infiltration rate through the stockpiles to less than or equal to 1 percent of mean annual rainfall. Under very low flow conditions (less than 1 cm/yr), the rate of constituent transport by diffusion may become equal to or greater than the rate of transport by advection, even for long time frames. Under these conditions stockpile seepage quality and mass loading will become independent of the rate of infiltration. It is conceivable that these conditions will occur within waste rock stockpiles.

For leach ore stockpiles, drain-down of residual process solutions may be a significant or predominant constituent transport process. Drain-down will be estimated from empirical data obtained from leach solution flow rates to toe collections systems, according to the closure designs evaluated by the feasibility study (DP-1341, Condition 89) (Golder, 2004). As drain-down proceeds after closure, the downward drainage flux declines asymptotically as water content in the stockpile decreases.

After the preliminary results from the cover design studies are made available, supplemental analyses and scoping modeling runs will be conducted to determine what types of additional analyses and simulation are necessary. If deemed necessary by these analyses, fluid flow models will be developed for distinct hydrogeologic units in each stockpile. These units will generally correspond to the under-dump drainage systems as depicted in Figure 1-1. The drainages will be modeled separately where sufficient seepage flow information is available for calibration.

Based upon review of the literature presented in the *Revised Seepage Investigation of Leach Ore Stockpiles and Waste Rock Stockpiles Interim Report* (EnviroGroup, 2005a), PDTI decided to use the computer code HYDRUS for the numerical modeling of stockpile seepage. The

HYDRUS program is a finite element model for simulating the movement of water, heat, and multiple solutes in variably saturated media. The program numerically solves the Richards' equation for saturated-unsaturated water flow and Fickian-based advection-dispersion equations for heat and solute transport. The flow equation incorporates a sink term to account for water uptake by plant roots. The heat transport equation considers conduction as well as convection with flowing water. The solute transport equations consider advective-dispersive transport in the liquid phase and diffusion in the gaseous phase. The transport equations also include provisions for nonlinear and/or nonequilibrium reactions between the solid and liquid phases, linear equilibrium reactions between the liquid and gaseous phases, zero-order production, and two first-order degradation reactions: one that is independent of other solutes and one that provides the coupling between solutes involved in sequential first-order decay reactions.

HYDRUS is run within a Microsoft Windows-based modeling environment. The model is supported by an interactive graphics-based interface for data preprocessing, generation of a structured mesh, and graphic presentation of the results. Optionally, the modeling environment includes a mesh generator for unstructured finite-element grids.

For runoff modeling, PDTI decided to use the SCS curve number method (Bedient and Huber, 1992). The curve number method is based on land use and hydrologic soil group. The runoff amounts were calculated with the following equation (Bedient and Huber, 1992, Equation 2.20):

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S}$$

Where S (inches) = (1000/CN) – 10

Q = Runoff from the stockpile surfaces (inches)

P = Precipitation (inches)

CN = Curve number

Daily precipitation amounts were taken from the Fort Bayard weather station, located approximately 20 miles northeast of the Tyrone Mine. Climatic data for the Fort Bayard site were used because it is the longest and most comprehensive record of data available for the

Tyrone Mine. The runoff amounts were calculated in an Excel spreadsheet using the daily precipitation data from Fort Bayard for January 1897 through July 2005, excluding a total of 19 months that were missing five or more days of precipitation data. A curve number of 88 was assigned to the uncovered stockpile surfaces since the area is considered to be disturbed land with little or no vegetation (fallow) and SCS hydrologic group C characteristics. A curve number of 84 was assumed for the covered stockpile surfaces based on open space land in fair condition (50 percent grass cover) with SCS hydrologic group D characteristics.

The following assumptions were made for the runoff calculations:

- The precipitation data record from Fort Bayard defines the range of precipitation scenarios that might be expected at Tyrone.
- Runoff can be estimated by applying the SCS curve number method to daily rainfall data, assuming average antecedent moisture conditions.
- Curve numbers of 88 and 84 are appropriate for the uncovered and covered stockpile surfaces, respectively.
- Daily precipitation totals of less than 0.27 (CN=88) and 0.38 (CN=84) inches yield zero runoff.

2.2.3.2 Geochemical Modeling

Based upon review of the literature presented in the *Revised Seepage Investigation of Leach Ore Stockpiles and Waste Rock Stockpiles Interim Report* (EnviroGroup, 2005a), PDTI recommended the Geochemists Work Bench (GWB) modeling platform, which has kinetic reaction path simulation and reaction path finding capabilities that are similar to EQ3/6 (Wolery, 1992) and utilizes the same thermodynamic databases. These databases are the most comprehensive and have the highest internal consistency of any databases in the world.

GWB is a proprietary package of geochemical modeling software developed by Dr. Craig Bethke at the University of Illinois (Bethke, 2004a). The codes in GWB can simulate all of the

ARD processes occurring in stockpiles. The model also provides rapid input/output and graphing capabilities based on a graphical user interface. GWB has the capability to not only simulate reactions paths, but also has rapid path tracing and display capabilities to quickly render output as graphs for rapid and higher quality interpretation. For example, rapid generation of Eh-pH diagrams is a capability of GWB through the use of the model Act2.

The GWB modeling platform is being used for ARD estimation at educational, government, and private institutions. For example, Kim Lappakko's research team at the Minnesota Department of Natural Resources currently uses GWB to support the laboratory kinetic testing and field application work being conducted at that laboratory (Berndt, 2004).

The Xt software package, included in the most recent version of GWB Professional has numerical reactive transport simulation capabilities for one- and two-dimensional systems (Bethke, 2004b). The capabilities now represented in GWB Professional covers the following processes occurring in stockpiles:

- Mass transport by advection, diffusion and dispersion
- Fluid discharge at fixed or evolving rates owing to changes in permeability and viscosity
- Isothermal and polythermal models for all expected temperature ranges
- Homogeneous and heterogeneous material domains and initial conditions
- Specification of kinetic rate laws including catalysis
- Microbial metabolism and growth
- Surface complexation and sorption
- Redox equilibrium and disequilibrium
- Activity models for high TDS concentrations
- Gas buffering
- Equilibrium and kinetic heterogeneous reactions

This extended capability allows for multilayer stockpile seepage quality simulation and estimation of groundwater quality. The graphical capabilities also allow for direct display of concentration gradients in the system.

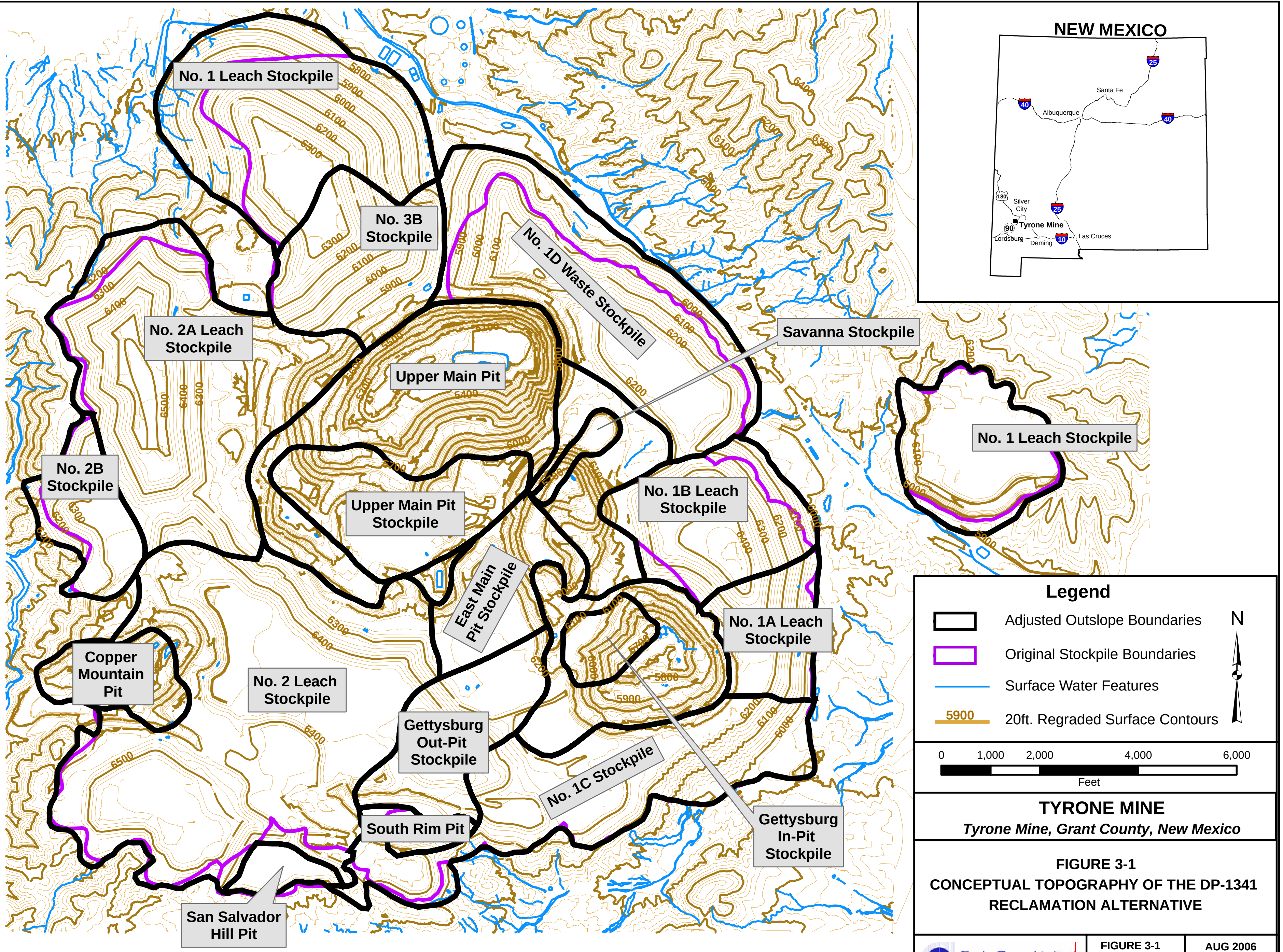
3. Alternatives Evaluation

The stockpile closure alternatives to be modeled include the provisional alternative stipulated by DP-1341. Additional alternatives may be developed at a later time in conjunction with the feasibility study (Condition 89) (Golder, 2004). The long-term mass loading and water quality impacts will be evaluated for a period consistent with the design life of the other facilities associated with mine closure. For example, the bonding requirement associated with water treatment is for 100 years. PDTI will use best methods and current practice to estimate future mass loading and water quality effects for a period determined from the closure alternative development process conducted for the feasibility study (Condition 89) (Golder, 2004). The overall performance objectives and conceptual designs for closure and reclamation of the major facilities at Tyrone will be based on the outcome of the supplemental supporting studies required in Supplemental Permit DP-1341 (NMED, 2003), including this study.

The models will be used to estimate the mass loading and the groundwater quality beneath the stockpiles during and after mine closure for the selected alternative reclamation scenario. The scope of the alternatives evaluation presently includes the provisional reclamation guidelines set forth in DP-1341. The conceptual topography of the stockpiles under the DP-1341 reclamation provisions (i.e., 3 to 1 interbench push-down slopes everywhere except where roads and drainages constrain the toe of the stockpiles) was rendered by Montgomery Watson Harza (MWH) using AutoCAD software (Figure 3-1). Where the toe of the stockpile was constrained, the interbench slope angle was set at 2.5 to 1 and the material was conceptually pulled back onto the tops of the stockpiles. This topography along with the under-dump topography was used to generate thickness contours for the stockpiles. The thicknesses of the stockpiles were entered into the geochemical model used to simulate seepage quality and mass loading. The long-term seepage quality and mass loading results for the DP-1341 reclamation alternative are compared to the long-term seepage quality and mass loading results for the existing stockpile configurations in Sections 4.4 and 6.1.

The alternatives analysis is being conducted to support studies being undertaken to fulfill the requirements of other conditions of the *Supplemental Discharge Permit for Closure DP-1341* (NMED, 2003). In particular, the mass loading modeling results will be used to assess post-

File Location: R:\PD-0447(Phelps-Dodge)\EGL_Directory\GIS_Ops\Project_Files\Tyrone\FIG3.1_Conceptual Top of Reclamation Alternative.mxd



TYRONE MINE

Tyrone Mine, Grant County, New Mexico

FIGURE 3-1
CONCEPTUAL TOPOGRAPHY OF THE DP-1341
RECLAMATION ALTERNATIVE

EnviroGroup Limited
Centennial, Colorado

FIGURE 3-1	AUG 2006
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closure groundwater quality in the supplemental groundwater study (DBS&A, 2003), in accordance with Condition 82 of the permit. Information on existing and future seepage and runoff quantity and quality will be used to augment the data required for the supplemental pit lake formation model (DBS&A, 2005) in accordance with Condition 83 of the permit. The overall mass loading performance will be used to guide alternatives evaluations as part of the feasibility study under Condition 89 of the permit (Golder, 2004). In addition, an evaluation of the impacts of geochemical processes on slope stability will be undertaken to support the *Supplemental Slope Stability Analysis* (Golder, 2003).

4. Results

The results of field testing and laboratory testing are provided in Sections 4.1 and 4.2, respectively. The seepage flow and runoff modeling results are presented in Section 4.3, and the results for the geochemical and mass loading model are contained in Section 4.4.

4.1 Field Testing

Table 4-1 provides the saturated hydraulic conductivities calculated for each stockpile infiltration test described in Appendix A of the *Revised Seepage Investigation of Leach Ore Stockpiles and Waste Rock Stockpiles Interim Report* (EnviroGroup, 2005a). The saturated hydraulic conductivity values ranged from 2.5 x 10^{-5} to 2.4 x 10^{-3} cm/s.

Table 4-1. Summary of Stockpile Infiltration Tests

Sample ID	Infiltration Test Type (falling head/constant head)	Saturated Hydraulic Conductivity (cm/s)
No. 1C stockpile		
1C-T1	Falling	1.57 x 10^{-4}
1C-T2	Falling	2.15 x 10^{-4}
1C-T3	Falling	9.74 x 10^{-5}
Savanna stockpile		
Savanna-T4	Constant	2.4 x 10^{-3} to 3.9 x 10^{-3}
Savanna-T8	Falling	4.80 x 10^{-4}
No. 3B stockpile		
3B-T5	Falling	4.78 x 10^{-5}
No. 2B and 2C stockpiles		
2B-T6	Falling	2.54 x 10^{-5}
2C-T7	Falling	4.78 x 10^{-5}

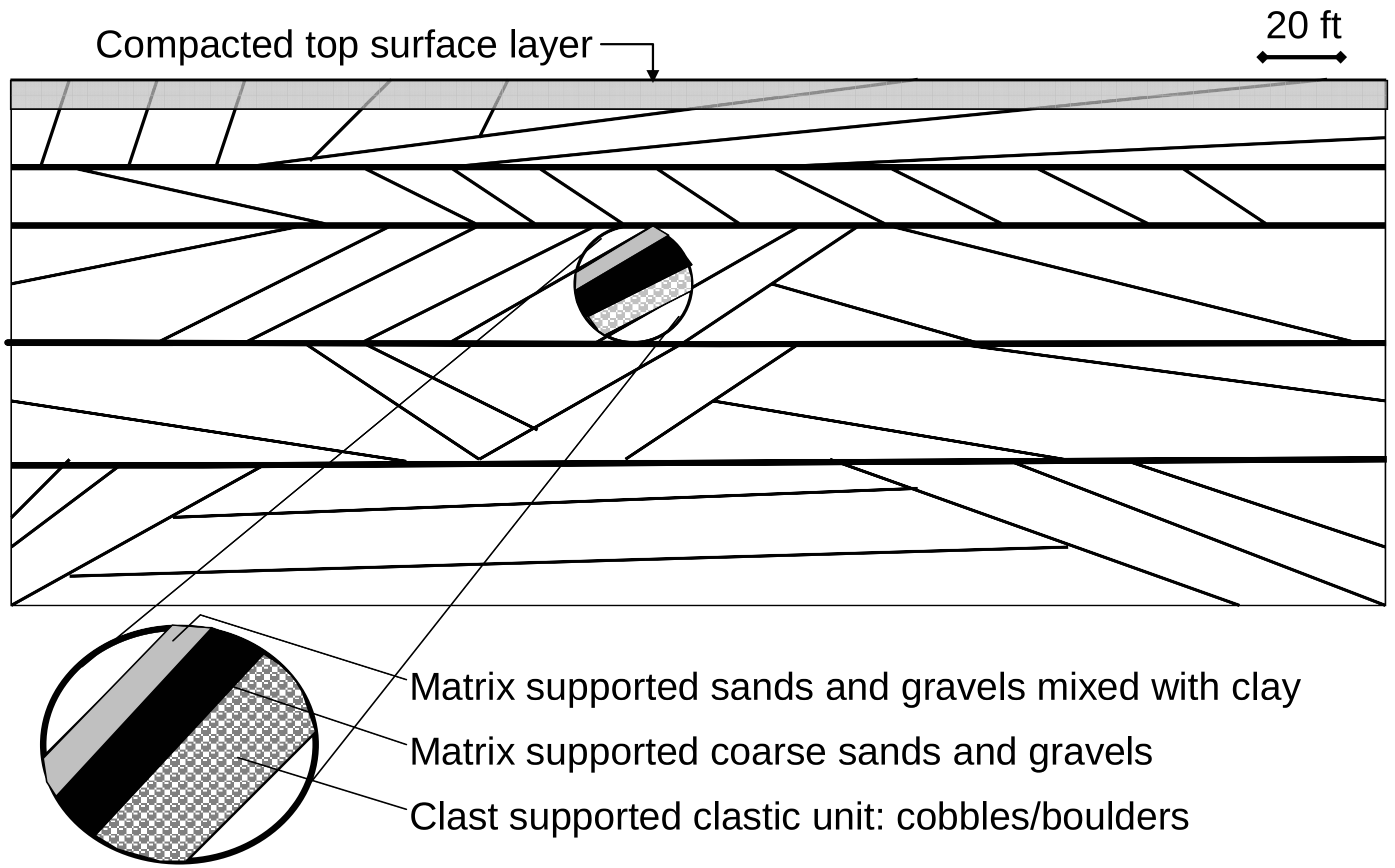
These values are generally lower by one to two orders of magnitude than the range of values measured during earlier field infiltration tests conducted for the cover design study (DBS&A, 1999a). The new tests were conducted primarily within interior sections of the stockpiles that had been previously buried prior to excavation. Only the top surfaces of stockpile materials were tested as part of the cover design study (DBS&A, 1999a). The lower stockpile interior saturated hydraulic conductivities values may be attributed to the compaction that occurred as a result of material burial and overburden loading. The saturated hydraulic conductivity measured during one test conducted on the top surface of the No. 3B stockpile was also low because of very heavy truck traffic and compaction.

Field observations of individual cuts through stockpile lifts were conducted as part of the seepage investigation. In general, the field observations indicated that four general types of materials could be found in almost all stockpile lifts. These include a compacted zone near the stockpile surface in which the physical and hydraulic characteristics of the materials have been altered by mine traffic. In addition, three general types of dump materials exist within each lift that lie at the angle of repose. These individual layers include (1) a clastic unit consisting of cobbles and boulders, (2) a matrix-supported unit consisting of coarse sands and gravels, and (3) a matrix-supported coarse unit consisting of sands and gravels mixed with clay. These units tend to occur in repeating and intergradational sets that are approximately 20 to 40 feet in length and 10 to 15 feet in width, lie at angle of repose, and may or may not be parallel to the face of the dump. These units interfinger and are oriented at acute to obtuse angles to each other (Figure 4-1); hence, the layers do not form contiguous and parallel strata as depicted in the conceptual model presented in the *Stockpile and Tailing Pond Seepage Investigation* (DBS&A, 1999b, Figure 4-5). Water that flows down the unit would tend to intersect the interface with another unit and then proceed to flow parallel to that unit in a different direction.

Additionally, descriptions of stockpile materials can be found in the test pit logs of Appendix A in the *Supplemental Stability Study of Waste Rock Piles and Leach Ore Stockpiles, Interim Report for DP-1341, Condition 78, Tyrone Mine* (Golder, 2005).

4.2 Laboratory Testing

The laboratory results for both hydraulic testing and MWMP testing are discussed in Sections 4.2.1 and 4.2.2, respectively.



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Tyrone Inc.

TYRONE MINE DP-1341 CONDITION 81

Unit Stratigraphy of Cut Section of the No. 1C Stockpile

Figure 4-1

Daniel B. Stephens & Associates, Inc.

10/31/06

4.2.1 Hydraulic Testing

The results of the laboratory hydraulic testing of the stockpile materials are provided in Appendix B of the *Revised Seepage Investigation of Leach Ore Stockpiles and Waste Rock Stockpiles Interim Report* (EnviroGroup, 2005a) and summarized in Table 4-2. In general, the range of hydraulic properties found in these samples is similar to those reported for stockpile materials in the cover design study (DBS&A, 1999a). The median saturated hydraulic conductivity determined through laboratory testing was one to two orders of magnitude higher or lower than the field test values for the same site. This indicates that larger-scale macropores and other field-scale structures are controlling flow in the stockpiles.

4.2.2 Meteoric Water Mobility Procedure Testing

The results of the MWMP testing performed on the No. 1C stockpile cut bench samples are provided in Appendix C of the *Revised Seepage Investigation of Leach Ore Stockpiles and Waste Rock Stockpiles Interim Report* (EnviroGroup, 2005a). The results for these materials show that the paste pH ranges between 2.72 and 5.23. The final extract pH ranges between 2.45 and 4.71. The initial pH of the distilled deionized water was approximately 4.83. Therefore all of the materials sampled are capable of producing some acid when meteoric water comes in contact with the rock. The acidity of the extract solution ranged from less than 1 to 10,700 milliequivalents per liter (meq/L). There was no detectable alkalinity in any of the extracts. The calculated TDS of the extracts ranged from 1,260 to 17,800 milligrams per liter (mg/L) and the sulfate concentrations ranged from 856 to 10,700 mg/L. The leach extracts with the highest TDS and sulfate had the lowest extract pH values.

Fluoride, aluminum, cadmium, cobalt, copper, manganese, nickel, and zinc were detected in all of the extracts. In some of the MWMP extracts, boron, barium, beryllium, iron, molybdenum, and lead were also detected. The concentrations of fluoride, aluminum, copper, manganese, and zinc were consistently high and ranged from a few to more than 1,000 mg/L.

