

**Project Report** 

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# Resolution Copper Mining Resolution Project Geochemistry

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# FINAL DRAFT REPORT: Prediction of Block Cave Water Chemistry





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# **Abbreviations**

- ALT Apache Leap Tuff
- atm atmospheres (pressure)
- CAP Central Arizona Project
- DRA Decision and Reliability Analysis
- EPS East Plant Site
- g gram
- gpm gallons per minute
- kg kilogram
- L/s liters per second
- m<sup>2</sup>/g square meters per gram (surface area)
- mg/L milligram per liter
- mol mole
- POC Point of Compliance
- RCM Resolution Copper Mining
- TDS total dissolved solids
- TSF Tailings Storage Facility
- tonne metric ton (1000 kg)





# 1. Summary

This report presents the results from a simulation model designed to predict the chemistry of water that will be collected in the underground workings of the Resolution Copper Project mine. The collected water will be a mixture of groundwater drainage from the Apache Leap Tuff (ALT) and Deep Groundwater along with Mine Service water and blowdown water from subsurface cooling systems. This water will be pumped to the surface and blended into the process and tailings water circuit as an additional water source to minimize freshwater makeup water requirements. Water contained in ore moisture comprises an additional source of water from the underground mine to the ore processing and tailings circuit.

The simulation model provides predictions of mean annual concentrations for a 45-year period that covers the life of mine. The primary findings of the simulation results are summarized below:

- The different water types that are expected to be collected, mixed, and pumped to the surface include the following:
  - ALT groundwater: The water draining vertically through the fractured block cave is expected to be primarily ALT groundwater. The ALT water, which contains alkalinity, will leach sulfide oxidation products from the ore zones where oxygen is present from ventilation systems. This water is predicted to be acidic. Potentially acidic conditions are expected for the lower levels of the block cave where oxygen from ventilations systems and elevated temperatures will promote sulfide mineral oxidation.
  - Deep Groundwater: This additional groundwater source is expected to flow into the mine from areas peripheral to the block cave. Deep Groundwater is expected to take on a chemical composition similar to that currently observed for Shaft 9, which naturally has a near neutral pH with measurable alkalinity and elevated sulfate concentrations.
  - Mine Service Water: Water brought into the mine for cooling system, dust suppression, drilling, and other uses, is expected to have a composition that is also similar to Shaft 9/10 water.
  - Blowdown Water: Water from refrigeration blowdown is assumed to have a composition based on its original source of freshwater makeup but evaporated to a total dissolved solids (TDS) concentration of 2500 mg/L.
- The numerical simulation model generates chemical compositions for these different water types, mixes them in proportion to their flow rates, and also applies specified equilibrium reaction processes to generate the chemistry of the water that would either be pumped from the underground or brought to the surface as ore moisture. Kinetic leaching processes to represent the effects of sulfide mineral oxidation and metal leaching are incorporated into the model based on laboratory data and scaling parameters developed for the conditions of the ore zones of the block cave. The model simulations of water and chemical balances are dynamic according to a panel mining sequence of Panel 2 followed by Panel 5. These panels have the highest





sulfide mineral contents and therefore expected to provide conservative estimates of water chemistry.

- Model simulation results for water that will be pumped to the surface predict acidic solutions (pH ~ 5) with sulfate concentrations in the range of about 2300 to 2400 mg/L. Mineral acidity is comprised primarily of aluminum and manganese with a lesser amount as iron. Metal concentrations are highest for copper (~120-150 mg/L) and zinc (~7-10 mg/L). Concentrations for other important constituents are ~15-25 mg/L for fluoride, 0.6 to 1 mg/L for selenium, and 0.01-0.02 mg/L for arsenic.
- Simulation results for ore moisture predict slightly more acidic water at pH values of about from 4.4 to 4.6 and sulfate concentrations up to 3800 mg/L. Metal concentrations are highest for copper reaching 680 mg/L for ore moisture. Selenium concentrations range up to 3.3 mg/L for ore moisture.
- The primary source of acidity and metals is the oxidation of sulfide minerals in the ore zones through which ALT water is expected to flow in its passage through the block cave before reaching mine sumps. The acidity is partially neutralized by mixing with alkalinity-containing water from the ALT, Deep Groundwater, Mine Service water, and blowdown water in sumps. Ore moisture is more acidic and concentrated than pumped water because it is not mixed with other water types.