Selected MWMP results for each geochemical borehole are summarized in Table 4-3, including the Tyrone COCs pH, sulfate, EC, fluoride and metals (aluminum, copper, iron, manganese, zinc, cadmium, cobalt, chromium, nickel, and lead). These results were reported previously in

Table 4-2. Summary of Saturated and Unsaturated Hydraulic Properties from Laboratory Tests

Sample Number	K_{sat} (cm/s)	α (cm^{-1})	N (dimensionless)	θ_r (%)	θ_s (%)
2B-T6 (0-3)	4.30×10^{-4}	0.0169	1.1942	0.0000	0.3415
2B-T6 (1-4)	3.20×10^{-4}	0.0096	1.1978	0.0000	0.3180
2B-T6 (3-6)	2.90×10^{-5}	0.0069	1.2283	0.0000	0.3166
3B-T5 (0-3)	2.00×10^{-4}	0.0250	1.1690	0.0000	0.3189
3B-T5 (2-5)	1.30×10^{-5}	0.0084	1.1995	0.0000	0.3079
3B-T5 (3-6)	1.20×10^{-4}	0.0169	1.1945	0.0000	0.3434
1C-T1 (0-3)	5.80×10^{-3}	0.1709	1.2569	0.0259	0.3520
1C-T1 (4-7)	9.90×10^{-3}	0.1577	1.3566	0.0626	0.3575
1C-T1 (10-13)	3.90×10^{-2}	0.2904	1.1759	0.0054	0.3050
1C-T2 (0-3)	5.70×10^{-2}	0.0486	1.8834	0.0621	0.2797
1C-T2 (5-8)	1.50×10^{-2}	0.2994	1.4896	0.0165	0.3260
1C-T2 (11-14)	1.90×10^{-2}	0.1501	1.4751	0.0416	0.3278
1C-T3 (0-3)	6.00×10^{-7}	0.0004	1.3300	0.0000	0.3270
1C-T3 (4-7)	4.20×10^{-5}	0.0078	1.2596	0.0000	0.3611
1C-T3 (7-10)	9.50×10^{-7}	0.0002	1.4495	0.0000	0.2977
2C-T7 (0-3)	2.20×10^{-4}	0.0019	1.2933	0.0000	0.3101
2C-T7 (1-4)	1.10×10^{-4}	0.0033	1.2398	0.0000	0.3237
2C-T7 (2-5)	7.70×10^{-5}	0.0727	1.1638	0.0000	0.3170
Savannah-T4 (0-3)	1.50×10^{-6}	0.0005	1.4253	0.0000	0.2740
Savannah-T4 (12-15)	1.50×10^{-7}	0.0002	1.9374	0.0000	0.2471
Savannah-T4 (30-33)	1.90×10^{-6}	0.0029	1.2990	0.0000	0.2552
Savannah-T8 (0-3)	8.40×10^{-7}	0.0002	1.4714	0.0000	0.2522
Savannah-T8 (3-6)	6.70×10^{-7}	0.0025	1.3255	0.0000	0.2515
Savannah-T8 (6-9)	8.90×10^{-6}	0.0009	1.3467	0.0000	0.2590

K_{sat} = Horizontal saturated hydraulic conductivity
α = 1/air-entry value
N = Fitting parameter
θ_r = Residual moisture content
θ_s = Saturated moisture content

Table 4-3. Statistical Summary for Selected Meteoric Water Mobility Procedure Results

Parameter (units)	TBGC-1		TBGC-2		TBGC-3		TBGC-4		TBGC-5		TBGC-6		TBGC-7		TBGC-7A	
	No. 3B Stockpile		No. 1 Leach Stockpile		No. 1 Leach Stockpile		No. 1 Leach Stockpile		No. 1C Stockpile		East Main Stockpile		No. 2 Leach Stockpile		No. 2A Leach Stockpile	
	Mean	*Std. Dev.*	Mean	*Std. Dev.*	Mean	*Std. Dev.*	Mean	*Std. Dev.*	Mean	*Std. Dev.*	Mean	*Std. Dev.*	Mean	*Std. Dev*	Mean	*Std. Dev.*
pH (su)	4.97	*1.17*	3.61	*0.36*	4.02	*0.32*	3.76	*0.34*	4.86	*0.98*	3.81	*0.69*	3.35	*0.39*	3.57	*0.35*
EC (µmhos/cm)	1,835	*2,341*	4,169	*1,217*	3,286	*737*	2,504	*1,085*	1,840	*1,507*	2,896	*978*	5,102	*1,478*	4,697	*1,412*
Acidity (mg/L)	1,205	*2,339*	2,202	*998*	1,191	*484*	980	*642*	477	*870*	1,259	*1,042*	3,076	*1,405*	3,070	*1,554*
SO_4 (mg/L)	1,791	*2,860*	3,942	*1,576*	2,640	*755*	2,047	*1,103*	1,376	*1,537*	2,489	*1,199*	5,047	*1,965*	4,925	*1,969*
F (mg/L)	11.9	*32.0*	27.5	*10.2*	15.4	*5.25*	11.5	*7.92*	8.02	*8.49*	27.5	*21.8*	55.0	*21.0*	61.4	*25.9*
Al (mg/L)	149	*294*	196	*152*	87.8	*58.4*	92.8	*65.2*	46.0	*95.6*	170	*150*	361	*211*	374	*199*
Cu (mg/L)	310	*646*	449	*427*	336	*146*	208	*124*	115	*178*	282	*217*	233	*303*	205	*209*
Fe (mg/L)	10.9	*24.3*	19.2	*40.3*	1.70	*4.16*	4.42	*6.76*	0.88	*2.71*	21.6	*25.7*	62.1	*63.2*	55.6	*60.9*
Mn (mg/L)	27.1	*53.0*	186	*73.0*	178	*89.1*	79.4	*47.4*	48.1	*70.5*	64.6	*42.9*	135	*62.8*	130	*66.0*
Zn (mg/L)	39.8	*123*	110	*44.4*	73.7	*34.9*	40.4	*25.9*	21.1	*32.4*	116	*48.5*	162	*67.0*	176	*77.4*
Cd (mg/L)	0.230	*0.685*	0.467	*0.322*	0.103	*0.046*	0.079	*0.083*	0.228	*0.337*	1.23	*0.679*	1.42	*0.607*	1.48	*0.713*
Co (mg/L)	0.806	*1.40*	2.19	*1.51*	2.13	*0.954*	1.01	*0.597*	0.871	*1.26*	1.12	*0.611*	2.83	*1.86*	2.09	*0.816*
Cr (mg/L)	0.014	*0.026*	0.063	*0.092*	ND	*ND*	ND	*ND*	ND	*ND*	0.033	*0.037*	0.080	*0.074*	0.046	*0.032*
Ni (mg/L)	0.259	*0.413*	0.677	*0.263*	0.727	*.315*	0.383	*0.210*	0.174	*0.208*	0.352	*0.274*	0.604	*0.230*	0.929	*0.359*
Pb (mg/L)	0.096	*0.181*	0.055	*0.035*	0.051	*0.032*	0.021	*0.008*	0.021	*0.029*	0.113	*0.107*	0.078	*0.081*	0.040	*0.062*

Std. Dev. = Standard deviation
su = Standard units
EC = Electrical conductivity

µmhos/cm = Micromhos per centimeter
mg/L = Milligrams per liter
ND = Not detected (a value of half the detection limit was assumed for calculation of statistics)

the *Supplemental Materials Characterization of the Leached Ore Stockpiles and Waste Rock Stockpiles Final Report* (EnviroGroup, 2005c).

The synthetic precipitation leach procedure (SPLP) test was used on fresh rock and stockpile materials samples for the PMC and SMC (DBS&A, 1997a, 1997c). The SPLP test uses a 1 to 20 rock to water ratio and the MWMP uses a 1 to 1 rock to water ratio. Therefore the MWMP results are not compared to the previous SPLP results.

4.2.2.1 pH

MWMP extracts are acidic to neutral (pH values range between 2.5 and 6.8), and the MWMP pH profiles provided in Appendix B of the *Supplemental Materials Characterization of the Leached Ore Stockpiles and Waste Rock Stockpiles Final Report* (EnviroGroup, 2005c) are similar to the paste pH profiles. The extract pH values in waste rock stockpile boreholes TBGC-1 and TBGC-5 are generally higher and more varied than in the other boreholes drilled into leach ore stockpile material. The extract pH values of the waste rock stockpile boreholes TBGC-1 and TBGC-5 ranges between 3 and 7, whereas the pH of the leach ore stockpile extracts generally ranges between 3 and 5. There is no trend of increasing or decreasing pH with depth or age of material.

4.2.2.2 Electrical Conductivity

EC in the MWMP extracts ranges from 100 to 7,000 µmhos/cm in the waste rock stockpile boreholes. In general, the extract EC values are higher in the leach ore stockpile boreholes, generally ranging from 1,000 to 9,000 µmhos/cm. The extract EC generally trends up as the pH trends down, but there is no relationship between EC and material depth or age.

4.2.2.3 Sulfate

The MWMP extract sulfate concentrations are between 23 and 11,000 mg/L in all samples. The sulfate concentrations are generally higher in the leach ore stockpile samples than in the waste rock stockpile samples. The sulfate concentrations generally track positively with the ABP and sulfide content in the material. There is also a trend in higher sulfate extract concentrations with lower extract pH. However sulfate concentrations do not appear to be related to the material depth or age.

4.2.2.4 Fluoride

The fluoride concentrations in the MWMP extracts generally range from less than 1 to 150 mg/L. The concentrations mobilized from waste rock stockpile material are generally lower than concentrations measured in leach ore material extracts. The fluoride concentrations trend upward with extract EC but do not track pH or sulfate significantly. There is no correlation of fluoride with depth or material age.

4.2.2.5 Metals

The metals aluminum, copper, iron, manganese, zinc, cadmium, cobalt, chromium, nickel, and lead were mobilized from the stockpile samples upon contact with meteoric water. Aluminum, copper, iron, manganese, and zinc had the highest concentrations in the MWMP extracts, ranging from below detection to more than 1,000 mg/L. Most concentrations were in the tens and hundreds mg/L and tended to increase at lower pH.

The metals cadmium, cobalt, chromium, nickel, and lead evolved relatively lower concentrations—from below detection to 10 mg/L—in the MWMP extracts. Most concentrations are near or below the detection limit when the extract pH was 6 or higher in the waste rock stockpile samples, and there is a general trend for the metal concentrations to be higher at low pH conditions.

The results show that metals are more readily mobilized from materials sampled from leach ore stockpiles than from waste rock stockpiles upon contact with meteoric water. In general, the concentration of metals goes up as the pH of the extracts goes down. There does not appear to be a correlation of metal concentrations with depth, which suggests that the metal mobility in older materials is not different from that in younger materials.

4.3 Seepage Flow and Runoff Modeling

The results of seepage flow modeling are presented in Section 4.3.1 and the results of runoff modeling are in Section 4.3.2.

4.3.1 Seepage Flow Modeling

This section briefly describes the results of seepage modeling that was conducted by DBS&A for the No. 2B (formerly designated as the 2A) stockpile at the Tyrone Mine (DBS&A, 2006). A copy of the report describing the results of the seepage modeling is provided in Appendix A.

DBS&A performed variably saturated flow modeling of stockpile seepage to support Tyrone Mine Site closure/closeout activities. A numerical model was developed using HYDRUS to simulate stockpile seepage after reclamation. Reclamation of the Tyrone Mine Site stockpiles will include regrading the stockpiles to a 3 to 1 slope, covering the stockpiles with 3 feet of suitable borrow material, and vegetating the cover. The numerical model was based on a cross section through the western portion of the No. 2B stockpile and simulated seepage under two infiltration rates: 6.5 and 0.4 centimeters per year (cm/yr). The higher infiltration rate represents 16.1 percent of short-term average annual precipitation, and the lower infiltration rate represents 1 percent of short-term average annual precipitation.

The numerical modeling presented in this report is based on previous stockpile seepage modeling presented by DBS&A (1999b). The previous model simulated seepage through the western portion of the No. 2B stockpile prior to reclamation. The stockpile slope was set to 1.5 to 1 (approximate angle of repose) with no cover material, approximating current conditions. The previous modeling was conducted to evaluate, through model calibration, the amount of precipitation that infiltrated into the stockpile and subsequently into colluvium and bedrock materials that underlie the stockpile. The previous numerical model was calibrated to flow measurements at Seep 5E, located at the toe of the No. 2B stockpile. Results from the previous modeling analysis were used as a starting point for the new model developed to evaluate stockpile seepage under regraded conditions.

The internal structure of the regraded stockpile was represented by the same layered structure as used in the previous seepage modeling presented by DBS&A (1999b). The same boundary conditions and hydraulic properties also apply. The only difference is that the model domain was extended to accommodate the push-down material from the regrading. The thickness of the material above the alluvium was also thinner owing to the spreading out of material. For the uncovered case, a constant flux rate of 6.5 cm/yr was applied to the top surface and outslope of the stockpile, to simulate the infiltration of water from precipitation. This flux rate was determined from water balance analyses conducted for the Tyrone Mine stockpiles and sensitivity analyses conducted using the previous seepage model (DBS&A, 1999b). The regraded stockpile scenario with the applied infiltration of 6.5 cm/yr was run for a sufficient period of time to obtain steady-state simulated conditions. Although this approach was used to provide an internally consistent set of initial conditions for the predictive simulation for the covered stockpile, it is unlikely that the regarded stockpile will attain a steady-state condition with regard to moisture content once it is regraded, but prior to installation of a cover.

To determine the effect of covering the 3.5:1 slope, the steady-state simulation was modified with a reduced infiltration rate of 0.4 cm/yr, which is 1 percent of short-term mean annual precipitation. Although the simulation was run for a period of 1,000 years to evaluate the time required for the reduced seepage through the stockpile to obtain a new steady state, most of the changes in simulated water content and fluxes occur within about 30 years or less.

Several figures in the modeling report (Appendix A) illustrate the results of the simulations

- Figure 7 illustrates the change in pressure head at selected observation nodes over a 1,000-year duration. The results are plotted on a log scale so the initial changes can be observed.

- Figure 8 illustrates the simulated pressure head in the cross-sectional profile at 50 years.

- Figure 9 illustrates the simulated flux across the bottom boundary of the model through time.

These figures indicate that changes in simulated pressure head and boundary flux beneath the regraded, covered stockpile begin at about 3 years and continue for more than 30 years, although much of the simulated changes have occurred by about 30 years. For the covered stockpile predictive transient simulations, the flux rate out of the base of the bedrock represents about 35 percent of the total basal seepage, whereas the flow through the alluvial channel and to the catchment areas represents about 65 percent of the total basal seepage.

4.3.2 Stockpile Runoff Modeling

This section describes the results of runoff modeling that was conducted for the Tyrone Mine stockpile surfaces. Runoff amounts were estimated by the SCS curve number method (Bedient and Huber, 1992), which is based on land use and hydrologic soil group. A curve number of 88 was assigned to the uncovered stockpile surfaces since the area is considered to be disturbed land with little or no vegetation (fallow) and SCS hydrologic group C characteristics. A curve number of 84 was assumed for the covered stockpile surfaces based on open space land in fair condition (50 percent grass cover) with SCS hydrologic group D characteristics.

The calculated runoff amounts for the two curve numbers were totaled for every month in the period of record that was not missing more than five days of data, and a long-term average was then determined for each month of the year. The average monthly runoff volumes were calculated by multiplying the runoff amounts by the total stockpile acreage, and these values were summed to provide an annual total. The calculated stockpile area for the uncovered stockpiles surfaces as of 2004 was approximately 3,471 acres. The estimated covered stockpile area based on the DP-1341 closure plan is approximately 3,884 acres. Table 4-4 contains the monthly and annual Fort Bayard precipitation totals and results of the stockpile runoff calculations for the uncovered and covered stockpile surfaces.

4.4 Geochemical Modeling

A geochemical model was developed that simulates stockpile seepage quality and determines the annual mass loading of dissolved constituents to groundwater from basal seepage emanating from the leach ore and waste rock stockpiles. The details of the mass loading model are presented as a technical memo in Appendix B. The conceptual model, model calibration, and model results are presented below in Sections 4.3.1, 4.3.2, and 4.3.3, respectively.

4.4.1 Conceptual Model

The geochemical stockpile seepage quality model was developed for the Tyrone Mine using the geochemical computer code X1t, a one-dimensional reactive transport code of the modeling package Geochemist's Workbench (GWB) (Bethke, 2004a, 2004b). The code solves the mass balance equations for kinetic and equilibrium heterogeneous reactions involving minerals and fluids while solving for mass transport along the flow path. The implementation of this code is described further in Appendix B.

Table 4-4. Tyrone Mine Stockpile Runoff Results

Month	Average Fort Bayard Precipitation [a] (inches)	Uncovered Stockpile Average Runoff [b]		Covered Stockpile Average Runoff [c]	
		inches	acre-feet	inches	acre-feet
January	0.88	0.07	19	0.03	11
February	0.86	0.06	17	0.03	9
March	0.70	0.04	10	0.02	6
April	0.39	0.02	6	0.01	3
May	0.46	0.04	12	0.02	7
June	0.80	0.09	26	0.05	17
July	3.22	0.40	116	0.24	76
August	3.29	0.46	133	0.28	90
September	2.01	0.29	84	0.18	57
October	1.24	0.20	59	0.13	43
November	0.78	0.09	26	0.05	17
December	1.05	0.08	25	0.04	14
Annual	15.70	1.84	531	1.08	351

[a] Average Fort Bayard precipitation amounts determined from January 1897 through July 2005 daily data, excluding 19 months that were missing 5 or more days of data.
[b] A curve number of 88 was assumed for the uncovered stockpile surfaces.
[c] A curve number of 84 was assumed for the covered stockpile surfaces.

The conceptual model presented in this report is refined from the conceptual model presented as part of the stockpile outslope evaluation (DBS&A, 2001, Appendix C) in order to evoke the X1t simulation. The essential components of the conceptual model are shown in Figure 4-2. In an X1t simulation, the user sets the initial mineralogy of the medium and chemical composition of the pore fluid. Over the course of the simulation, an unreacted fluid of specified composition enters the end of the domain and reacts as it passes along the linear coordinate.

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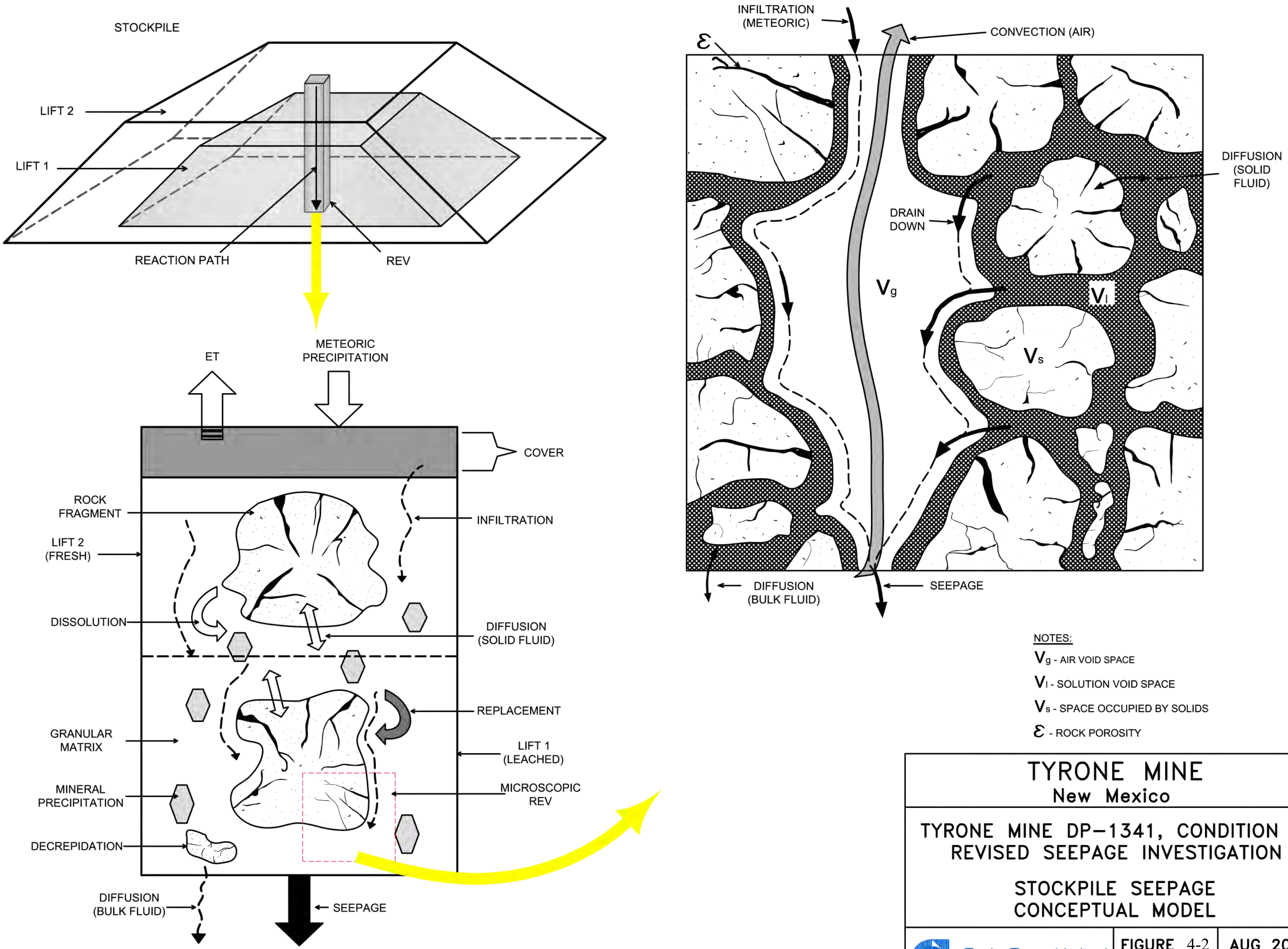

NOTES:

V_g - AIR VOID SPACE

V_l - SOLUTION VOID SPACE

V_s - SPACE OCCUPIED BY SOLIDS

ε - ROCK POROSITY

Not to scale, illustration only

TYRONE MINE
New Mexico

TYRONE MINE DP–1341, CONDITION 81 REVISED SEEPAGE INVESTIGATION

STOCKPILE SEEPAGE CONCEPTUAL MODEL

EnviroGroup Limited
Centennial, Colorado

EnviroGroup Limited Centennial, Colorado	FIGURE 4-2	AUG 2006
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The assumptions used in the mass loading modeling that was conducted as part of the stockpile outslope evaluation (DBS&A, 2001) are:

- Standard temperature and pressure (STP) (i.e., 25ºC and 1 bar of pressure)
- Steady-state infiltration and vertical flow of meteoric water through the stockpiles
- Stockpile materials are randomly distributed and homogeneous
- Distinct pore waters are perfectly mixed at the point where basal seepage forms
- Steady-state constituent dissolution from stockpiles and constant chemical reaction rates
- Precipitation and dissolution of solids from stockpile pore waters under the condition of partial equilibrium, but no adsorption, desorption, or ion-exchange reactions

These assumptions were modified for the purposes of this revised seepage investigation.

The conceptual model portrayed in Figure 4-2 includes the following components and assumptions for the stockpile systems:

- A range of temperatures measured in stockpiles
- Mass transport by one-dimensional vertical advection, diffusion, and dispersion
- Variable inlet fluid compositions and infiltration rates
- Homogeneous material domains and initial conditions
- Specification of kinetic rate laws for mineral reactants
- Redox equilibrium
- Gas buffering under variable oxygen partial pressures
- Equilibrium and kinetic heterogeneous reactions

These components and assumptions were integrated into the X1t geochemical model that was developed and calibrated for the purposes of the mass loading estimations. The geochemical model is used to simulate stockpile seepage quality. The predicted seepage quality is then used to estimate mass loading by multiplying the simulated seepage quality times the volumetric rate of discharge. Hence, mass loading is defined by the following equation:

$$M \text{ (grams per year)} = Q \times C$$

Where M = mass loading
Q = annual stockpile discharge amount or basal seepage volume (liters)
C = concentration of constituent (grams per liter)

The mass loading can be used as a measure of the potential impact to groundwater quality from stockpile seepage. This measure can be derived for the existing condition and the DP-1341 closure design to estimate relative performance. Because the seepage quality from different closure designs can vary, it is necessary to model each scenario in order to determine the relative mass loading under the different infiltration performances.

4.4.2 Mass Loading Model Calibration

The No. 1 leach stockpile was selected to calibrate the Tyrone Mine mass loading model. The seepage calibration process involved adjusting the mineral reaction rates until the simulated output concentrations best matched the concentrations observed in seepage samples collected in the past five years from perched zone wells 1-5 and 1-6. These wells are located at the toe of the No. 1 leach stockpile. The mineral reaction rates were adjusted in the different calibration runs according to the values listed in Table 4-5.

Table 4-5. Seepage Calibration Run List of Mineral Reaction Rates

Calibration Run	Mineral Rate Constant (moles/cm^2/s)					
	Potassium Feldspar	Albite	Muscovite	Chlorite	Pyrite	Chalcocite
No1Stockpile_cal1	10^{-15}	10^{-15}	1.6 x 10^{-18}	10^{-15}	4.0 x 10^{-13}	4.0 x 10^{-13}
No1Stockpile_cal4	10^{-15}	10^{-15}	1.6 x 10^{-18}	5.0 x 10^{-15}	10^{-13}	2.0 x 10^{-14}
No1Stockpile_cal5	10^{-15}	10^{-15}	1.6 x 10^{-18}	8.0 x 10^{-15}	2.0 x 10^{-13}	2.0 x 10^{-14}
No1Stockpile_cal9	7.0 x 10^{-16}	3.0 x 10^{-16}	3.0 x 10^{-18}	9.0 x 10^{-15}	1.5 x 10^{-13}	2.0 x 10^{-14}
No1Stockpile_cal12	7.0 x 10^{-16}	5.0 x 10^{-17}	1.6 x 10^{-18}	9.0 x 10^{-15}	1.7 x 10^{-13}	2.0 x 10^{-14}

Note: Quartz and kaolinite rates were held constant at 1.6 x 10^{-18} moles/cm2/s for all model runs.

Figures 13 through 19 of Appendix B show the results of the transport model calibration runs for the No. 1 leach stockpile from model year 0 to 500 for sulfate, total dissolved solids, iron, pH, magnesium, copper, and aluminum. These graphs illustrate how the composition of the leach solution changes as it passes through and reacts with the composite stockpile materials. In general, these figures show that the predicted concentrations at the base of the stockpile increase over time, reaching a peak, and then decrease over time. Equilibrium with mineral phases controls the long-term concentrations with respect to some constituents.

The 20- to 40-year simulated seepage concentrations are compared to the perched zone wells 1-5 and 1-6 seepage concentrations shown in Figures 6 through 12 of Appendix B. The Table 4-5 parameters for calibration run No1Stockpile_cal12 produced the best match of the 20- to 40-year simulated seepage concentrations to actual well 1-5 and 1-6 seepage concentrations. This run is considered to be the calibrated run and these mineral rate constants were used for the base case Tyrone Mine mass loading model runs. In some of the sensitivity runs the rate of pyrite was increased or decreased based on the physicochemical conditions being simulated.

4.4.3 Mass Loading Model Results

The calibrated mass loading model presented above was used to estimate future stockpile seepage quality and mass loading conditions after mine closure based on (1) the existing configuration and (2) the DP-1341 closure plan. The model was first developed using the existing angle of repose stockpile surfaces with no cover material, allowing approximately 6.5 cm/yr of precipitation to infiltrate into the stockpiles after closure. The model was then updated with the terms of the DP-1341 closure plan by regrading the stockpile outslopes and reducing stockpile infiltration to 1 percent of the local mean annual precipitation (0.4 cm/yr) through cover installation. The results of the geochemical mass loading model for both scenarios include a prediction of stockpile seepage quality and mass loading through time.

A summary of the mass loading modeling results under both scenarios is presented in the following subsections for each of the Tyrone Mine stockpiles and complexes, and the model year 100 results are tabulated in Table 4-6. The complete mass loading results for all model runs are provided in Appendix C, including graphic results of the modeling parameters through time at the maximum stockpile depth and through stockpile depth at model years 10, 100, and 500.

Table 4-6. Tyrone Mine Mass Loading Results at Model Year 100

Stockpile	Scenario	Area (m^2)	Sulfate Mass Loading (mg/yr)	Seepage Volume (m^3/yr)	Sulfate Concentration [a] (mg/L)
No. 1 Leach	Existing	687,395	2.5 x 10^{12}	44,681	55,922
	DP-1341	758,460	2.7 x 10^{11}	3,034	87,720
No. 1 Leach Complex	Existing	3,375,069	1.6 x 10^{13}	219,380	71,295
	DP-1341	3,653,764	1.6 x 10^{12}	14,615	107,084
No. 1C Waste	Existing	1,346,918	1.4 x 10^{12}	87,550	16,189
	DP-1341	1,369,828	1.4 x 10^{11}	5,479	25,377
No. 1D Waste	Existing	1,249,461	1.1 x 10^{12}	81,215	13,106
	DP-1341	1,756,914	1.2 x 10^{11}	7,028	17,396
No. 2 Leach Complex	Existing	5,117,105	1.4 x 10^{13}	332,612	41,083
	DP-1341	5,345,853	1.1 x 10^{12}	21,383	53,741
No. 2B Waste	Existing	383,511	6.8 x 10^{11}	24,928	27,089
	DP-1341	454,820	9.3 x 10^{10}	1,819	51,223
No. 3 Leach	Existing	1,058,422	6.0 x 10^{12}	68,797	86,596
	DP-1341	1,550,707	6.4 x 10^{11}	6,203	102,445
No. 3B Waste	Existing	827,924	1.0 x 10^{12}	53,815	18,729
	DP-1341	826,208	8.5 x 10^{10}	3,305	25,676
Mine total	Existing	14,045,806	4.2 x 10^{13}	912,977	45,923
	DP-1341	15,716,554	4.1 x 10^{12}	62,866	64,504

[a] Mine total sulfate concentrations are the infiltration volume weighted average sulfate concentrations for the stockpile scenario.

m^2 = square meters
mg/yr = milligrams per year
m^3/yr = cubic meters per year
mg/L = milligrams per liter

4.4.3.1 Sensitivity Analysis for No. 1 Leach and 2B Waste Stockpiles

A series of sensitivity runs were completed for the No. 1 leach stockpile and No. 2B waste stockpile with the calibrated model. Model parameters that were varied include temperature, oxygen concentration, sericite rate, scale factor, and porosity. The pyrite rate was adjusted with changes to temperature and oxygen concentrations, and modifying the porosity essentially altered the stockpile moisture content. Table 4-7 contains the model parameters values varied from the base case run for each of the eight sensitivity runs.

Table 4-7. Model Sensitivity Analysis

Model Parameter	Base Case	Sensitivity Run [a]							
		1	2	3	4	5	6	7	8
Temperature [b] (ºC)	25	*40*	40	40	40	40	40	40	40
Oxygen fugacity [c]	0.2	0.2	*0.02*	*0.002*	0.2	0.2	0.2	0.2	0.2
Sericite rate (moles/cm^2/s)	1.6×10^{-18}	1.6×10^{-18}	1.6×10^{-18}	1.6×10^{-18}	*1.6×10^{-16}*	*1.6×10^{-14}*	1.6×10^{-18}	1.6×10^{-18}	1.6×10^{-18}
Surface area [d] (cm^2/g)	40	40	40	40	40	40	*400*	*4*	40
Porosity (%)	MWMP value	MWMP value	MWMP value	MWMP value	MWMP value	MWMP value	MWMP value	MWMP value	*1.5 x MWMP value*

[a] The sensitivity analysis includes a total of 9 runs. Sensitivity input parameters that varied from the base case values are italicized.

[b] Pyrite reaction rate was calculated as a function of the temperature of the stockpile at 1.7×10^{-3} and 4.25×10^{-13} moles/cm^2/s at 25 and 40°C, respectively.

[c] Pyrite reaction rate was calculated as a function of the oxygen content of the stockpile at 1.7×10^{-13}, 1.7×10^{-14}, and 1.7×10^{-15} moles/cm^2/s at 0.2, 0.02, and 0.002 oxygen fugacity, respectively.

[d] Surface area was set an order of magnitude lower for pyrite, chalcocite, and quartz at 4, 40, and 0.4 cm^2/g instead of 40, 400, and 4 cm^2/g, respectively.

4.4.3.1.1 Existing Stockpile Scenario. The first series of sensitivity runs were completed for the existing stockpile configuration with no cover material. The model year 100 mass loading results of the existing No. 1 leach stockpile for each parameter in the model, including seepage pH and stockpile porosity, are contained in Table 4-8. The maximum stockpile depth simulated sulfate concentrations and seepage pH results of these runs for the No. 1 leach stockpile over the 500-year modeling period are shown in Figures 4-3 and 4-4, respectively. For the base case run, the sulfate concentration increased over time to 105,400 mg/L at model year 170 and then slowly decreased, while the pH slowly decreased to below 1 at about 100 years into the run and then increased to 2 over the remainder of the 500-year model period. The effect of increasing the model temperature (sensitivity run 1) dramatically raised sulfate concentrations, which reached a peak of 197,600 mg/L at model year 140. The pH values were similar to the base case for the majority or the run, but increased to almost 4 near the end of the modeling period.

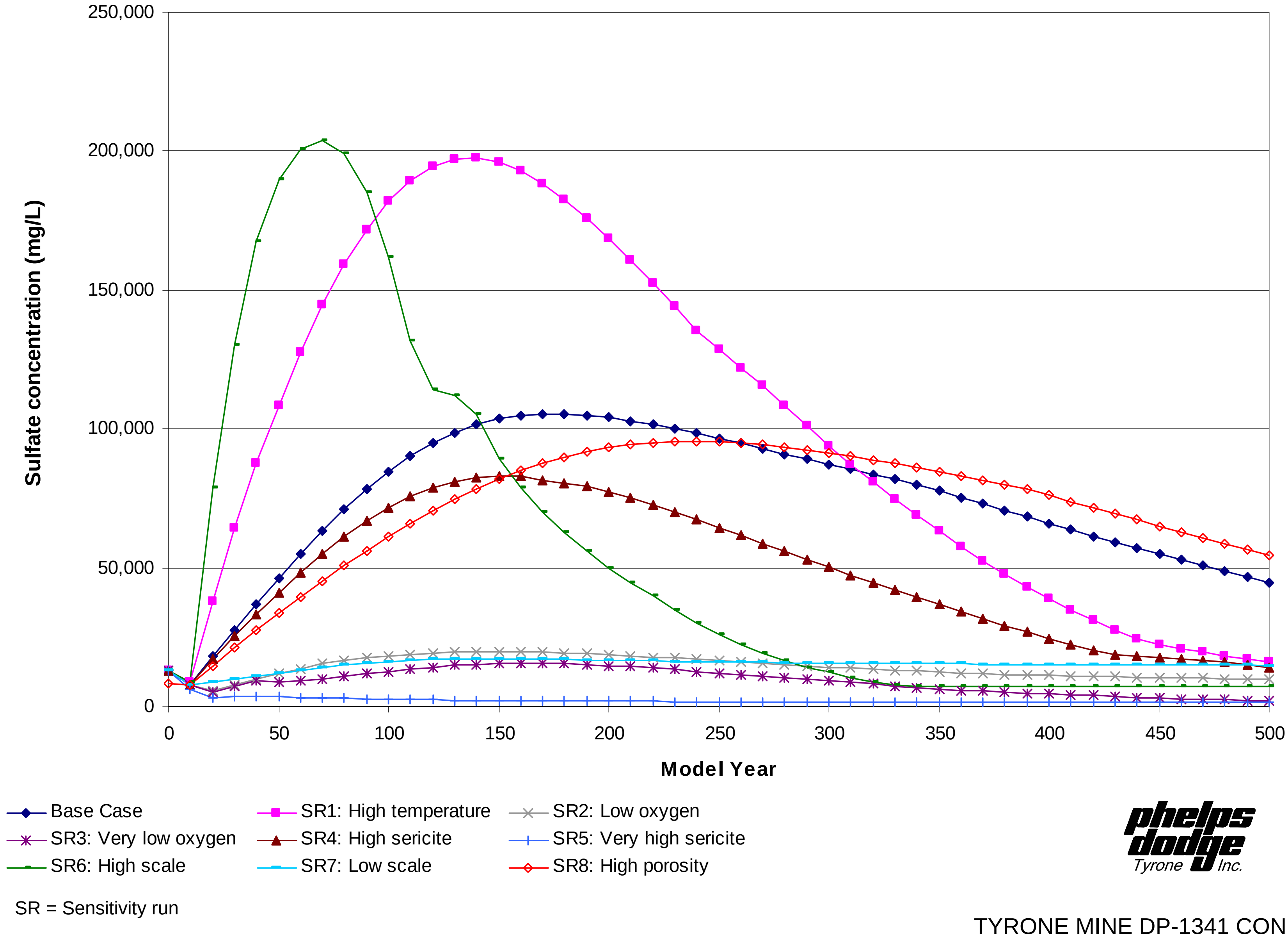
For sensitivity runs 2 and 3, the oxygen concentration was lowered, resulting in much lower sulfate concentrations as compared to the base case run with only relatively small changes in concentrations over time, while the pH for these runs rose to above 4 and between 6 and 7, respectively. The sericite rate was increased two orders of magnitude in sensitivity run 4, and the results are similar to the base case with slightly lower sulfate concentrations and pH values between 2 and 4. For sensitivity run 5, the sericite rate was increased an additional two orders of magnitude, resulting in the lowest sulfate concentrations of any of the sensitivity runs and a pH between 4 and 5.

Increasing the scaling constant (sensitivity run 6) increased the sulfate concentration to a peak of 203,600 mg/L at model year 70, the highest of any of the sensitivity runs, and then the sulfate concentration drops off dramatically with time. The pH values in sensitivity run 6 decreased to about 1 while the sulfate was increasing and then increased to a pH around 4 for the remainder of the model run. Lowering the scale factor (sensitivity run 7) results in sulfate concentrations similar to those simulated in the low oxygen sensitivity runs 2 and 3 and pH values between 1 and 2. For sensitivity run 8, the porosity was increased by a factor of 1.5, which caused the sulfate release curve to be flattened or stretched from the base case, but had little effect on the seepage pH.

Table 4-8. No. 1 Stockpile Mass Loading Model Results at Year 100 for the Existing Configuration

Parameter	Base Case	Sensitivity Run							
		1	2	3	4	5	6	7	8
Aluminum (mg/yr)	2.3×10^{11}	2.1×10^{11}	6.2×10^{8}	1.1×10^{5}	2.5×10^{11}	3.0×10^{8}	7.6×10^{10}	3.4×10^{10}	1.9×10^{11}
Bicarbonate (mg/yr)	2.7×10^{7}	1.7×10^{7}	3.0×10^{7}	1.2×10^{8}	2.8×10^{7}	3.0×10^{7}	2.6×10^{7}	2.9×10^{7}	2.8×10^{7}
Calcium (mg/yr)	4.1×10^{9}	3.5×10^{10}	4.8×10^{9}	4.8×10^{9}	4.1×10^{9}	2.7×10^{9}	1.3×10^{9}	4.8×10^{9}	7.3×10^{9}
Chloride (mg/yr)	1.3×10^{9}	1.0×10^{9}	1.5×10^{9}	1.5×10^{9}	1.3×10^{9}	8.5×10^{8}	8.7×10^{8}	1.5×10^{9}	2.3×10^{9}
Cobalt (mg/yr)	4.6×10^{7}	3.7×10^{7}	5.5×10^{7}	5.5×10^{7}	4.6×10^{7}	3.1×10^{7}	3.2×10^{7}	5.4×10^{7}	8.3×10^{7}
Copper (mg/yr)	1.6×10^{11}	1.5×10^{11}	9.3×10^{10}	1.4×10^{8}	1.6×10^{11}	2.6×10^{10}	1.2×10^{12}	2.1×10^{10}	1.3×10^{11}
Fluoride (mg/yr)	7.1×10^{8}	1.5×10^{9}	8.4×10^{8}	2.5×10^{8}	7.1×10^{8}	4.8×10^{8}	4.8×10^{8}	8.3×10^{8}	1.3×10^{9}
Iron (mg/yr)	1.8×10^{10}	8.1×10^{11}	1.7×10^{6}	2.5×10^{6}	1.3×10^{8}	8.5×10^{5}	1.4×10^{7}	1.0×10^{10}	1.5×10^{10}
Magnesium (mg/yr)	9.3×10^{10}	8.6×10^{10}	6.5×10^{10}	7.7×10^{10}	9.3×10^{10}	5.8×10^{9}	6.7×10^{10}	1.8×10^{10}	7.9×10^{10}
Manganese (mg/yr)	2.2×10^{10}	5.1×10^{10}	2.7×10^{5}	1.4×10^{2}	2.2×10^{9}	9.6×10^{3}	1.9×10^{9}	6.0×10^{9}	1.9×10^{10}
Nickel (mg/yr)	1.7×10^{7}	1.4×10^{7}	2.0×10^{7}	2.0×10^{7}	1.7×10^{7}	1.2×10^{7}	1.2×10^{7}	2.0×10^{7}	3.0×10^{7}
Potassium (mg/yr)	1.7×10^{10}	3.4×10^{2}	9.1×10^{9}	5.1×10^{9}	2.3×10^{10}	1.6×10^{10}	7.1×10^{11}	1.4×10^{6}	1.2×10^{10}
Silica (mg/yr)	4.8×10^{9}	6.1×10^{9}	4.1×10^{9}	1.0×10^{9}	4.9×10^{9}	2.4×10^{9}	4.5×10^{9}	5.1×10^{9}	4.9×10^{9}
Sodium (mg/yr)	7.8×10^{9}	2.7×10^{9}	3.4×10^{10}	4.6×10^{10}	7.8×10^{9}	3.3×10^{9}	5.4×10^{10}	6.1×10^{8}	5.6×10^{9}
Sulfate (mg/yr)	2.5×10^{12}	5.3×10^{12}	5.0×10^{11}	4.2×10^{11}	2.1×10^{12}	9.8×10^{10}	3.6×10^{12}	4.1×10^{11}	2.1×10^{12}
Zinc (mg/yr)	2.6×10^{9}	2.1×10^{9}	3.1×10^{9}	3.1×10^{9}	2.6×10^{9}	1.8×10^{9}	1.8×10^{9}	3.1×10^{9}	4.7×10^{9}
TDS (mg/yr)	3.1×10^{12}	6.7×10^{12}	7.1×10^{11}	5.6×10^{11}	2.6×10^{12}	1.6×10^{11}	5.8×10^{12}	5.1×10^{11}	2.6×10^{12}
pH (su)	1.15	1.23	4.54	6.55	2.25	4.66	3.01	1.90	1.22
Porosity (%)	14.45	14.71	14.70	14.64	14.18	10.10	12.32	14.56	21.87

mg/yr = Milligrams per year
TDS = Total dissolved solids
su = Standard units



phelps dodge Tyrone Inc.

TYRONE MINE DP-1341 CONDITION 81

No. 1 Stockpile

Sulfate Concentrations through Time at 65-Meter Depth

Figure 4-3

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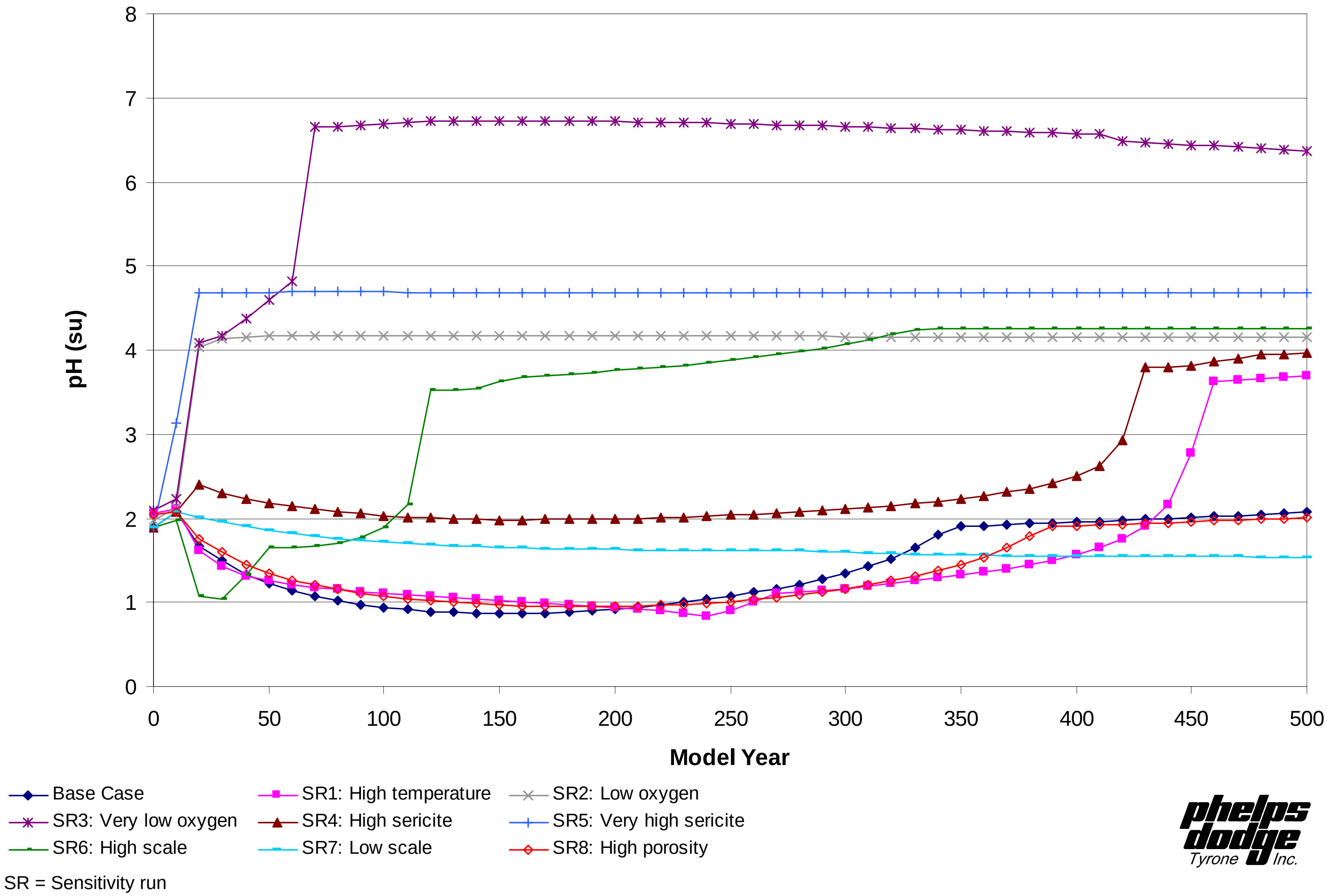

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TYRONE MINE DP-1341 CONDITION 81

No. 1 Stockpile

Seepage pH through Time at 65-Meter Depth

Figure 4-4

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The model year 100 mass loading results of the existing No. 2B waste stockpile for each parameter in the model, including seepage pH and stockpile porosity, are contained in Table 4-9. The maximum stockpile depth simulated sulfate concentrations and seepage pH results of the base case and sensitivity runs for the No. 2B waste stockpile are shown in Figures 4-5 and 4-6, respectively. For the base case run, the sulfate concentration increased over time to just under 60,000 mg/L at model year 150 and then slowly decreased, while the pH remained between 2 and 3 for most of the run, increasing to above 3 in the last 100 years. In general, the results for the No. 2B waste stockpile sensitivity runs show similar patterns to the results of the No. 1 leach stockpile sensitivity runs, although the sulfate concentrations are significantly lower and the pH values a little higher for the waste rock sensitivity runs.