Sensitivity analyses show that results are most dependent on the two primary scaling factors in the model. These factors are the thickness of the oxidation zone and the extrapolation of leaching rates from laboratory temperature to mine temperatures. Simulations using the outer boundaries of these parameters predict a change in pH of about  $\pm 0.2$  to 0.3 units and  $\pm 10\%$ for sulfate concentrations. Metals show a similar range in concentrations in the sensitivity analyses for oxidation thickness and temperature factor. Results are less sensitive to the inflow rate of Deep Groundwater and ALT water.





# 2. General

## 2.1 Introduction

The Resolution Copper Mining, LLC (RCM) plans to construct a block cave mining operation at the Resolution Project site. Mine construction and development over time will result in groundwater inflow to the block cave with subsequent drainage to the lower levels where it will mix with water from other sources. The drainage water moving through the ore zones of the block cave will interact with the metal sulfides and other minerals at temperatures that are expected to be greater than 40°C in the lower elevations of the cave. These interactions in combination with  $O_2$  circulated through the working levels of the mine by ventilation systems will result in the oxidation of the sulfide minerals thereby altering the chemistry of the water that will drain through the ore zones of the block cave.

The contact water from the ore zones will be collected in sumps and mixed with mine service and blowdown water from cooling and ventilation systems, such that sump water pumped to the surface will be a mixture of water from a number of sources. The water mixture from the sump will be pumped to the surface and added into the process water circuit. Once in the process water circuit, the underground mine water will become a component of the chemistry of the water contained in the tailings storage facility (TSF).

## 2.2 Decision and Reliability Analysis Objectives

The work described in this report was carried out within the framework of the Decision and Reliability Analysis (DRA) process that has been developed by RCM. The DRA is based on concepts in EPA (2006) and is used to guide and organize the different data collection and modeling efforts underway for the Resolution Project. The model described in this report was developed to address the following problem statement and objectives:

Sulfide oxidation and metal leaching have the potential to impact the chemistry of water obtained from the underground mining operations, including both sump water and water contained in ore moisture. Water from the underground will be mixed into the process and tailings circuits; hence its chemistry has the potential to affect both ore processing and tailings generation. In addition, water stored in tailings represents a source of chemical loads that could be transported from the TSF to outside receptors; hence, understanding chemical loads from the underground to the tailings provides information relevant to assessing potential transport of chemicals to outside receptors.

The block cave geochemistry model is a key starting point for the series of hydrologic and geochemical models being developed to predict the potential chemical impacts of mining operations.

# 2.3 Goals

The work presented in this report has goals that are relevant to both the operational mine life and closure planning. The goals specific to the operational life are:

• Predict the chemical composition of water that will be removed from the underground mine and changes in that composition with time over the mine life





• Provide information to assess effects of adding underground mine water to process and tailings water; this subject will be addressed in a separate report.

The goals specific to mine closure planning are to:

• Provide a water chemistry for the underground at the end of mining that may be relevant to future modeling evaluations if required.



# 3. Conceptual Model

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A conceptualization of the block cave hydrogeochemical system is shown in Figure 3-1. The geological units are conceptualized based on knowledge of the subsurface (RCM, 2014). The main features of this conceptualization are:

- The block cave mine will be constructed in a series of vertical panels. As material is removed from the bottoms of the panel, a fracture network will propagate upward, resulting in subsidence and changing the hydraulic properties of the rock in the cave zone. The fracture network will eventually reach the Apache Leap Tuff (ALT), which is an aquifer. Once the fracture network intersects the ALT, its stored water content and future recharge will flow downward through the sulfide ore zones of the panels before reaching the lower levels of the mine where it will be collected in sumps.
- Within the sulfide ore zones, the supply of air from ventilation will allow O<sub>2</sub> to move into fractured zones by diffusion and some amount of advection, creating a thin oxidation zone where the O<sub>2</sub> comes in direct contact with sulfide minerals before being consumed within the matrix of the fractured rock. The rock surfaces in the lower elevations of the block cave are expected to have elevated temperatures in excess of 40°C. Laboratory kinetic results for samples of sulfide-bearing rock from the block cave indicate a high potential for acid generation and metal leaching at ambient laboratory temperature (MWH, 2013). Given the supply of O<sub>2</sub> from ventilation and acceleration of oxidation rates caused by elevated temperatures, the oxidation of sulfide minerals in the oxidation zone is expected to result in in acid generation and metal leaching. The ALT water and the moisture content of ore are assumed to leach oxidation products during passage through the oxidized zone of the panel and take on an acidic chemistry.
- Groundwater models indicate there will be a lateral flow of water to the lower levels of the block cave from the rock units surrounding the vertical expression of the fractured rock. This inflow is referred to as Deep Groundwater. It is assumed that the Deep Groundwater bypasses the majority of the sulfide oxidation zones by flowing downward along the outer margins of the fracture system of the block cave to sumps where it will mix with ALT water. The chemical composition of water in the Deep Groundwater is assumed to be the same was what is currently observed in Shaft 9/10, which has elevated SO<sub>4</sub> and TDS concentrations and near-neutral pH.
- Mine service water used for a variety of uses in the underground will also be collected in the lower level sumps. It is assumed that this water originates as freshwater but takes on the same chemical composition as Deep Groundwater (Shaft 9/10 chemistry) after exposure to mined materials during drainage to lower level sumps.
- The lower level sumps will also collect blowdown water generated by the underground cooling systems. Underground blowdown water is assumed to have a chemical composition that originated as freshwater, but has been subjected to evapoconcentration to such an extent that it will have a TDS concentration of 2500 mg/L.