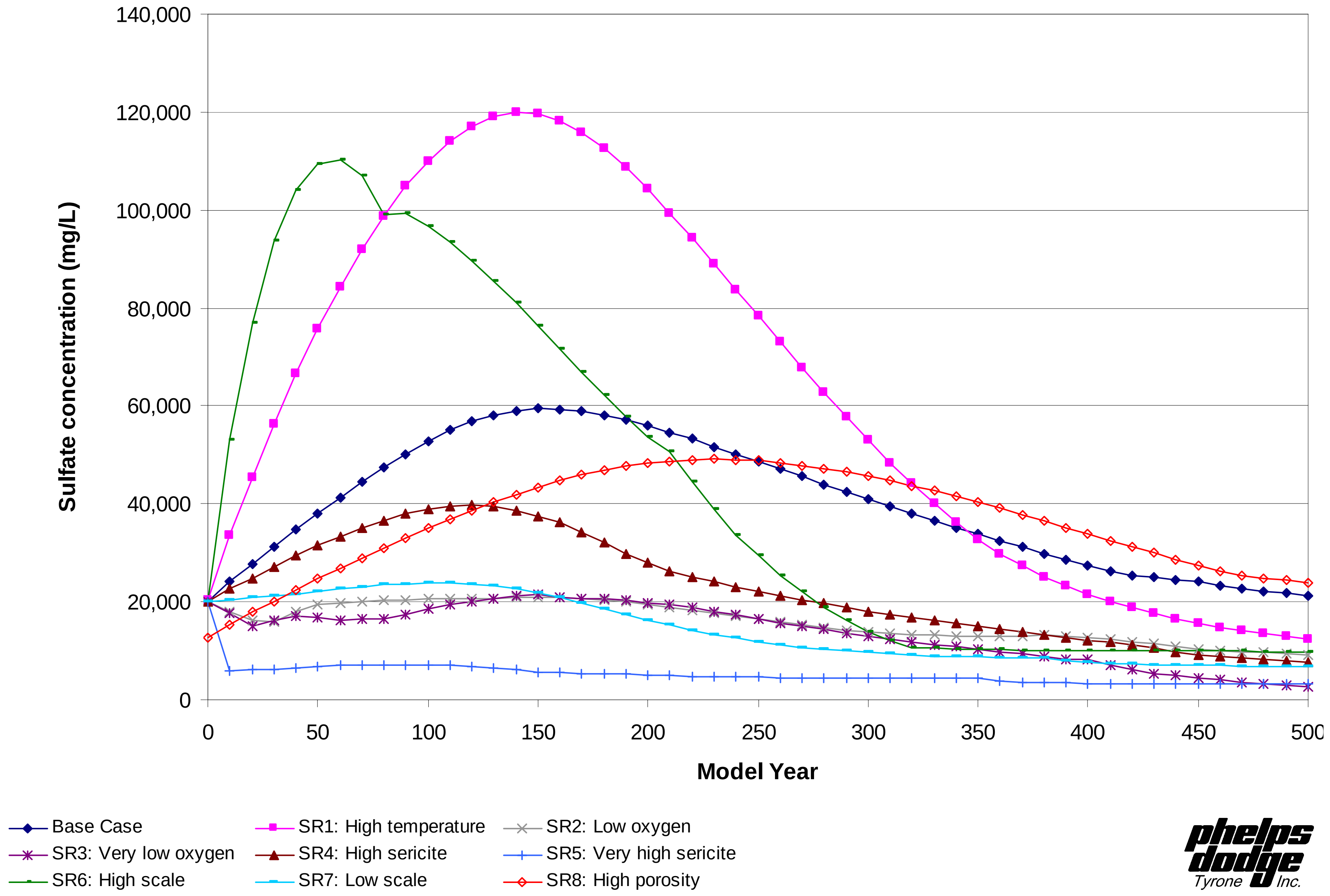
4.4.3.1.2 DP-1341 Closure Plan Scenario. The second series of sensitivity runs were completed for the DP-1341 closure plan stockpile configuration. The model year 100 mass loading results of the DP-1341 No. 1 leach stockpile for each parameter in the model, including seepage pH and stockpile porosity, are contained in Table 4-10. The maximum stockpile depth simulated sulfate concentrations and seepage pH results of these runs over the 500-year modeling period are shown in Figures 4-7 and 4-8, respectively. For the base case run with the DP-1341 closure plan, the sulfate concentration continually increased over the 500-year model period, reaching approximately 250,000 mg/L at year 500, while the pH decreased to about 1. Increasing the model temperature (sensitivity run 1) increased the sulfate concentrations to the highest level of any of the sensitivity runs, reaching about 300,000 mg/L by model year 300, while the pH decreased to about 0.75, the lowest level of any of the sensitivity runs.

For sensitivity runs 2 and 3, the oxygen concentration was lowered, resulting in sulfate concentrations that only increased slightly over time, while the pH reached just above 4 for sensitivity run 2 and near neutral for sensitivity run 3. The sericite rate was increased two orders of magnitude in sensitivity run 4, resulting in sulfate concentrations that were lower than the base case, peaking at about 162,000 mg/L by year 430 and then decreasing, while the pH remained close to 2 for the entire run. For sensitivity run 5, the sericite rate was increased another two orders of magnitude, resulting in the lowest sulfate concentrations of any of the sensitivity runs and pH values between 4.5 and 5.

Table 4-9. No. 2 Stockpile Mass Loading Model Results at Year 100 for the Existing Configuration

Parameter	Base Case	Sensitivity Run 1	2	3	4	5	6	7	8
Aluminum (mg/yr)	4.5×10^{10}	1.0×10^{11}	1.7×10^{9}	2.1×10^{8}	9.0×10^{9}	1.8×10^{9}	1.8×10^{9}	2.2×10^{10}	3.9×10^{10}
Bicarbonate (mg/yr)	1.6×10^{7}	1.1×10^{7}	1.7×10^{7}	3.2×10^{7}	1.6×10^{7}	1.7×10^{7}	1.5×10^{7}	1.6×10^{7}	1.6×10^{7}
Calcium (mg/yr)	7.5×10^{9}	6.4×10^{9}	8.0×10^{9}	8.0×10^{9}	7.5×10^{9}	8.6×10^{9}	5.9×10^{9}	8.4×10^{9}	6.8×10^{9}
Chloride (mg/yr)	2.1×10^{8}	2.0×10^{8}	2.3×10^{8}	2.3×10^{8}	2.1×10^{8}	2.2×10^{8}	1.7×10^{8}	2.3×10^{8}	2.0×10^{8}
Cobalt (mg/yr)	1.0×10^{8}	9.7×10^{7}	1.1×10^{8}	1.1×10^{8}	1.0×10^{8}	1.1×10^{8}	8.4×10^{7}	1.1×10^{8}	1.0×10^{8}
Copper (mg/yr)	9.9×10^{10}	9.6×10^{10}	8.4×10^{9}	1.3×10^{9}	1.0×10^{11}	9.0×10^{9}	4.2×10^{11}	1.9×10^{10}	8.0×10^{10}
Fluoride (mg/yr)	2.9×10^{9}	4.8×10^{8}	3.1×10^{9}	5.4×10^{8}	3.0×10^{9}	3.3×10^{9}	2.4×10^{9}	3.2×10^{9}	2.9×10^{9}
Iron (mg/yr)	2.3×10^{7}	1.0×10^{11}	3.9×10^{5}	6.1×10^{5}	1.1×10^{7}	4.3×10^{5}	2.5×10^{5}	2.4×10^{7}	2.3×10^{7}
Magnesium (mg/yr)	5.9×10^{10}	5.7×10^{10}	5.1×10^{10}	5.3×10^{10}	5.7×10^{10}	1.4×10^{10}	6.6×10^{10}	1.6×10^{10}	4.9×10^{10}
Manganese (mg/yr)	2.7×10^{8}	1.0×10^{10}	1.1×10^{4}	2.7×10^{3}	2.6×10^{6}	2.9×10^{3}	1.1×10^{6}	5.3×10^{7}	2.0×10^{8}
Nickel (mg/yr)	5.0×10^{7}	4.7×10^{7}	5.5×10^{7}	5.5×10^{7}	5.1×10^{7}	5.4×10^{7}	4.1×10^{7}	5.5×10^{7}	4.9×10^{7}
Potassium (mg/yr)	5.3×10^{9}	2.0×10^{2}	6.6×10^{9}	7.3×10^{9}	2.3×10^{8}	6.4×10^{9}	1.7×10^{11}	3.2×10^{8}	3.6×10^{9}
Silica (mg/yr)	2.8×10^{9}	3.7×10^{9}	7.9×10^{8}	3.9×10^{8}	2.8×10^{9}	9.8×10^{8}	2.7×10^{9}	2.9×10^{9}	2.8×10^{9}
Sodium (mg/yr)	2.1×10^{9}	2.1×10^{9}	2.2×10^{9}	2.2×10^{9}	2.2×10^{9}	2.2×10^{9}	2.0×10^{10}	3.6×10^{8}	1.7×10^{9}
Sulfate (mg/yr)	6.8×10^{11}	1.5×10^{12}	2.6×10^{11}	2.6×10^{11}	4.6×10^{11}	1.2×10^{11}	1.2×10^{12}	2.4×10^{11}	5.7×10^{11}
Zinc (mg/yr)	1.0×10^{10}	9.5×10^{9}	1.1×10^{10}	1.1×10^{10}	1.0×10^{10}	1.1×10^{10}	8.2×10^{9}	1.1×10^{10}	1.0×10^{10}
TDS (mg/yr)	9.1×10^{11}	1.9×10^{12}	3.6×10^{11}	3.5×10^{11}	6.5×10^{11}	1.8×10^{11}	1.9×10^{12}	3.3×10^{11}	7.6×10^{11}
pH (su)	2.51	1.66	5.02	5.80	3.64	4.85	3.78	2.95	2.55
Porosity (%)	14.59	14.79	14.86	14.87	14.30	14.29	12.87	14.80	22.30

mg/yr = Milligrams per year
TDS = Total dissolved solids
su = Standard units



SR = Sensitivity run

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TYRONE MINE DP-1341 CONDITION 81

No. 2B Stockpile

Sulfate Concentrations through Time at 85-Meter Depth

Figure 4-5

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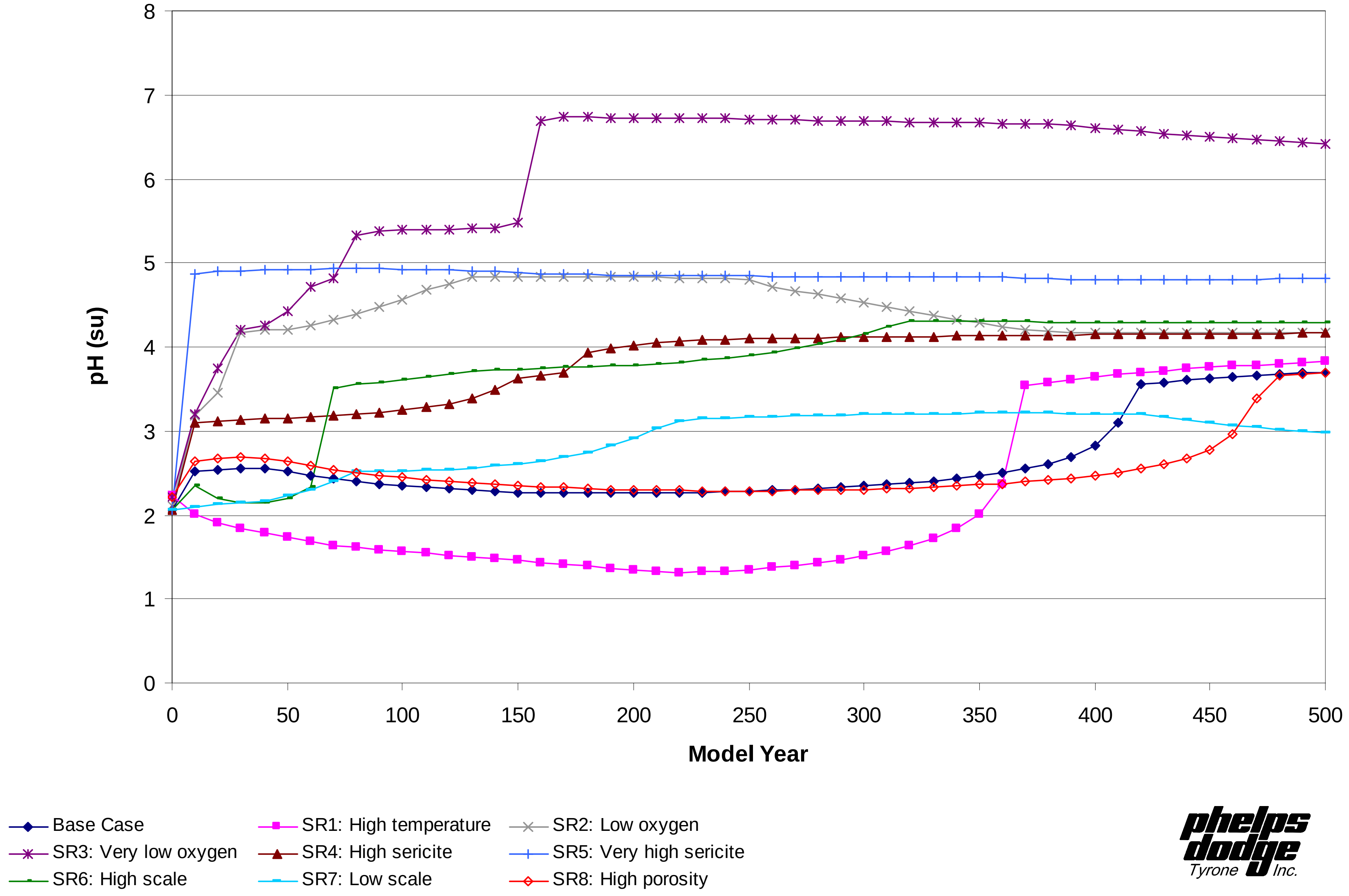

SR = Sensitivity run

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TYRONE MINE DP-1341 CONDITION 81

No. 2B Stockpile

Seepage pH through Time at 85-Meter Depth

Figure 4-6

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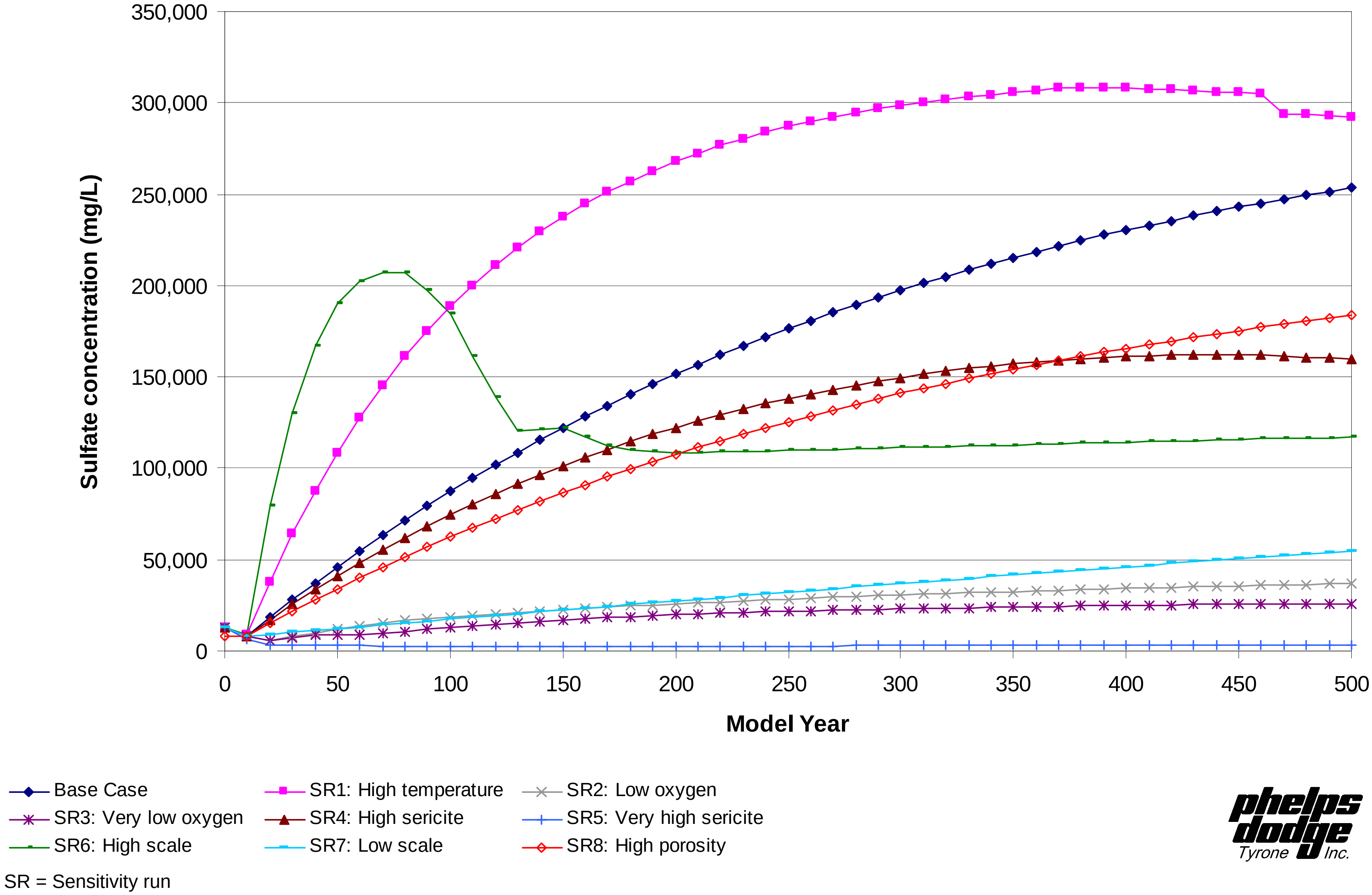
Table 4-10. No. 1 Stockpile Mass Loading Model Results at Year 100 for the DP-1341 Closure Plan

Parameter	Base Case	Sensitivity Run							
		1	2	3	4	5	6	7	8
Aluminum (mg/yr)	2.4×10^{10}	2.2×10^{10}	1.1×10^{8}	3.1×10^{3}	2.8×10^{10}	9.9×10^{7}	3.6×10^{10}	4.3×10^{9}	1.7×10^{10}
Bicarbonate (mg/yr)	1.8×10^{6}	1.1×10^{6}	2.0×10^{6}	8.6×10^{6}	1.8×10^{6}	2.0×10^{6}	1.5×10^{6}	1.9×10^{6}	1.8×10^{6}
Calcium (mg/yr)	8.6×10^{8}	5.8×10^{8}	9.4×10^{8}	9.5×10^{8}	8.8×10^{8}	8.8×10^{8}	5.3×10^{7}	9.4×10^{8}	9.2×10^{8}
Chloride (mg/yr)	2.7×10^{8}	2.3×10^{8}	2.9×10^{8}	2.9×10^{8}	2.7×10^{8}	3.0×10^{8}	2.3×10^{8}	2.9×10^{8}	2.9×10^{8}
Cobalt (mg/yr)	9.8×10^{6}	8.4×10^{6}	1.1×10^{7}	1.1×10^{7}	9.9×10^{6}	1.1×10^{7}	8.5×10^{6}	1.1×10^{7}	1.0×10^{7}
Copper (mg/yr)	1.7×10^{10}	1.6×10^{10}	9.2×10^{9}	5.9×10^{6}	1.7×10^{10}	1.7×10^{9}	1.1×10^{11}	2.4×10^{9}	1.2×10^{10}
Fluoride (mg/yr)	1.5×10^{8}	1.5×10^{8}	1.6×10^{8}	1.8×10^{7}	1.5×10^{8}	1.7×10^{8}	1.3×10^{8}	1.6×10^{8}	1.6×10^{8}
Iron (mg/yr)	2.9×10^{9}	9.0×10^{10}	8.6×10^{4}	1.4×10^{5}	1.3×10^{7}	5.2×10^{4}	6.2×10^{6}	1.4×10^{9}	2.0×10^{9}
Magnesium (mg/yr)	1.0×10^{10}	9.4×10^{9}	7.5×10^{9}	8.1×10^{9}	1.0×10^{10}	4.4×10^{8}	1.2×10^{10}	2.3×10^{9}	7.4×10^{9}
Manganese (mg/yr)	4.5×10^{9}	7.5×10^{9}	2.9×10^{4}	4.4×10^{0}	2.4×10^{8}	6.3×10^{2}	6.8×10^{8}	8.7×10^{8}	2.7×10^{9}
Nickel (mg/yr)	3.6×10^{6}	3.0×10^{6}	3.9×10^{6}	3.9×10^{6}	3.6×10^{6}	3.9×10^{6}	3.1×10^{6}	3.9×10^{6}	3.8×10^{6}
Potassium (mg/yr)	1.5×10^{9}	7.5×10^{0}	6.8×10^{8}	3.7×10^{8}	2.4×10^{9}	1.1×10^{9}	8.7×10^{10}	1.1×10^{5}	9.7×10^{8}
Silica (mg/yr)	3.1×10^{8}	3.7×10^{8}	3.3×10^{8}	8.7×10^{7}	3.2×10^{8}	1.7×10^{8}	2.6×10^{8}	3.4×10^{8}	3.3×10^{8}
Sodium (mg/yr)	7.5×10^{8}	2.9×10^{8}	3.4×10^{9}	4.3×10^{9}	8.3×10^{8}	4.2×10^{8}	7.0×10^{9}	7.0×10^{7}	5.1×10^{8}
Sulfate (mg/yr)	2.7×10^{11}	5.7×10^{11}	5.4×10^{10}	4.4×10^{10}	2.3×10^{11}	9.3×10^{9}	5.5×10^{11}	5.2×10^{10}	1.9×10^{11}
Zinc (mg/yr)	5.6×10^{8}	4.8×10^{8}	6.1×10^{8}	6.1×10^{8}	5.7×10^{8}	6.2×10^{8}	4.9×10^{8}	6.1×10^{8}	5.9×10^{8}
TDS (mg/yr)	3.3×10^{11}	7.2×10^{11}	7.8×10^{10}	5.9×10^{10}	2.9×10^{11}	1.5×10^{10}	8.0×10^{11}	6.6×10^{10}	2.4×10^{11}
pH (su)	0.99	1.15	4.33	6.59	2.14	4.70	1.83	1.72	1.12
Porosity (%)	14.26	14.53	14.49	14.45	13.99	10.15	11.73	14.36	21.33

mg/yr = Milligrams per year
TDS = Total dissolved solids
su = Standard units



phelps dodge Tyrone Inc.

TYRONE MINE DP-1341 CONDITION 81

No. 1 Stockpile DP-1341 Closure Plan

Sulfate Concentrations through Time at 65-Meter Depth

Figure 4-7

Daniel B. Stephens & Associates, Inc.