• Water pumped from the lower level sumps to the surface will be mixed with blowdown water from surface East and West Plants in either sumps or pipes. The chemical composition of this blowdown water is assumed to be the same as the underground blowdown water with a TDS concentration of 2500 mg/L. This mixture of water types will be pumped into the process and tailings circuit at the West Plant.



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Figure 3-1. Conceptualization of the block cave hydrogeochemical system





# 4. Modeling Framework

## 4.1 Software

The model was developed with a combination of GoldSim (version 11.1.3) and PHREEQC (Parkhurst and Appelo, 2013). GoldSim was used for the water and chemical mass balance components of the model. PHREEQC was used for the reactive processes that affect water chemistry as a result of leaching and solution mixing, including aqueous speciation, solubility, oxidation kinetics, and adsorption. The WATEQ4F.DAT thermodynamic database was used for the PHREEQC calculations. This database was modified by the addition of basis species and thermodynamic data for Sb, Be, Co, Cr, Hg, Mo, Tl, and V. Thermodynamic data for these elements were obtained from the MINTEQ.V4.DAT database. The chemical portions of the model include calculations for:

• Ca, Mg, Na, K, Cl, HCO<sub>3</sub>, SO<sub>4</sub>, SiO<sub>2</sub>, F, NO<sub>3</sub>-N, Al, Sb, As, Ba, Be, B, Cd, Cr, Co, Cu, Fe, Pb, Mn, Hg, Mo, Ni, Se, Ag, Tl, Zn, and pH.

The PHREEQC geochemical model was integrated directly into the GoldSim water balance model, so that changes to water chemistry resulting from reactive processes are made at each time step in the simulations and incorporated directly into the simulation results (Eary, 2007).

#### 4.2 Simulation Period

The simulation period was 2026 through 2070. This time period is based on the estimated starting and ending years for mine production. A one-month time step was used for calculations over the 45-year simulation period for a total of 540 time steps. Both the water balance and PHREEQC calculations are conducted at each time step.



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# 5. Model Development and Parameters

## 5.1 Calculation Sequence

The model was developed according to the conceptual model shown in Figure 3-1. The conceptual model includes both water balance and chemical balance components. The calculation sequence for combining these components into a single model is shown in Figure 5-1. The major components of the model are described in the following sections.

#### 5.2 Water Balance

The water balance, including inflows from the ALT and Deep Groundwater system for the underground mine, was provided by RCM as annual average flow rates over the mine life. The Mine Service and Blowdown water components are from recent evaluations of underground water use estimations. This water balance can be split into major components that are described in the following sections.

#### 5.2.1 Lower Level Sump

Flows to the Lower Level Sump include the following:

- ALT inflow
- Deep Groundwater inflow
- Mine Service Water that contacts the mine workings through various uses
- Underground blowdown water

The primary loss of water from the Lower Level Sump is:

Ventilation Loss

Figure 5-2 shows the flows over time predicted to enter the Lower Level Sump. The major flows to this sump are Mine Service water and ALT inflow. Deep Groundwater inflow is also a major inflow for the first 10 years but decreases substantially after longer times. The flows shown in Figure 5-2 for the ALT and Mine Service do not include water that will become entrained in fractured ore, which is referred to as ore moisture. A small flow of blowdown water from the underground refrigeration systems will also be collected in the Lower Level Sump.