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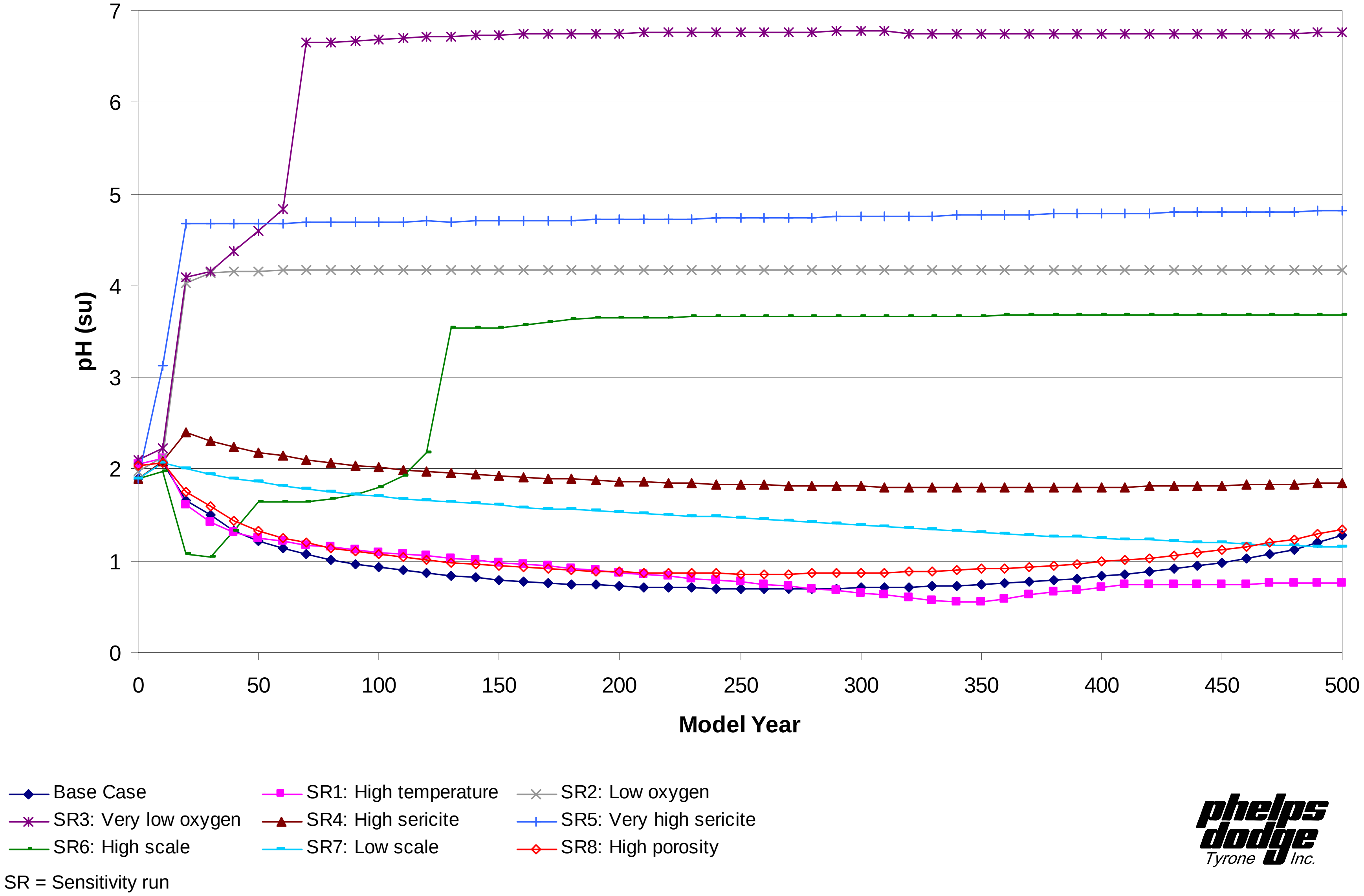

phelps dodge Tyrone Inc.

TYRONE MINE DP-1341 CONDITION 81

No. 1 Stockpile DP-1341 Closure Plan
Seepage pH through Time at 65-Meter Depth

Figure 4-8

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Increasing the scaling constant an order of magnitude in sensitivity run 6 raised the release rate for sulfate, which reached a concentration of approximately 207,000 mg/L at model year 70 with a pH between 1 and 2. Afterward the sulfate concentration dropped dramatically, leveling off above 100,000 mg/L, while the pH to rose to about 3.7. Lowering the scale factor (sensitivity run 7) resulted in much lower sulfate concentrations, similar to but higher than the low oxygen sensitivity runs 2 and 3, and pH values between 1 and 2. For sensitivity run 8, the porosity was multiplied by a factor of 1.5, resulting in sulfate concentrations and seepage pH patterns similar to the base case run, but with a peak sulfate concentration of only about 184,000 mg/L at model year 500.

The model year 100 mass loading results of the DP-1341 No. 2B waste stockpile for each parameter in the model, including seepage pH and stockpile porosity, are contained in Table 4-11. The maximum stockpile depth simulated sulfate concentrations and seepage pH results of the base case and sensitivity runs for the No. 2B waste stockpile are shown in Figures 4-9 and 4-10. For the base case run with the DP-1341 closure plan, the sulfate concentration continually increased over the 500-year model period, reaching 114,500 mg/L at model year 500, while the pH was just above 2 for the majority of the modeling period. In general, the sulfate concentration and seepage pH results for the DP-1341 No. 2B waste stockpile sensitivity runs showed similar patterns to the DP-1341 No. 1 leach stockpile sensitivity runs, a relationship mentioned previously between the existing leach and waste rock sensitivity runs.

4.4.3.2 No. 1 Leach Stockpile Complex Results

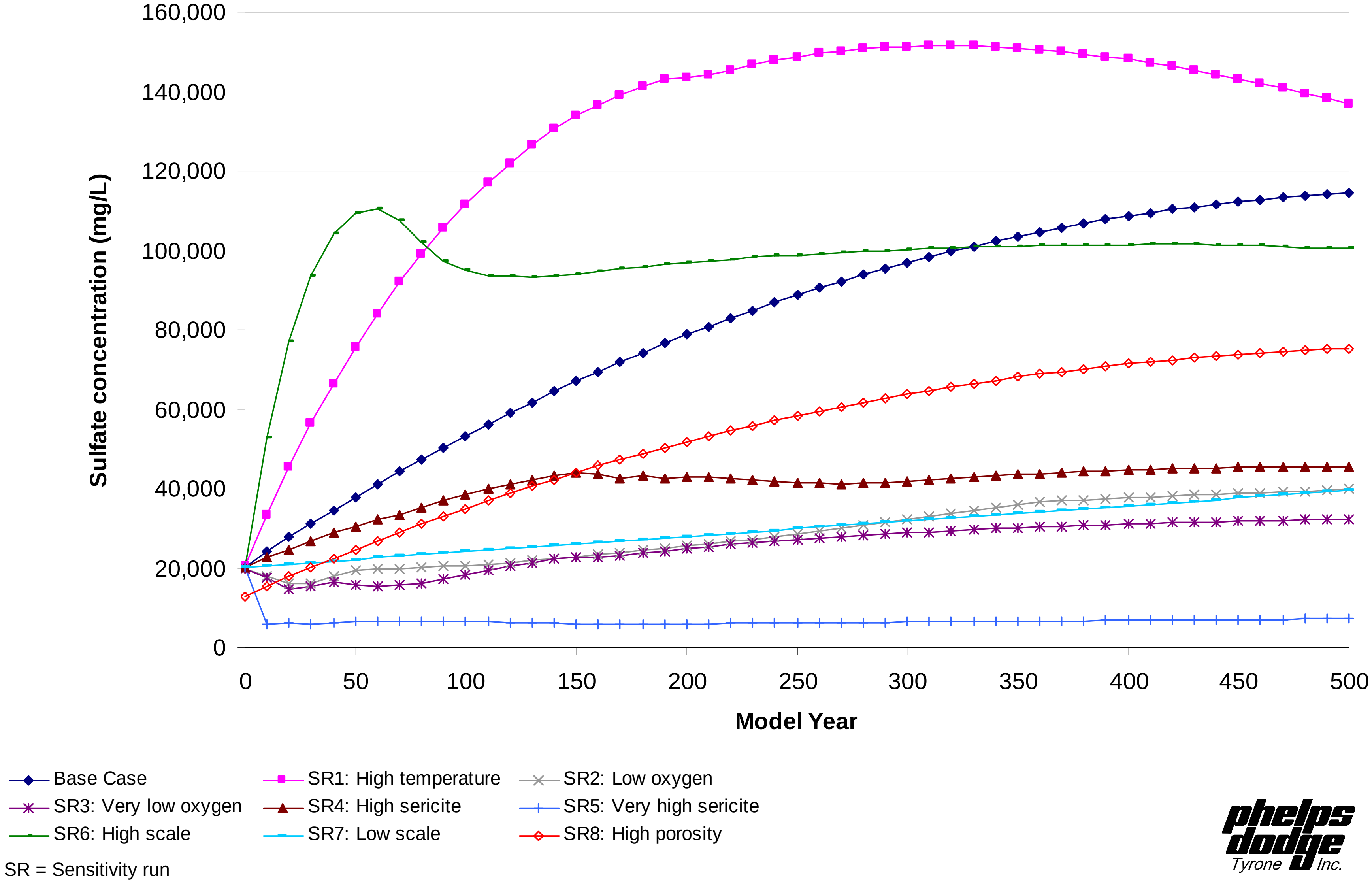
The simulated sulfate concentrations at maximum stockpile depth of the existing and DP-1341 base case runs for the No. 1 leach stockpile complex over the 500-year modeling period are shown in Figure 4-11. The trend in sulfate concentrations is similar for the two scenarios until model year 150. For the existing configuration, the sulfate concentration increased over time to a peak of approximately 175,000 mg/L at model year 220 and then decreased to below 100,000 mg/L. The DP-1341 model run sulfate concentrations continually increased over the modeling period, reaching just over 300,000 mg/L by model year 500.

The maximum stockpile depth simulated seepage pH of the existing and DP-1341 base case runs for the No. 1 leach stockpile complex over the 500-year modeling period are shown in Figure 4-12. Both scenarios show similar trends, but after model year 250, the existing scenario seepage pH values were slightly higher and increased to 2 by the end of the 500-year modeling period, while the DP-1341 model run pH values continued to decrease to below 1.7.

Table 4-11. No. 2B Stockpile Mass Loading Model Results at Year 100 for the DP-1341 Closure Plan

Parameter	Base Case	Sensitivity Run							
		1	2	3	4	5	6	7	8
Aluminum (mg/yr)	7.0 x 10^{9}	1.3 x 10^{10}	3.6 x 10^{8}	1.3 x 10^{7}	2.7 x 10^{9}	3.0 x 10^{8}	4.1 x 10^{8}	4.3 x 10^{9}	4.5 x 10^{9}
Bicarbonate (mg/yr)	1.1 x 10^{6}	7.2 x 10^{5}	1.2 x 10^{6}	1.4 x 10^{6}	1.1 x 10^{6}	1.3 x 10^{6}	1.0 x 10^{6}	1.2 x 10^{6}	1.1 x 10^{6}
Calcium (mg/yr)	6.8 x 10^{8}	4.2 x 10^{8}	7.3 x 10^{8}	7.5 x 10^{8}	6.6 x 10^{8}	8.7 x 10^{8}	2.1 x 10^{8}	8.0 x 10^{8}	7.3 x 10^{8}
Chloride (mg/yr)	4.4 x 10^{7}	4.1 x 10^{7}	4.6 x 10^{7}	4.6 x 10^{7}	4.5 x 10^{7}	4.8 x 10^{7}	4.2 x 10^{7}	4.6 x 10^{7}	2.8 x 10^{7}
Cobalt (mg/yr)	2.2 x 10^{7}	2.0 x 10^{7}	2.3 x 10^{7}	2.3 x 10^{7}	2.2 x 10^{7}	2.4 x 10^{7}	2.1 x 10^{7}	2.3 x 10^{7}	1.4 x 10^{7}
Copper (mg/yr)	1.2 x 10^{10}	1.2 x 10^{10}	2.2 x 10^{9}	1.4 x 10^{8}	1.3 x 10^{10}	5.8 x 10^{8}	5.2 x 10^{10}	3.0 x 10^{9}	8.2 x 10^{9}
Fluoride (mg/yr)	6.2 x 10^{8}	5.2 x 10^{7}	6.5 x 10^{8}	3.4 x 10^{7}	6.3 x 10^{8}	5.8 x 10^{8}	5.8 x 10^{8}	6.4 x 10^{8}	3.9 x 10^{8}
Iron (mg/yr)	2.6 x 10^{6}	1.5 x 10^{10}	2.4 x 10^{4}	2.0 x 10^{4}	2.7 x 10^{6}	2.9 x 10^{4}	1.3 x 10^{4}	2.3 x 10^{6}	2.1 x 10^{6}
Magnesium (mg/yr)	7.8 x 10^{9}	7.5 x 10^{9}	6.7 x 10^{9}	6.6 x 10^{9}	8.0 x 10^{9}	1.2 x 10^{9}	1.4 x 10^{10}	2.5 x 10^{9}	5.2 x 10^{9}
Manganese (mg/yr)	4.1 x 10^{7}	1.5 x 10^{9}	4.1 x 10^{3}	2.8 x 10^{2}	6.6 x 10^{5}	1.8 x 10^{2}	1.8 x 10^{5}	1.4 x 10^{7}	2.3 x 10^{7}
Nickel (mg/yr)	1.1 x 10^{7}	9.9 x 10^{6}	1.1 x 10^{7}	1.1 x 10^{7}	1.1 x 10^{7}	1.1 x 10^{7}	1.0 x 10^{7}	1.1 x 10^{7}	6.8 x 10^{6}
Potassium (mg/yr)	5.1 x 10^{8}	7.3 x 10^{-1}	5.7 x 10^{8}	7.7 x 10^{8}	8.7 x 10^{4}	4.6 x 10^{8}	2.6 x 10^{10}	1.0 x 10^{8}	3.1 x 10^{8}
Silica (mg/yr)	2.0 x 10^{8}	2.5 x 10^{8}	1.1 x 10^{8}	3.2 x 10^{7}	2.0 x 10^{8}	6.7 x 10^{7}	1.8 x 10^{8}	2.0 x 10^{8}	2.0 x 10^{8}
Sodium (mg/yr)	2.6 x 10^{8}	2.5 x 10^{8}	2.6 x 10^{8}	2.6 x 10^{8}	2.6 x 10^{8}	2.7 x 10^{8}	2.5 x 10^{9}	5.4 x 10^{7}	1.7 x 10^{8}
Sulfate (mg/yr)	9.3 x 10^{10}	1.9 x 10^{11}	3.6 x 10^{10}	3.3 x 10^{10}	6.9 x 10^{10}	1.2 x 10^{10}	1.8 x 10^{11}	4.2 x 10^{10}	6.2 x 10^{10}
Zinc (mg/yr)	2.2 x 10^{9}	2.0 x 10^{9}	2.3 x 10^{9}	2.3 x 10^{9}	2.2 x 10^{9}	2.3 x 10^{9}	2.0 x 10^{9}	2.3 x 10^{9}	1.4 x 10^{9}
TDS (mg/yr)	1.2 x 10^{11}	2.5 x 10^{11}	5.0 x 10^{10}	4.4 x 10^{10}	9.6 x 10^{10}	1.9 x 10^{10}	2.7 x 10^{11}	5.6 x 10^{10}	8.3 x 10^{10}
pH (su)	2.35	1.57	4.57	5.39	3.25	4.92	3.62	2.53	2.45
Porosity (%)	14.58	14.78	14.83	14.84	14.28	14.33	12.55	14.80	22.29

mg/yr = Milligrams per year
TDS = Total dissolved solids
su = Standard units



phelps dodge Tyrone Inc.

TYRONE MINE DP-1341 CONDITION 81

No 2B Stockpile DP-1341 Closure Plan

Sulfate Concentrations through Time at 75-Meter Depth

Figure 4-9

Daniel B. Stephens & Associates, Inc.

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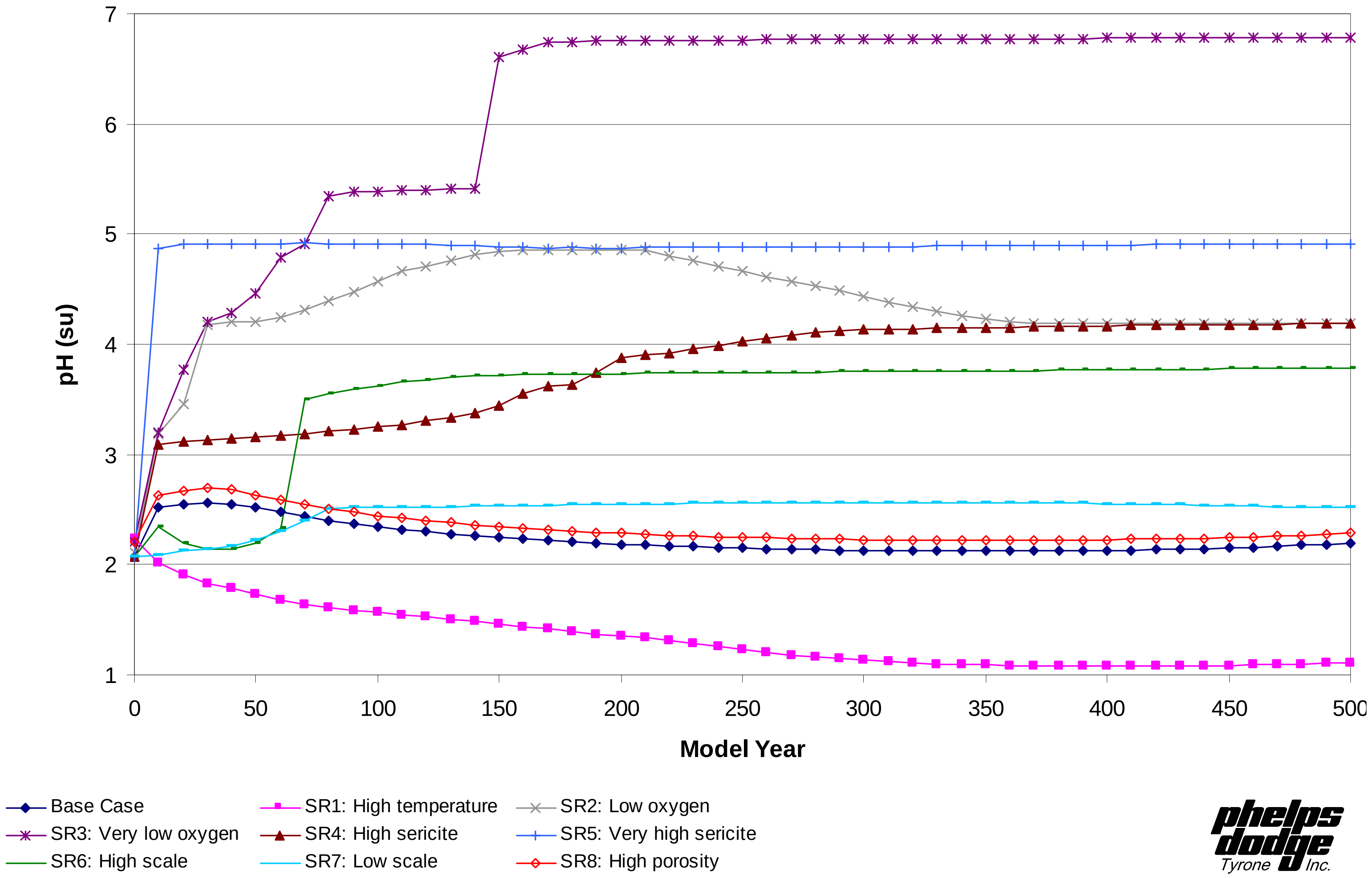

SR = Sensitivity run

TYRONE MINE DP-1341 CONDITION 81

No. 2B Stockpile DP-1341 Closure Plan
Seepage pH through Time at 85-Meter Depth

Figure 4-10

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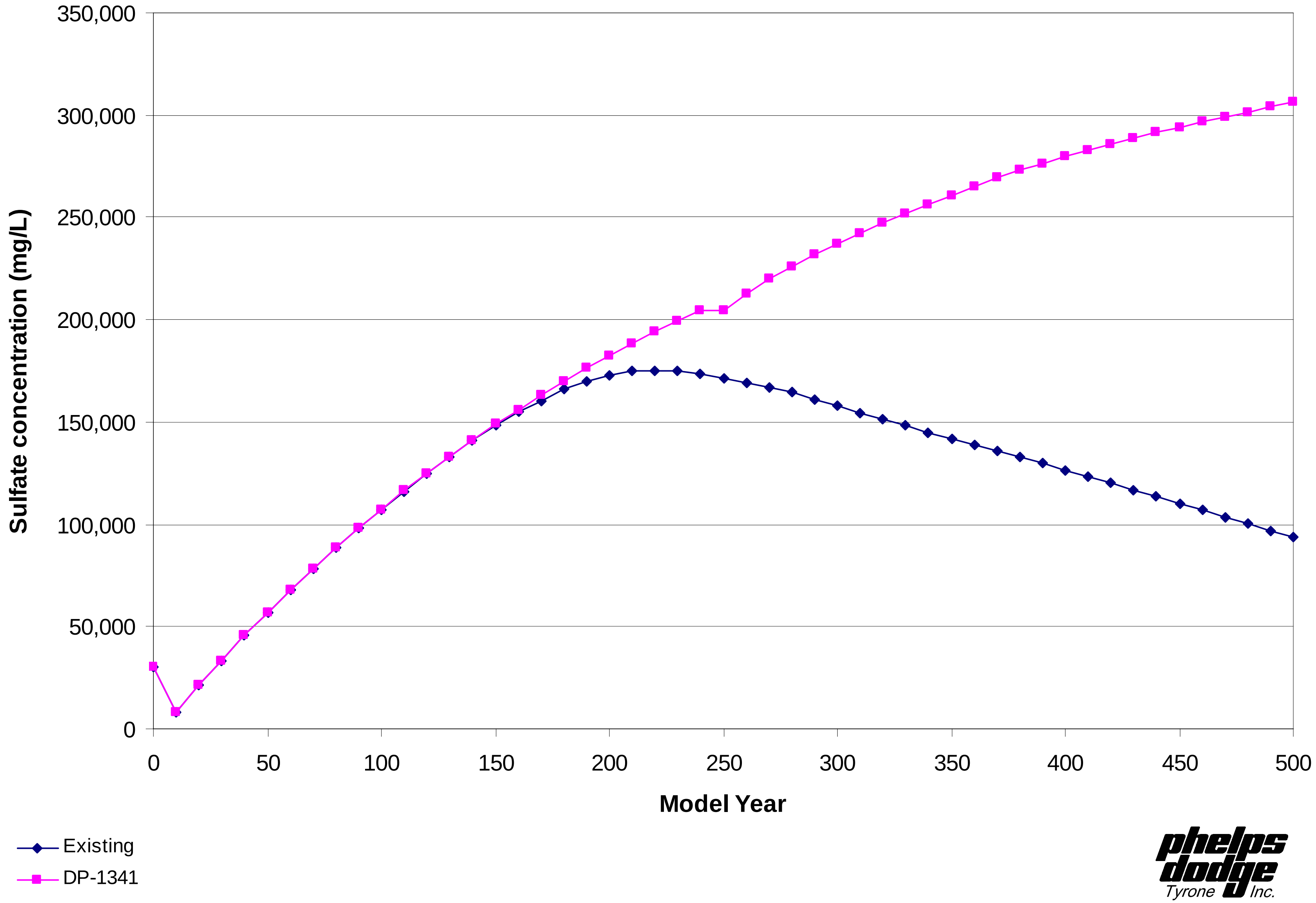

Phelps Dodge Tyrone Inc.