#### 5.2.2 Upper Level Sump

The Upper Level Sump conceptually represents a position in the upper elevations of the underground mine where blowdown water flows from the refrigeration systems at the East and West Plants are added to the water pumped from the Lower Level Sump before entering the process circuit (Figure 3-1). The predicted flows for the Upper Level Sump are shown in Figure 5-3. Blowdown flows from the East and West Plants are relatively small compared to the flow from the Lower Level Sump.







Figure 5-1. Calculation sequence for the numerical model of water chemistry from the block cave







Figure 5-2. Flows to the Lower Level Sump



Figure 5-3. Flows to the Upper Level Sump



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## 5.2.3 Total Water Removed

Figure 5-4 shows the total rates of water removed from the underground. Most of the water is from the sumps and will be pumped to the surface. However, a substantial equivalent flow of water at a rate up to 917 gpm will be conveyed to the West Plant as ore moisture (Figure 5-4). This flow rate is based on an assumed moisture content of 4% and the mine schedule for ore and waste production shown on the right y-axis in Figure 5-4.

In the ore moisture calculations, the ore is assumed to have a negligible water content prior to being mined but will pick up entrained water from both the ALT inflow and Mine Service water used for dust suppression, drilling, and spray down, reaching a moisture content of 4%. It is assumed that one third of this 4% water content is from the ALT given sufficient flow from the ALT and the remainder of two thirds from Mine Service water.



Figure 5-4. Total water removed from the underground and ore production





# 5.3 Chemical Balance

The chemical balance portion of the model was developed by assigning each of the water flows entering the sumps a chemical composition and then mixing those compositions in proportion to their flow rates. Ore moisture was also assigned a chemical composition. There are two types of water chemistry assignments in the model:

- Static chemistries these are the chemical compositions for water balance components that are expected to remain relatively constant over the mine life, including:
  - Freshwater (primary source of makeup for Mine Service water)
  - o Blowdown water
  - o Deep Groundwater
  - o Mine Service water
- Dynamic these are the chemical compositions for water balance components that are expected to change with time over the mine life due to sulfide oxidation and leaching processes expected to occur in the ore zones. They include the following:
  - o ALT inflow
  - o Ore Moisture

The following sections describe how those chemistries were developed.

#### 5.3.1 Static Chemistries

#### 5.3.1.1 Freshwater

Renewable freshwater makeup for the mine will be comprised of water from the Central Arizona Project (CAP) canal and banked Recovery Wells. The chemistry of the CAP canal water was defined from the average of 12 monthly samples from 2010 reported for the CAP McKellips Station<sup>1</sup> (Table 5-1). The average composition was calculated using PHREEQC's solution mixing function to preserve ionic charge balance and account for aqueous speciation reactions. The McKellips Station data did not include results for most metals; hence, concentrations of 0 mg/L were used for these metals in model inputs.

The chemical composition for the Recovery Wells was based on data from the 2012 water quality report for Superior, Arizona obtained from the Arizona Water Company (average of Wells #1, #2, #3, and EPDS) (Table 5-1). The report contained concentrations for As, Ba, Cr, Cu, Pb, F, NO<sub>3</sub>, Cl, and Na. Concentrations for all other unreported parameters were assumed to be the same as CAP canal water or 0 mg/L.

Based on guidance from RCM, 25% of renewable water will be obtained from the CAP canal and 75% from the Recovery Wells. Table 5-1 gives the chemical compositions for this mixture.

<sup>&</sup>lt;sup>1</sup> <u>http://www.cap-az.com/Operations/WaterQuality/H2OQuality/WaterQualityData.aspx?location=mckellips</u>