TYRONE MINE DP-1341 CONDITION 81

No. 1 Complex

Sulfate Concentrations through Time at Maximum Depth

Figure 4-11

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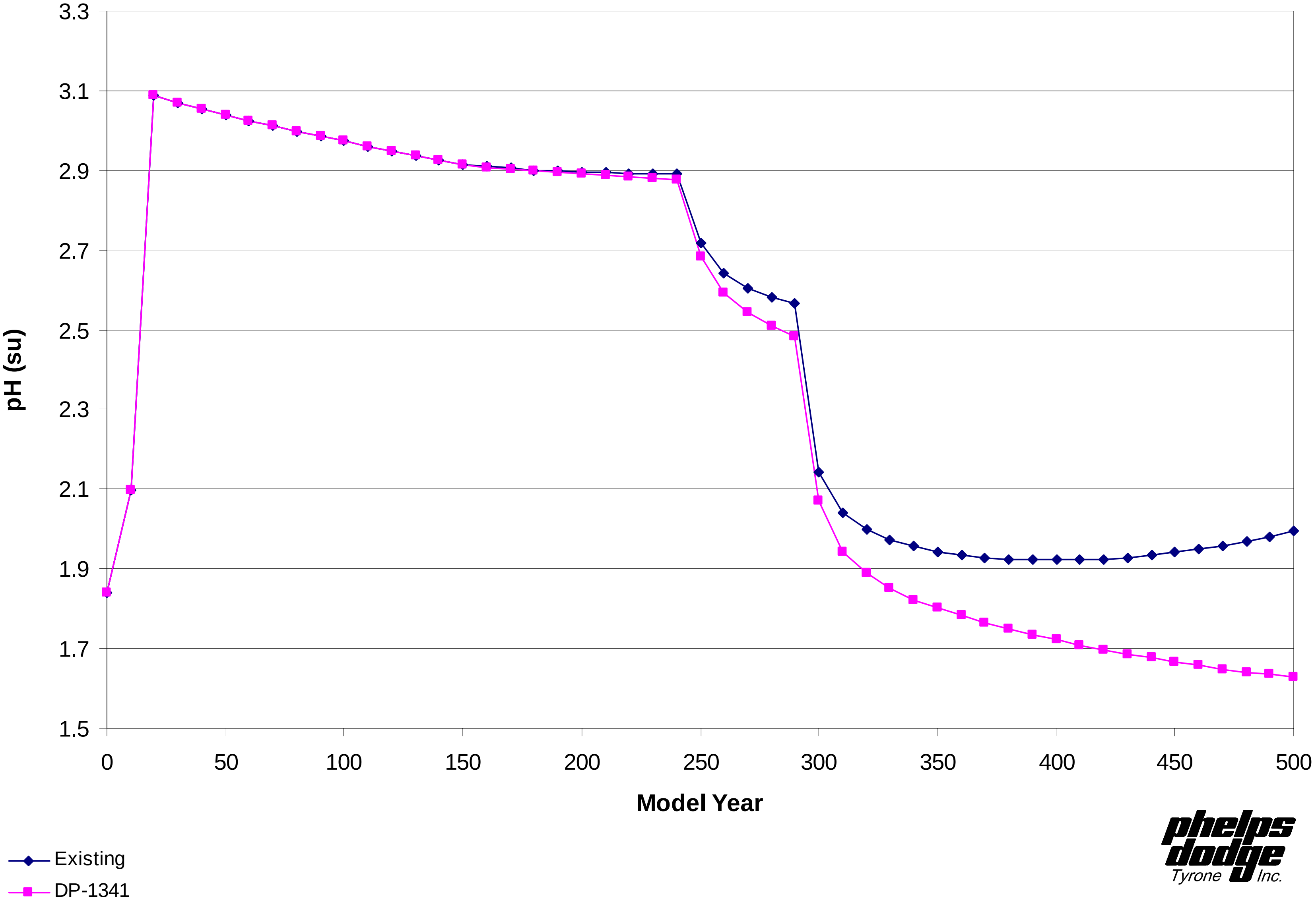

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TYRONE MINE DP-1341 CONDITION 81

No. 1 Complex

Seepage pH through Time at Maximum Depth

Figure 4-12

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4.4.3.3 No. 1C Waste Stockpile Results

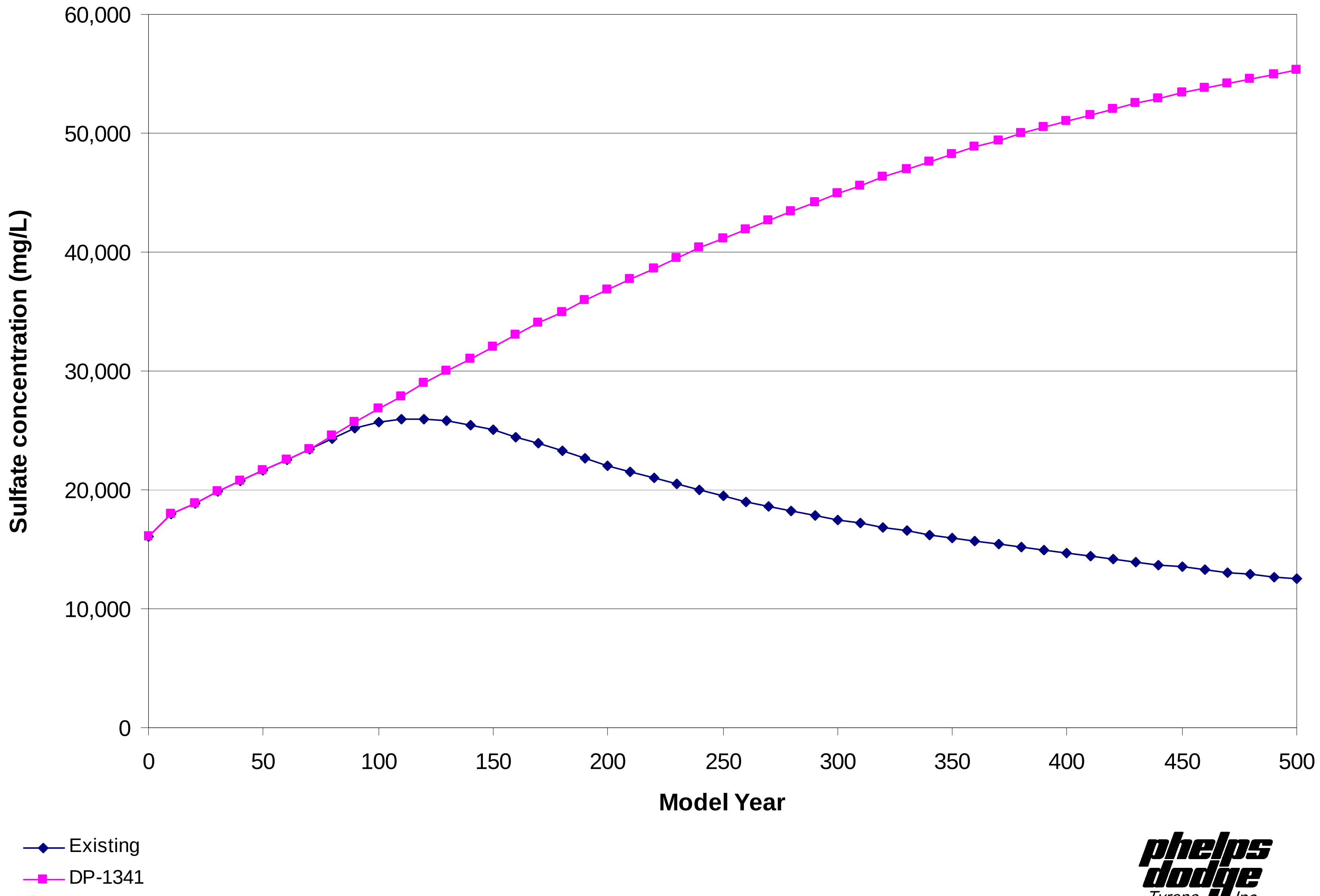
The simulated sulfate concentrations at maximum stockpile depth of the existing and DP-1341 base case runs for the No. 1C waste stockpile over the 500-year modeling period are shown in Figure 4-13. The trend in sulfate concentrations for the two scenarios is similar until model year 70. For the existing configuration, the sulfate concentration increased over time to a peak of 26,000 mg/L at model year 120 and afterward slowly decreased. The DP-1341 model run sulfate concentrations were similar to the existing results for the first 100 years, but continued to increase throughout the 500-year modeling period, reaching almost 55,000 mg/L.

The maximum stockpile depth simulated seepage pH of the existing and DP-1341 base case runs for the No. 1C waste stockpile over the 500-year modeling period are shown in Figure 4-14. Seepage pH for both scenarios increased to about 4 by model year 80, where the existing configuration pH remained steady for the remainder of the model run, while the DP-1341 configuration began to slowly decrease to 3.75.

4.4.3.4 No. 1D Waste Stockpile

The simulated sulfate concentrations at maximum stockpile depth of the existing and DP-1341 base case runs for the No. 1D waste stockpile over the 500-year modeling period are shown in Figure 4-15. The trend in sulfate concentrations for the two scenarios is similar until model year 100. For the existing configuration, the sulfate concentration increased over time to a peak just under 23,000 mg/L at model year 170 and then slowly decreased, while the DP-1341 model run sulfate concentrations continued to rise, reaching almost 50,000 mg/L by model year 500.

The maximum stockpile depth simulated seepage pH of the existing and DP-1341 base case runs for the No. 1D waste stockpile over the 500-year modeling period are shown in Figure 4-16. Both scenarios show similar trends, but after model year 200, the existing scenario seepage pH values were slightly higher and increased to almost 4 by the end of the 500-year modeling period, while the DP-1341 model run pH continued to decrease.



phelps dodge Tyrone Inc.

TYRONE MINE DP-1341 CONDITION 81

No. 1C Stockpile

Sulfate Concentrations through Time at Maximum Depth

Figure 4-13

Daniel B. Stephens & Associates, Inc.

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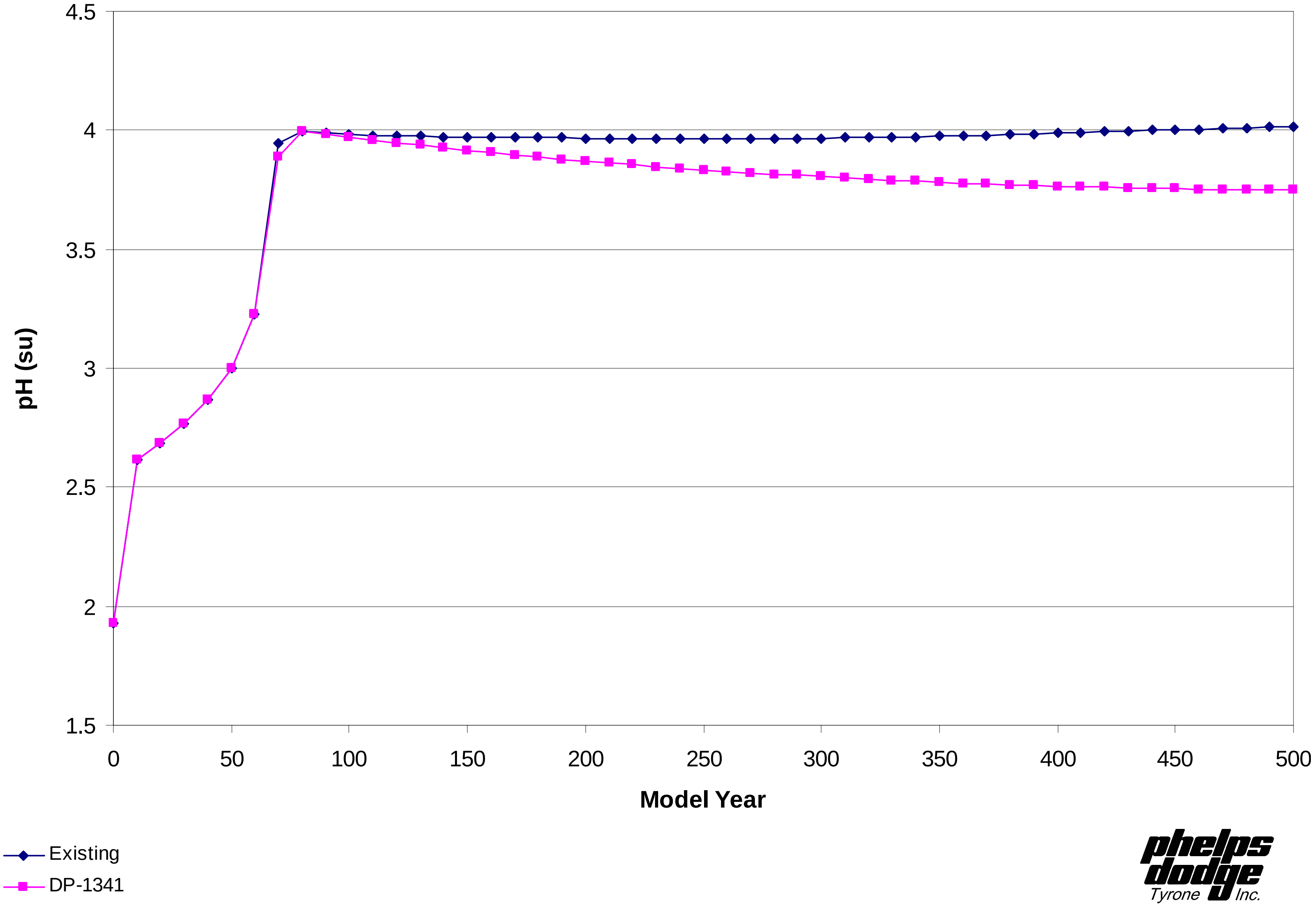

phelps dodge
Tyrone Inc.

TYRONE MINE DP-1341 CONDITION 81

No. 1C Stockpile

Seepage pH through Time at Maximum Depth

Figure 4-14

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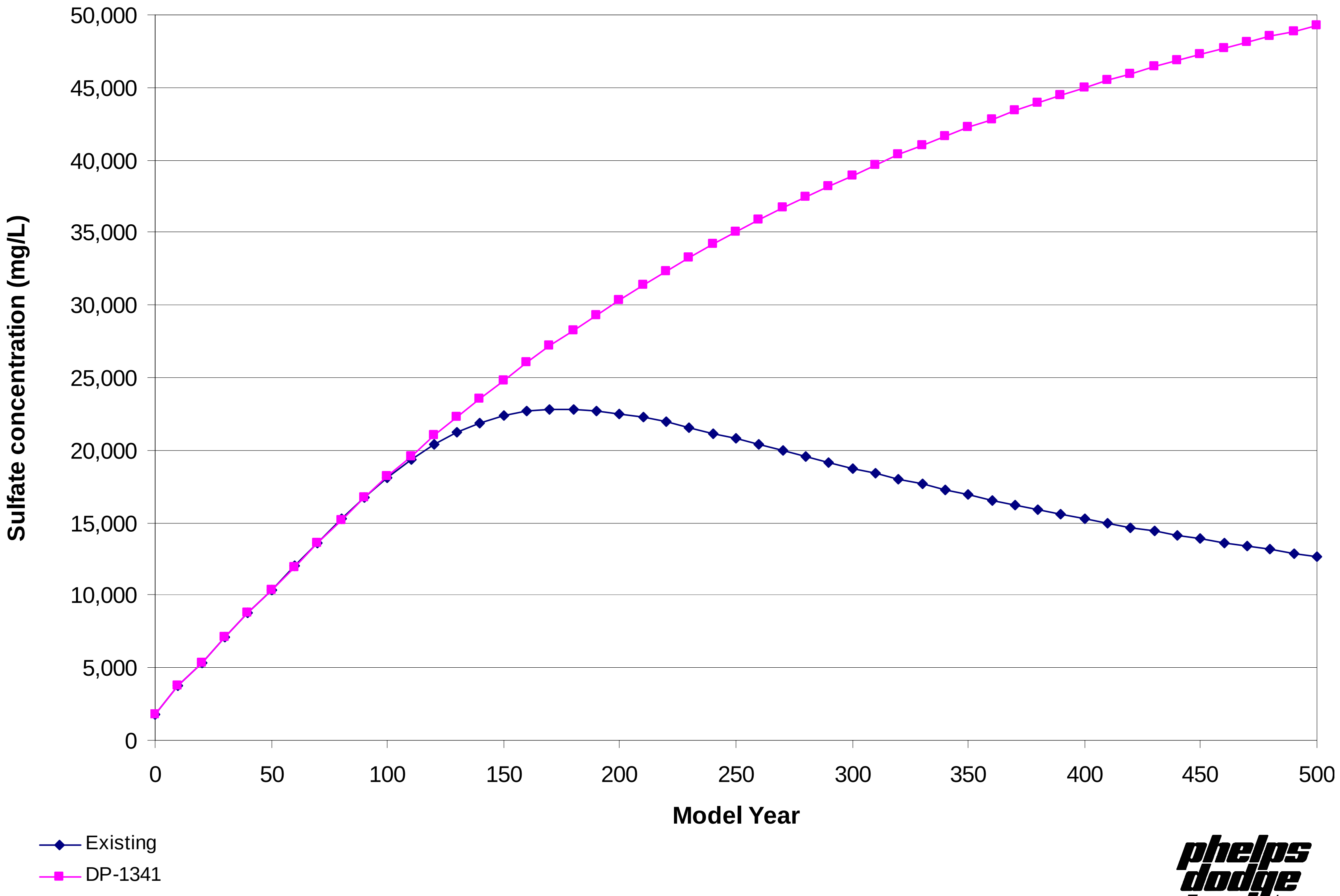

TYRONE MINE DP-1341 CONDITION 81

No. 1D Stockpile

Sulfate Concentrations through Time at Maximum Depth

Figure 4-15

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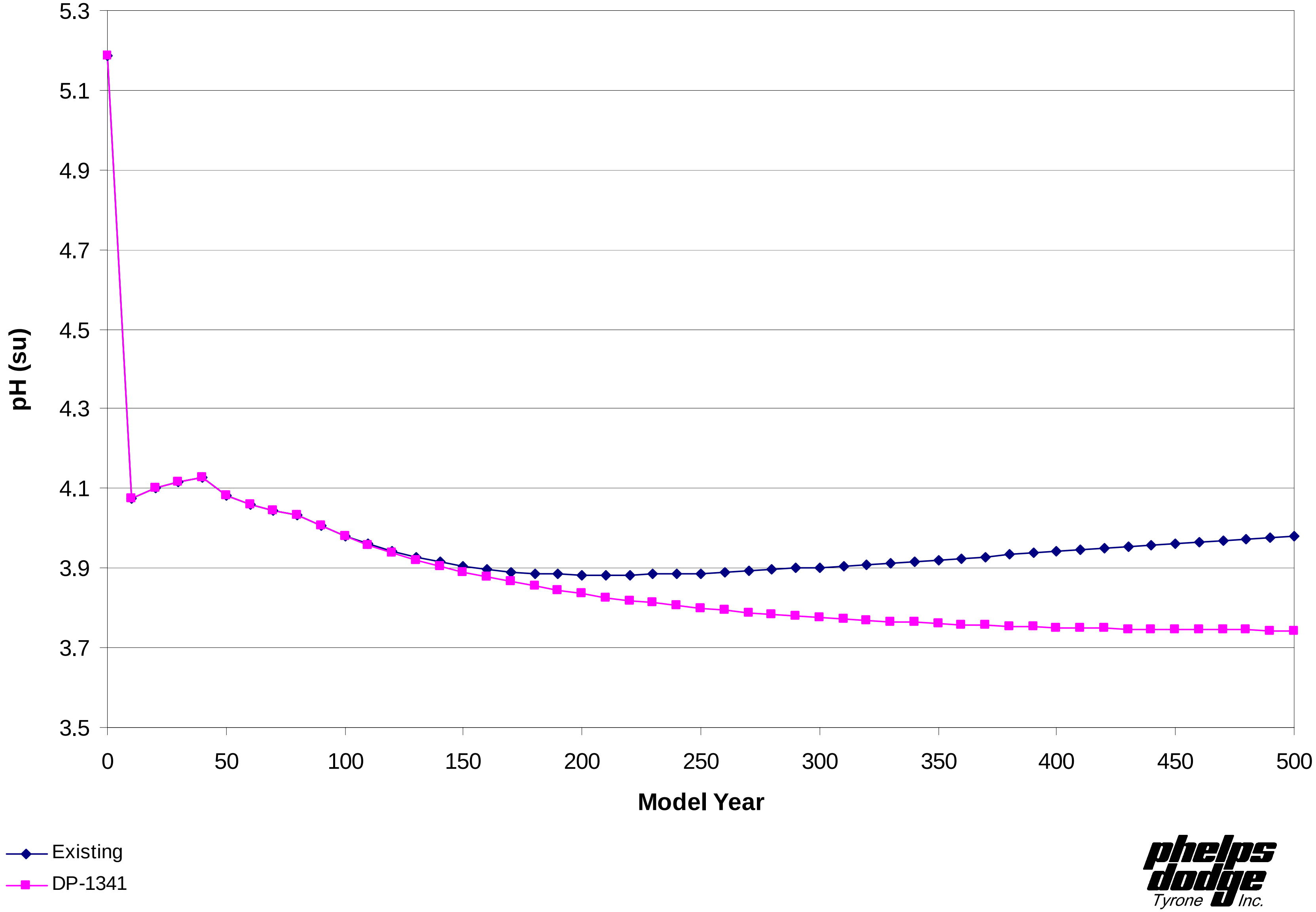

Figure 4-16

TYRONE MINE DP-1341 CONDITION 81

No. 1D Stockpile

Seepage pH through Time at Maximum Depth

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4.4.3.5 No. 2 Leach Stockpile Complex Results

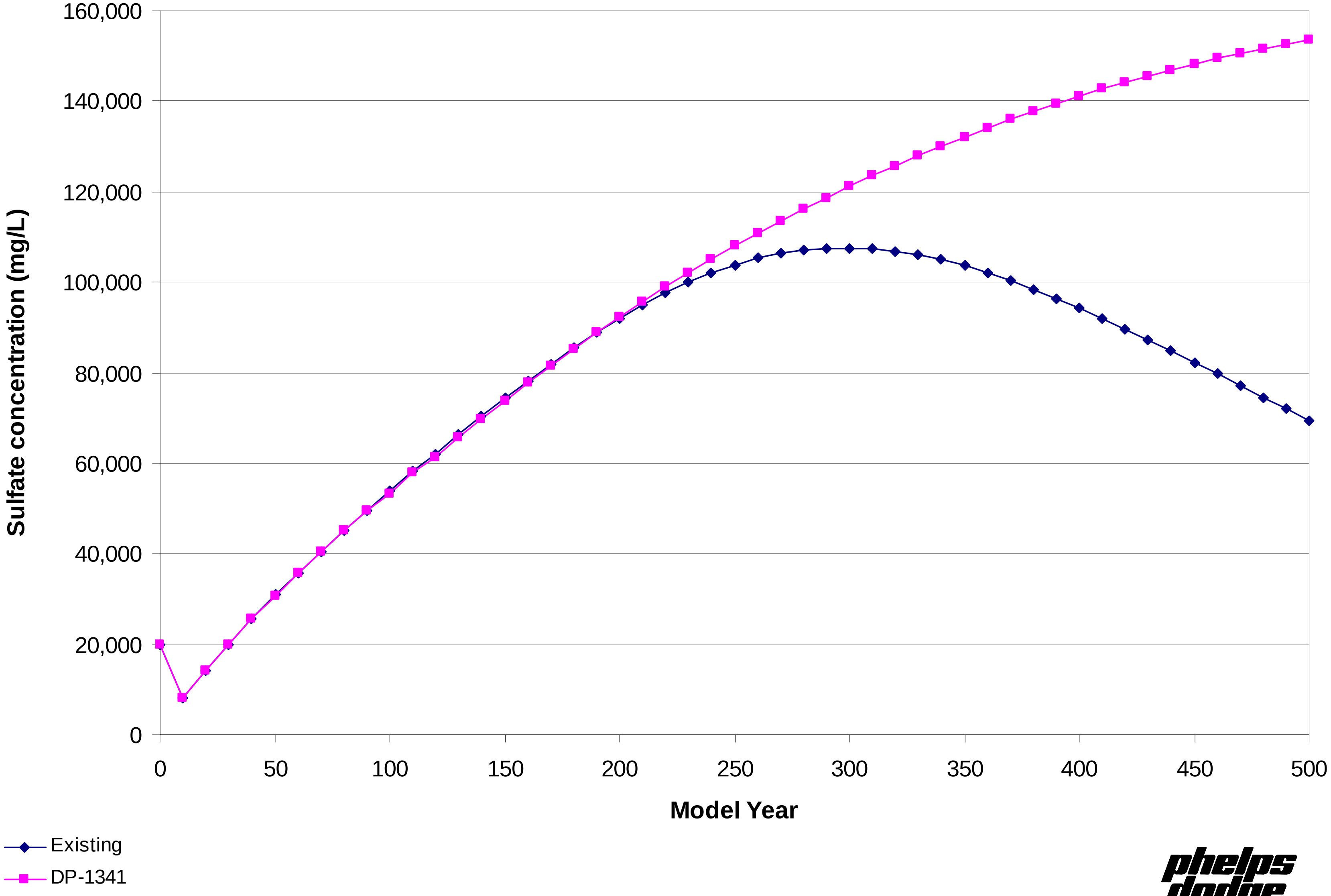
The simulated sulfate concentrations at maximum stockpile depth of the existing and DP-1341 base case runs for the No. 2 leach stockpile complex over the 500-year modeling period are shown in Figure 4-17. The trend in sulfate concentrations is similar for the two scenarios until model year 200. For the existing configuration, the sulfate concentration increased over time to a peak of 107,600 mg/L at model year 300 and then decreased. The DP-1341 model run sulfate concentrations continually increased over the modeling period, reaching just under 154,000 mg/L by model year 500.

The maximum stockpile depth simulated seepage pH of the existing and DP-1341 base case runs for the No. 2 leach stockpile complex over the 500-year modeling period are shown in Figure 4-18. Both scenarios show similar trends, but the existing scenario seepage pH values were slightly higher after model year 250 and increased to above 2.1 by the end of the 500-year modeling period, while the DP-1341 model run pH continued to decrease.

4.4.3.6 No. 3 Leach Stockpile

The simulated sulfate concentrations at maximum stockpile depth of the existing and DP-1341 base case runs for the No. 3 leach stockpile over the 500-year modeling period are shown in Figure 4-19. The trend in sulfate concentrations is similar for both scenarios until model year 200. For the existing configuration, the sulfate concentration increased over time to a peak just under 203,500 mg/L at model year 320 and then slowly decreased, while the DP-1341 model run sulfate concentrations continued to rise, reaching almost 285,000 mg/L by model year 500.

The maximum stockpile depth simulated seepage pH of the existing and DP-1341 base case runs for the No. 3 leach stockpile over the 500-year modeling period are shown in Figure 4-20. Both scenarios exhibit similar trends, but the existing scenario seepage pH values were slightly higher after model year 250 and increased steadily above 1.6 by the end of the 500-year modeling period, while the DP-1341 model run pH increased at a slower rate, not quite reaching 1 before the end of the model run.



phelps dodge Tyrone Inc.

TYRONE MINE DP-1341 CONDITION 81

No. 2 Complex

Sulfate Concentrations through Time at Maximum Depth

Daniel B. Stephens & Associates, Inc.

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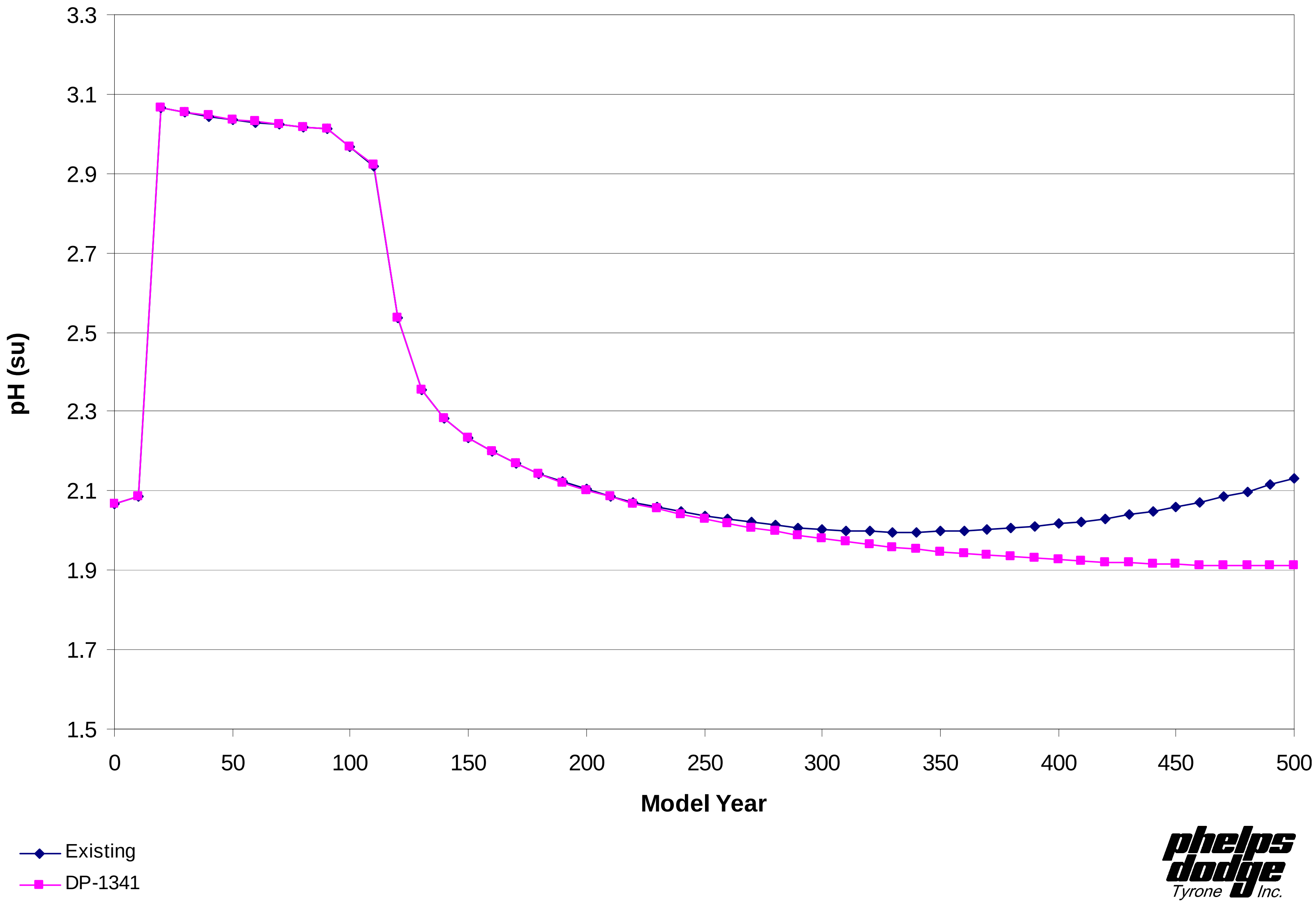
Figure 4-17



phelps dodge Tyrone Inc.

TYRONE MINE DP-1341 CONDITION 81

No. 2 Complex

Seepage pH through Time at Maximum Depth

Figure 4-18

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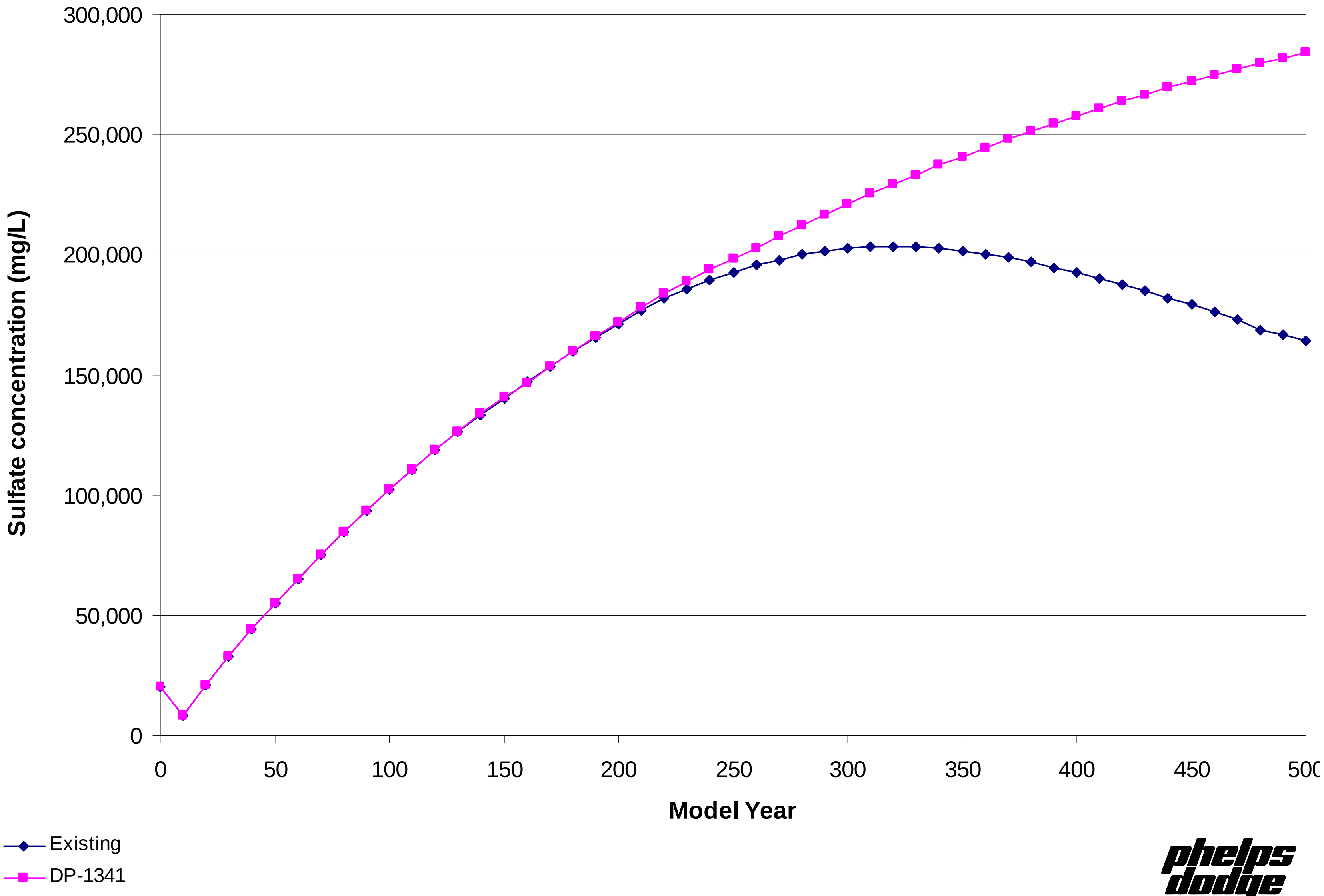

phelps dodge Tyrone Inc.

TYRONE MINE DP-1341 CONDITION 81

No. 3 Stockpile

Sulfate Concentrations through Time at Maximum Depth

Figure 4-19

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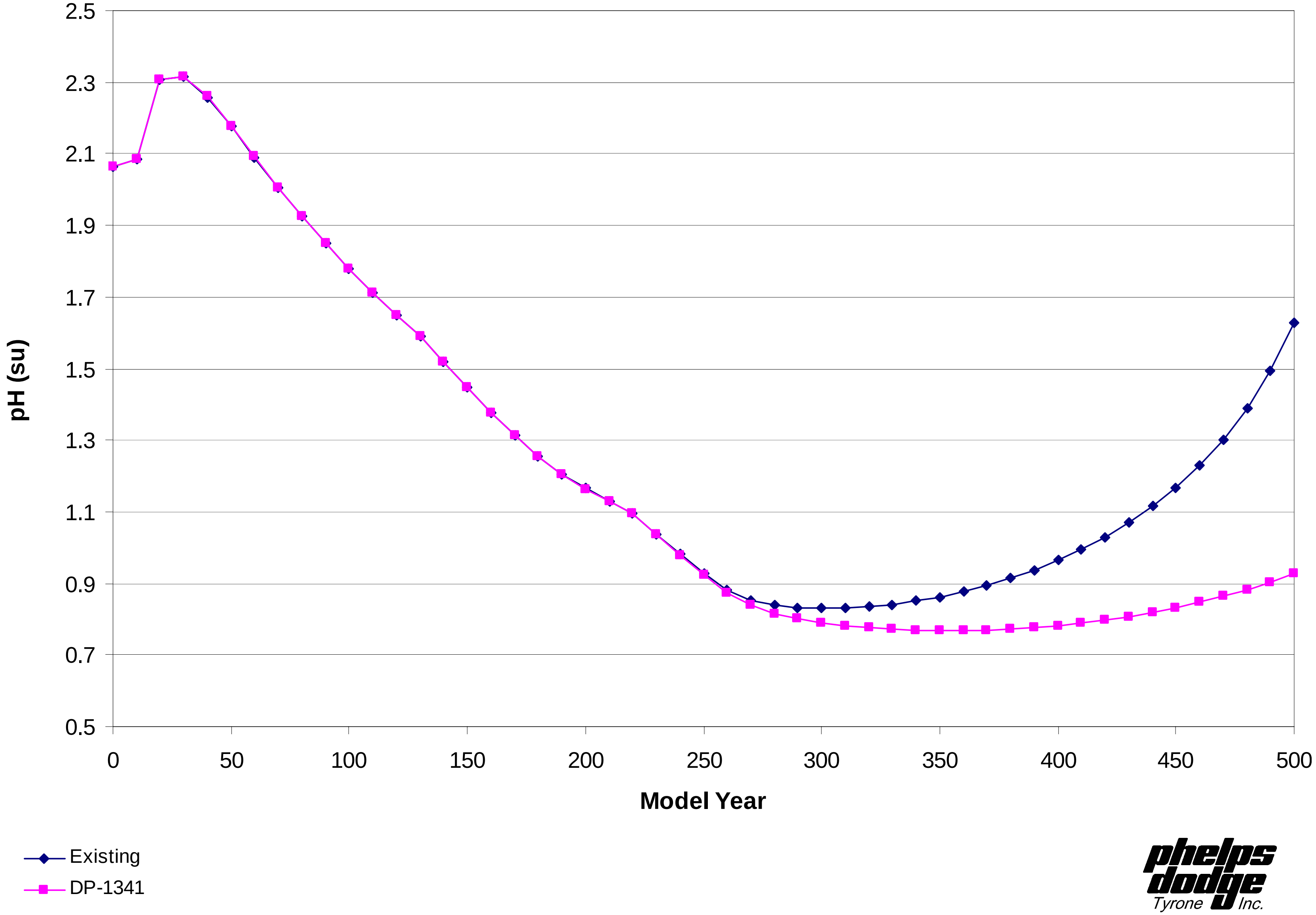

phelps dodge Tyrone Inc.

TYRONE MINE DP-1341 CONDITION 81

No. 3 Stockpile

Seepage pH through Time at 65-Meter Depth

Figure 4-20

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4.4.3.7 No. 3B Waste Stockpile

The simulated sulfate concentrations at maximum stockpile depth of the existing and DP-1341 base case runs for the No. 3B waste stockpile over the 500-year modeling period are shown in Figure 4-21. The trend in sulfate concentrations is similar for the two scenarios until model year 100. For the existing configuration, the sulfate concentration increased over time to a peak just under 29,000 mg/L at model year 150 and then slowly decreased to about 12,000 mg/L prior to the end of the model run. The DP-1341 model run sulfate concentrations continued to slowly rise during the entire model run and reached almost 43,000 mg/L by year 500.

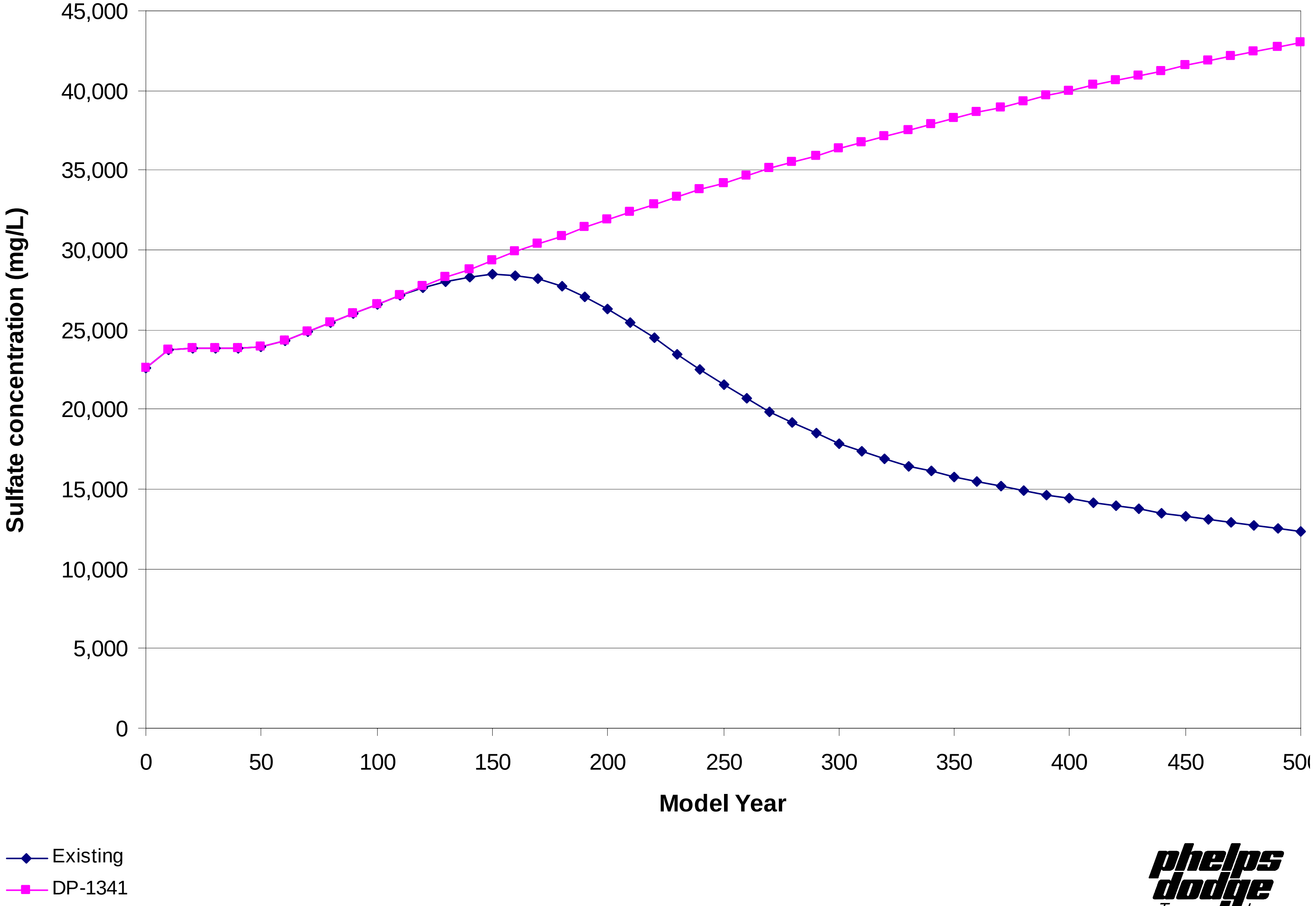
The maximum stockpile depth simulated seepage pH of the existing and DP-1341 base case runs for the No. 3B waste stockpile over the 500-year modeling period are shown in Figure 4-22. For both scenarios the pH is fairly steady around 4 for the majority of the modeling period, although the DP-1341 scenario pH appears to have slowly decreased over time.

4.4.3.8 Sulfate Mass Loading Results

The mass loading modeling results for the base case runs at model year 100 under the existing and DP-1341 closure plan scenarios for each stockpile at the Tyrone Mine are summarized in Table 4-6. The mine totals show about a 12 percent increase in the overall stockpile footprint area from the existing facility outlines to the regraded outslopes in the DP-1341 closure plan. The large decrease in seepage volume between the scenarios is due to the placement of a cover material that would decrease annual stockpile infiltration from 6.5 to 0.4 cm/yr. The base case model predicts an average sulfate concentration for the existing scenario of approximately 46,000 mg/L, while the DP-1341 closure plan average sulfate concentration is slightly higher at about 64,500 mg/L. Although the sulfate concentration is higher, the lower infiltration rate results in an order of magnitude decrease in the amount of sulfate mass loading, from 4.2×10^{13} to 4.1×10^{12} mg/yr between the scenarios. Similar patterns are seen for the individual stockpiles.

4.4.3.9 Mineral Precipitates

Minerals that are stable in a weathering environment were allowed to precipitate from stockpile seepage during each of the 500-year model runs. Some of these minerals act to reduce the concentration of sulfate (and other constituents) in solution, but may also act as reservoirs of



phelps dodge
Tyrone Inc.

TYRONE MINE DP-1341 CONDITION 81

No. 3B Stockpile

Sulfate Concentrations through Time at Maximum Depth

Figure 4-21

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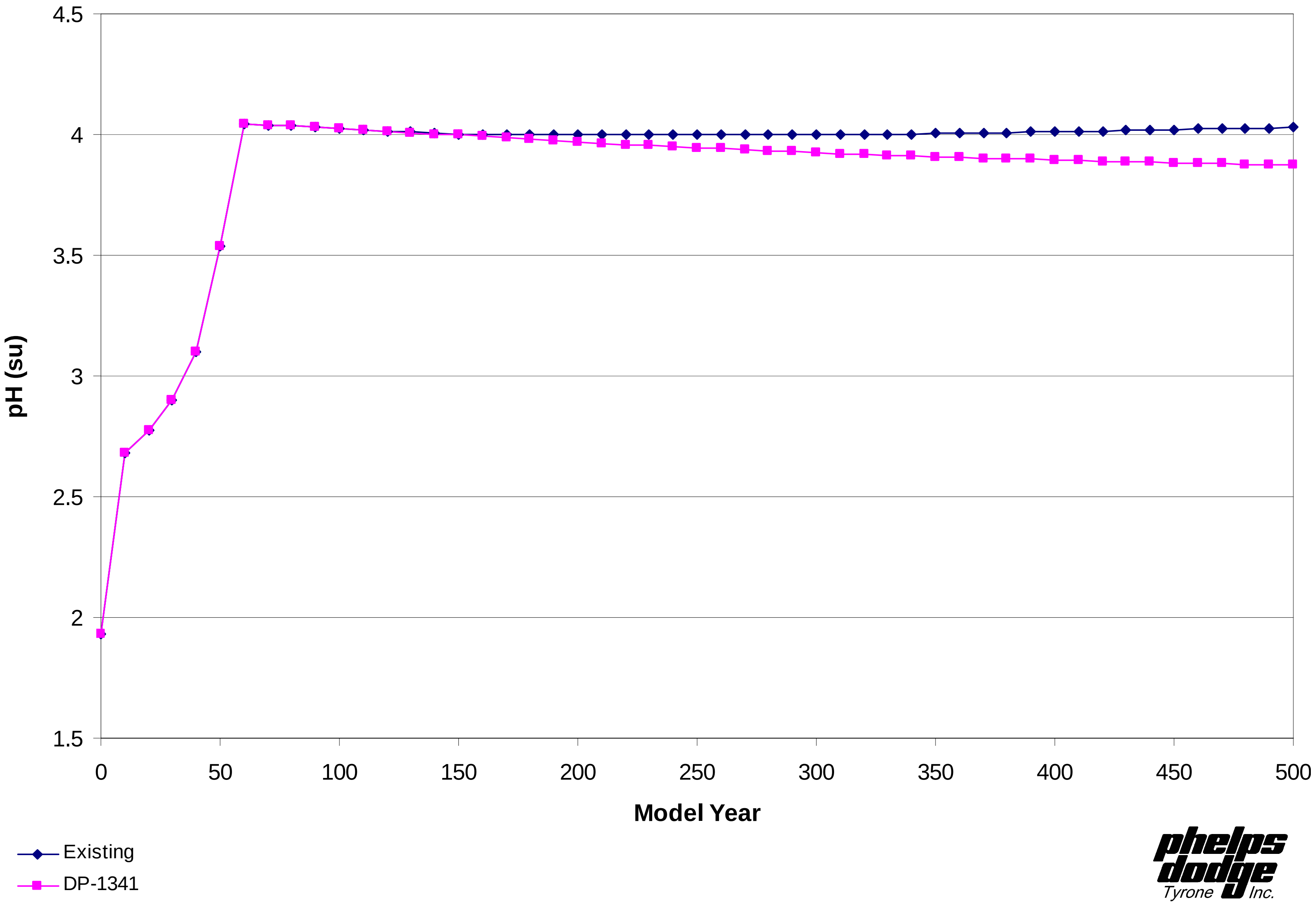

phelps dodge Tyrone Inc.

TYRONE MINE DP-1341 CONDITION 81

No. 3B Stockpile

Seepage pH through Time at Maximum Depth

Figure 4-22

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sulfate for future dissolution as pyrite decreases. Graphs showing the volume fraction of minerals deposited as a function of stockpile depth for all model runs at model year 100 are contained in Appendix C.

The minerals that precipitated along various stockpile depths at model year 100 for the base case runs include jarosite and sodium jarosite, alunite, amorphous silica, gypsum, antlerite, brochantite, chalcanthite, syngenite, and the clay mineral beidellite. Overall, the amount of minerals precipitated in the base case runs was between 0.3 and 1.25 percent of the total stockpile volume, except for the first 10-meter depth of the leach stockpiles. Therefore an insignificant amount of clay minerals are expected to form as a result of weathering reactions. A large amount of jarosite (3 to 4 percent) and sodium jarosite (0.5 to 0.8 percent) were deposited in the first 10 meters of the leach stockpiles, decreasing the stockpile porosity by an equal amount for the first 10-meter depth. Graphic results of stockpile porosity through time at the maximum stockpile depth and through stockpile depth at model years 10, 100, and 500 are provided in Appendix C for all of the model runs. Changes in porosity are an indication of the amount of mineral precipitation or dissolution with time and depth for the model runs.

5. Seepage Quantity and Quality Monitoring

Section 5.1 describes the seepage flow monitoring that is being conducted to support the seepage flow modeling investigations. Section 5.2 describes the seepage quality monitoring data available for this investigation and calibration of the geochemical model.

5.1 Seepage Flow Monitoring

Seepage and runoff quantity and flow measurements are conducted in accordance with monitoring requirements of PDTI's operational discharge permits. This information is reported to the NMED quarterly and annually. Recognizing the variable nature of stockpile runoff and seepage flow resulting from precipitation events, PDTI has conducted supplemental flow measurements and seepage sampling when and where feasible. The Tyrone stockpile benches are graded so that runoff flows toward the stockpile interior and collects at the break in the stockpile slope when heavy rainfall occurs.

Daily meteorological data are recorded in accordance with Condition 55 and as specified in the cover test plot study work plan for Condition 76 (Tetra Tech, 2003). Flows and quality of seepage into the 5E collection ponds were monitored as part of the *Stockpile and Tailing Pond Seepage Investigation* (DBS&A, 1999b), and the results of that investigation were summarized in Section 1.3.2.1. Seepage flow information is also compiled in the Tyrone Environmental Data Management System. These data show that seepage flows range from less than 1 gpm below waste rock stockpiles to more than a few hundred gpm below leach ore stockpiles.

5.2 Seepage Quality Monitoring

In addition to the meteoric water mobility testing on stockpile samples, sampling of water quality occurs on a quarterly and annual basis in accordance with PDTI's discharge plan permits. For example, stockpile seepage quality is presently monitored in the No. 3A leach stockpile and East Mine areas for existing DP-286 and pending DP-896, respectively. Additional seepage sample collection and analysis has been conducted, where needed, to achieve the data quality objectives specified in DP-1341, Condition 43, and other relevant conditions called out in the permit. These data are compiled into the Environmental Data Management System for Phelps Dodge New Mexico operations, which includes the Tyrone Mine. This database also includes stockpile seepage water quality monitoring data. A summary of the seepage data is provided in Appendix D.

Stockpile surface water and seepage monitoring results show that these waters are characterized by low pH and high sulfate concentrations. The range in seepage pH is less than 2 to greater than 7 and the range in seepage sulfate concentrations is less than 10 to more than 42,000 mg/L. The concentrations of aluminum, copper, iron, manganese, and zinc can also be high in surface water and seepage samples.

Surface water, including stockpile runoff flow, was monitored according to DP-1341 Condition 48. After an October 2003 rainfall event, a water quality sample was collected directly from the No. 1C stockpile surface along a depression where the runoff water collects. The results of this water quality sampling event are presented in Table 5-1. The stockpile runoff water quality shown in Table 5-1 is similar to the MWMP test results. The pH of the sample is 3.5 and the dissolved sulfate concentration is 1,430 mg/L. Some metals concentrations in the sample are also high. For example, dissolved aluminum is 114 mg/L and dissolved copper is 170 mg/L. Dissolved iron, manganese, and zinc are also high at 3.13, 52.1, and 28.9 mg/L, respectively.

Stormwater samples collected at outfalls under the National Pollution Discharge Elimination System (NPDES) permit were also analyzed for a more limited suite of constituents (Appendix D). The concentrations in these samples tend to be more dilute than those in the surface water sample collected directly from the stockpile surface. For example, the copper concentrations range from about 0.014 to 1,084 mg/L. The pH is also higher and ranges from slightly greater than 5 to slightly greater than 7.

Table 5-1. No. 1C Stockpile Runoff Water Quality

Parameter	Result
Alkalinity (mg/L as $CaCO_3$)	<1.0
Carbonate (mg/L as $CaCO_3$)	<1.0
Specific conductance (µmhos/cm)	1,840
Bicarbonate (mg/L as $CaCO_3$)	<1.0
pH (su)	3.50
Chloride (mg/L)	1.52
Fluoride (mg/L)	8.61
Sulfate (mg/L)	1430
Calcium (mg/L)	74.5
Potassium (mg/L)	1.4
Magnesium (mg/L)	66.2
Sodium (mg/L)	3.16
Silver (mg/L)	0.0072
Aluminum (mg/L)	114
Arsenic (mg/L)	<0.010
Boron (mg/L)	<0.040
Barium (mg/L)	<0.0020
Beryllium (mg/L)	0.0164
Cadmium (mg/L)	0.296
Cobalt (mg/L)	0.954
Chromium (mg/L)	<0.0060
Copper (mg/L)	170
Iron (mg/L)	3.13
Manganese (mg/L)	52.1
Molybdenum (mg/L)	0.0106
Nickel (mg/L)	0.176
Lead (mg/L)	0.0272
Selenium (mg/L)	<0.010
Silica (mg/L)	3.55
Thallium (mg/L)	<0.010
Vanadium (mg/L)	<0.0050
Zinc (mg/L)	28.9

Source: SVL Analytical report dated October 14, 2003

6. Estimation of Impacts

An estimation of the potential impacts to groundwater and surface water at the Tyrone Mine based on the stockpile mass loading analysis is presented in Section 6.1. Implementation of results of this revised seepage investigation into the source area groundwater transport model is presented in Section 6.2. A discussion regarding the slope stability analysis is contained in Section 6.3.

6.1 Mass Loading

The mass loading of a constituent from a stockpile facility is equal to the volumetric discharge of seepage from the stockpile times the concentration of a constituent (DBS&A, 2001). . The mass loading modeling results (Section 4.4 and Appendix C) show that sulfate and other constituent mass loading is approximately an order of magnitude higher for the existing uncovered stockpiles than for the DP-1341 covered stockpiles (Table 4-6). The reduction in mass loading that is achieved upon closure is attributed to a reduction in infiltration that is achieved with the cover. However, other factors may increase or decrease the mass loading of the DP-1341 closure scenario relative to the existing stockpile conditions. Decreases in oxygen levels can significantly decrease the mass loading, but it is uncertain whether the proposed cover will be able to limit oxygen ingress into the stockpiles. Regrading may change the outslope configuration so that it is more or less accessible to air and oxygen infiltration. Decreases in air infiltration may result in less pyrite oxidation, which will lower the temperature of the stockpiles. Lower temperatures will in turn decrease the rate of pyrite oxidation, further resulting in less mass loading of sulfate from the stockpile material. However, lower temperatures mean that less internal air convection will occur and internal convection has a drying effect on the stockpiles, but the magnitude of the drying effect has not been estimated. In addition, stockpile regrading may increase the surface area of the material such that increased mass loading will be realized.

It should be noted that partially covered stockpile scenarios were not considered in this modeling effort. The effect of a partial cover including top surfaces instead of the existing alternative would be to lower the differences in mass loading between the DP-1341 scenario and the alternative. Other alternatives, including covering the top surfaces and exterior outslopes to the pits, are being considered under the feasibility study by Golder (2004).

Another consideration is the fact that the infiltration rates were kept constant for all model years when in fact the infiltration rate will vary from year to year owing to variable precipitation. The effect of this assumption is to increase the difference in mass loading. Because wet year infiltration pulses move through the stockpiles more quickly, they will have lower concentrations, which will decrease the resulting mass loading. These precipitation pulses will move though the stockpiles more quickly in the case of uncovered stockpiles and result in less mass loading relative to covered stockpiles. Therefore the assumption of constant precipitation and constant infiltration increases the difference between the DP-1341 alternative and the existing scenario alternative.

6.2 Transport Model

The mass loading inputs will be integrated into a simplified transport model to simulate groundwater quality directly beneath the stockpiles as part of the supplemental groundwater study, in accordance with DP-1341, Condition 82 (DBS&A, 2003). The extent of the transport domain will be sufficient to provide source area estimates for a more extensive analysis of groundwater quality being conducted for the supplemental groundwater study. The stockpiles' mass loading will be dissolved into the vertical groundwater column beneath the stockpiles through simulated mixing and attenuation processes. The zone of impacted water beneath the water table will be varied according to bounding estimates of the thickness of the regional water table and the estimated depth of dissolved mass distribution. The travel time from the base of the stockpile to the water table and loading rate of the constituents will be evaluated based on the depth to the water table, bedrock properties, and other site-specific conditions. The travel time estimates and mass flux rates can be used to simulate the transition from present day to a post-closure steady-state condition. This condition will be governed largely by the average drain-down rate and infiltration rate into the covered or uncovered stockpile surfaces.

Updated water level, groundwater velocity, and porosity data from the Condition 82 study will be used in the transport simulations for existing mine site conditions. In addition, seepage fractions (fraction of stockpile seepage in a surface water or groundwater sample) can be estimated using geochemical analyses such as the magnesium concentrations in impacted and background groundwater (Bartlett, 1992). The estimated seepage fractions can be used to determine the existing seepage and mass loading rates for calibration of the transport model through comparison with existing groundwater quality data.

6.3 Stockpile Geochemical Stability

Geochemical stability relates to the reactivity of both gangue silicate minerals and sulfide minerals in the stockpile. Chemical weathering can have at least two qualitatively different influences on materials stability (McLemore et al., 2005). First, dissolution of silicate minerals by acidic solutions can result in reduction of grain size and generation of clay minerals. Secondly precipitates that form as a result of weathering can cement particles and increase cohesion. Silicates react according to the general equation:

> Primary silicate + H_2O + H_2SO_4 = ions in solution (Na^+, K^+, Ca^{2+}, Mg^{2+}, H_4SiO_4, SO_4^{2-}) + weathering products + mineral precipitates (i.e., clays and sulfates)

According to the relative reactions rates provided by Morin and Hutt (1997, Table 5.2.1-1), the Tyrone stockpile’s primary matrix silicate minerals are slow weathering to fast weathering.

Pyrite is present in all stockpiles and is reacting with oxygen to produce acidity, sulfate, and iron. The general pyrite oxidation equations are:

$$FeS_2 + 15/4O_2 + 7/2H_2O = Fe(OH)_3 + 2SO_4^{2-} + 4\ H^+$$

$$FeS_2 + 14Fe^{3+} + H_2O = 15Fe^{2+} + 2SO_4^{2-} + 16H^+$$

The precipitate $Fe(OH)_2$ can form cementations along with sulfate mineral precipitates.

The oxidation of pyrite in the Tyrone stockpiles generates pH conditions that are generally between 2.3 and 6.8 according to paste pH and MWMP results. The most common pH conditions were above 3 and do not promote rapid hydrolysis of silicate minerals in the rock matrix. Therefore, extensive formation of clay minerals in the stockpiles is not occurring. The geochemical modeling shows that some limited clay formation may be occurring over very long time periods in the Tyrone stockpiles. However, the amount of clay that is forming is not sufficient to affect the geochemical stability of the stockpile slopes. The generation of clay-size fines by chemical weathering may reduce the friction angle by 6 to 12 degrees (Williams, 2000). This reduction does not occur gradually as the clay fraction increases, but instead, relatively suddenly at a clay content of about 10 percent. At this clay content, the larger particles in the soil are no longer in direct contact with each other but instead tend to be supported in a matrix of clay-sized particles. However, increases of clay content of 10 percent as a result of chemical weathering are not predicted by the model.

Rock core samples were lithologically described as part of the *Supplemental Materials Characterization of the Leached Ore Stockpiles and Waste Rock Stockpiles*, preliminary and final reports (EnviroGroup, 2005b, 2005c). The examinations showed evidence for pervasive alteration of fresh host rocks as a result of supergene and hypogene alteration. Feldspars and mafic minerals such as hornblende and biotite are highly altered to clay assemblages as a result of hydrothermal alteration. Therefore, continued weathering in the stockpile is slowed by the presence of clays that are geochemically stable under weathering conditions. In the stockpile samples, feldspars to a large extent are altered to sericite as a result of hydrothermal alteration. The sulfide minerals pyrite, chalcopyrite, and chalcocite have also been identified. Pyrite is present in leach ore and waste rock stockpiles along with iron oxide weathering products. Jarosite and natrojarosite, both sulfate minerals that are the products of acid generation, were detected in the stockpile samples by XRD. The geochemical mass loading model successfully predicts the formation of jarosite under weathering and leaching conditions. These sulfate minerals can cement particles and increase cohesion within the stockpiles.

Few studies on stockpile weathering and geochemical stability are available in the literature. Two weathering studies at sites located in southwestern Montana and northern New Mexico are summarized below.

A study of a waste rock stockpile was conducted at the Golden Sunlight Mine, located in southwestern Montana, to determine the extent of weathering, characterize its geochemical variations, and correlate the extent of weathering with physical waste rock characteristics (Outlaw and Dollhopf, 1997). Material was first emplaced on the stockpile in the late 1980s. The primary rock types deposited were hydrothermally altered and mineralized shale and latite. These rocks contain an average of 8 percent sulfur, mostly in the form of pyrite. The study showed that weathering is more intense where the waste rock interface comes into contact with air and water at the surfaces of the waste rock. The extent of weathering is less deep within the pile although the deepest and oldest portions of the stockpile showed the highest degree of weathering. This indicates that weathering continues even in areas where air and water access are limited. Paste extracts from the most weathered rocks have the lowest sample pH and highest titratable acidity, soluble sulfate, iron, and aluminum.

These weathering trends were not discerned from analysis of the Tyrone stockpile geochemical results. It is inferred that the altered shale and latite at Golden Sunlight are more geochemically reactive than the altered Tertiary granodiorite stock and Precambrian granites at Tyrone.

Detailed weathering studies are being conducted on Molycorp's stockpiles located in northern New Mexico (McLemore et al., 2005). The work conducted thus far shows that paste pH increases with distance from the outer, oxidized zone toward the interior, which suggests that oxygen diffusion from the surface is supporting pyrite oxidation. The interior pyrite is reacting more slowly owing to less available oxygen. The Molycorp's studies are in progress and additional findings with respect to stockpile weathering processes are forthcoming.

7. Conclusions

The Tyrone stockpile characterization data have been reported in two principal reports as part of the 2001 CCP and in two reports for DP-1341, Condition 81. Other supporting studies provide additional information on mine materials. This database provides a sufficient repository of information on the character the materials at Tyrone for the purposes of closure and closeout planning.

The Tyrone stockpiles are composed predominantly of (1) a clastic unit consisting of cobbles/boulders, (2) a matrix-supported unit consisting of coarse sands and gravels, and (3) a matrix-supported unit consisting of sands and gravels mixed with clay. The mineralogy of these rocks is dominated by quartz, illite, K-feldspar, and plagioclase with lesser amounts of kaolinite, chlorite, pyrite, jarosite, and amorphous glass. The major components of these minerals are SiO_2, Al_2O_3, K_2O, Fe_2O_3, MgO, K_2O, CaO and S. Acid base accounting shows that the stockpiles have mean ABPs between –40 and –60 T $CaCO_3$/kton and the paste pH values range from 3 to 7. The MWMP tests show that acidity and metals (aluminum, copper, iron, manganese, zinc, cobalt, and nickel) are leached from the stockpile materials upon contact with meteoric water. Comparisons of data of fresh mine materials with those of stockpile materials of various ages shows that the materials properties are highly variable and that the variability of stockpile material properties is similar to that of the fresh mine materials. The sulfate content in the stockpile materials is significantly higher than that of fresh mine materials owing to the effects of pyrite oxidation. The leach ore materials are not significantly different from the waste rock materials, and the range in properties overlaps.

Sulfate is stored in the stockpiles in the form of jarosite and other sulfate minerals, which occur in significantly greater abundances in the stockpile materials as compared to fresh mine materials. Jarosite is a source of stored acidity and metals that is released upon contact with meteoric water. This reaction accounts for the release of sulfate, acidity, and metals concentrations found in MWMP extracts from stockpile samples. The leach ore stockpile materials do not appear to be more reactive than waste rock stockpile materials. Constituent concentrations are high in the MWMP extracts; however, the relative impacts on surface water and groundwater quality are dependent upon the mixing proportions of stockpile seepage with surface water and groundwater.

Stockpile runoff and seepage monitoring results show that these waters are characterized by low pH and high sulfate concentrations. The range in seepage pH is from less than 2 to greater than 7 and the range in seepage sulfate concentrations is from less than 10 to more than 42,000 mg/L. The concentrations of aluminum, copper, iron, manganese, and zinc can also be high in surface water and seepage samples. The high concentrations of dissolved constituents are a result of geochemical reactions between meteoric water and the stockpile materials. These are waters that have not yet been diluted by mixing with surface water or groundwater, and the impacts associated with runoff and seepage will depend upon the relative mixing volumes. It should be noted that some of the seepage that is being monitored is natural seepage that emanates where the groundwater table intersects the surface; not all of the seeps represent water that has for the most part passed through stockpiles.

The mass loading modeling results indicate that sulfate and other constituent mass loading may be approximately an order of magnitude higher for the existing uncovered stockpiles than for the scenario where stockpiles are regraded and covered as currently required in DP-1341. The reduction in mass loading that may be achieved upon closure in this manner is attributed to a reduction in infiltration that is achieved with the cover. However, the difference between the uncovered and covered scenarios may not be significant, because the uncertainty in modeling complex systems such as these is greater than this order of magnitude result. In other words, the two closure scenarios perform similarly within the uncertainty of our ability to model these systems, although the results do indicate some benefit to constructing a cover system that reduces infiltration.

Other factors may increase or decrease the mass loading of the DP-1341 closure scenario relative to additional stockpile closure scenarios that have not been captured in this modeling effort. Decreases in oxygen levels can significantly decrease the mass loading, but it is uncertain whether the proposed cover will be able to limit oxygen ingress into the stockpiles. Regrading may change the outslope configuration so that it is more or less accessible to air and oxygen infiltration. Decreases in air infiltration may result in less pyrite oxidation, which will lower the temperature of the stockpiles. Lower temperatures will in turn decrease the rate of pyrite oxidation, further resulting in less mass loading of sulfate from the stockpile material. However, lower temperatures mean that less internal air convection will occur and internal convection has a drying effect on the stockpiles, but the magnitude of the drying effect has not been estimated. In addition, stockpile regrading may increase the surface area of the material such that increased mass loading will be realized.

The scope of this study was to estimate the quality of water that may seep from the base of the various stockpile units at Tyrone under several closure scenarios. It was not within the scope of this study to estimate the resulting water quality if the seepage were to mix with groundwater at the site. Therefore, the results of this study do not indicate whether New Mexico groundwater quality standards would be met underneath the stockpile units for any of the closure scenarios modeled or whether the closure requirements currently prescribed in DP-1341 would result in compliance with these groundwater quality standards.

Geochemical analysis and geochemical modeling has shown that the stockpile materials at Tyrone are geochemically stable with respect to silicate matrix mineral reaction with water, air, and acidity. The levels of acidity produced in the stockpiles are relatively low, and most paste pH results are usually 3 and above. These conditions do not result in pervasive weathering and leaching of the primary rock-forming minerals at Tyrone. The materials have been subject to hypogene and supergene alteration as part of the ore-forming processes that have occurred over the course of millions of years, and significant alteration from their present state in the stockpiles will take very long periods of time.

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