Parameter	CAP Canal	Recovery Wells	Mixture (25% CAP + 75% Recovery Well)
Ca (mg/L)	72.3	30	41
Mg (mg/L)	27.4	7	12
Na (mg/L)	92.1	69.5	75
K (mg/L)	4.8	4.8	5
Cl (mg/L)	87.3	1.1	23
HCO₃ (mg/L)	122	180	159
SO <sub>4</sub> (mg/L)	258.5	32.5	140
SiO <sub>2</sub> (mg/L)	7.0	7.0	7.0
F (mg/L)	NA	0.4	0.3
NO <sub>3</sub> -N (mg/L)	0.3	2.0	1.6
Al (mg/L)	NA	NA	0
Sb (mg/L)	NA	NA	0
As (mg/L)	NA	0.006	0
Ba (mg/L)	0.13	0.01	0.039
Be (mg/L)	NA	NA	0
B (mg/L)	NA	NA	0
Cd (mg/L)	NA	NA	0
Cr (mg/L)	NA	0.004	0
Co (mg/L)	NA	NA	0
Cu (mg/L)	0.02	0.20	0.024
Fe (mg/L)	0.08	0.08	0.08
Pb (mg/L)	NA	0.002	0
Mn (mg/L)	0.005	0.005	0.005
Hg (mg/L)	NA	NA	0
Mo (mg/L)	NA	NA	0
Ni (mg/L)	NA	NA	0
Se (mg/L)	NA	NA	0
Ag (mg/L)	NA	NA	0
TI (mg/L)	NA	NA	0
Zn (mg/L)	NA	NA	0
pH (s.u.)	8.3	8.3	8.29

#### Table 5-1: Chemical compositions for CAP Canal and Recovery Well renewable sources

NA – not analyzed

#### 5.3.1.2 Blowdown Water

The makeup water used for refrigeration and cooling systems in both the underground and surface plants will be freshwater. The Blowdown water from these cooling systems will create small return flows to the underground sumps that have undergone some degree of evaporation through use for cooling. It has been assumed that the chemistry of Blowdown water can be represented by freshwater that has been evapoconcentrated to a TDS concentration of 2500 mg/L. The starting TDS concentration for the mixture of 25% CAP + 75% Recovery Well water is about 380 mg/L, so this mixture composition was concentrated by a factor of 6.6. The evapoconcentration calculation was made with PHREEQC. The resulting chemical composition for Blowdown water is given in Table 5-2.





Parameter	Blowdown Water
Ca (mg/L)	338
Mg (mg/L)	101
Na (mg/L)	627
K (mg/L)	40
Cl (mg/L)	189
HCO <sub>3</sub> (mg/L)	684
SO <sub>4</sub> (mg/L)	1130
SiO <sub>2</sub> (mg/L)	58.4
F (mg/L)	2.5
NO <sub>3</sub> -N (mg/L)	13.1
Al (mg/L)	0.0
Sb (mg/L)	0.0
As (mg/L)	0.0
Ba (mg/L)	0.3
Be (mg/L)	0.0
B (mg/L)	0.0
Cd (mg/L)	0.0
Cr (mg/L)	0.0
Co (mg/L)	0.0
Cu (mg/L)	0.2
Fe (mg/L)	0.7
Pb (mg/L)	0.0
Mn (mg/L)	0.0
Hg (mg/L)	0.0
Mo (mg/L)	0.0
Ni (mg/L)	0.0
Se (mg/L)	0.0
Ag (mg/L)	0.0
TI (mg/L)	0.0
Zn (mg/L)	338
pH (s.u.)	9.09
TDS (mg/L)	2504*

#### Table 5-2. Chemical composition for Blowdown water

 $TDS = Ca + Mg + Na + K + Cl + SO_4 + 0.4917^*HCO_3 + SiO_2 + F + Al + Fe + Mn + Ba + Co + Ni + Cu + Zn (Hem, 1989)$ 

#### 5.3.1.3 Deep Groundwater

Water is currently being pumped from the deep groundwater system from Shaft 9 and 10. It is assumed that the water in Shaft 9 and 10 is chemically representative of future water that will flow into shafts and ramps around the block cave and comes in contact with underground workings.

The composition of the Deep Groundwater system was calculated from the average of 22 samples collected from Shaft 9 prior to entering the water treatment plant that is currently in operation. The 22 samples used in the average were collected during the first half of 2015 after the chemical compositions had stabilized from a prior period of fluctuation that started in



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2009 when pump-down of water levels began. The average water chemistry was calculated using the solution mixing function in PHREEQC with equal mixing proportions for all samples. The resulting chemical composition is given in Table 5-3.

#### 5.3.1.4 Mine Service Water

Mine Service water is water directed to the underground and surface plants for cooling, dust suppression, drilling, and any other uses. Part of that water will be lost to ventilation systems. The remainder will drain to Lower Level sumps, a portion of which, may be reused for non-cooling uses in the underground. This water will originally be freshwater. However, it is assumed that after contact with various rock types in the subsurface, it will take on a chemical composition similar to Deep Groundwater. Based on this assumption, the chemistry of Mine Service Water collected in the Lower Level Sump is assumed to be the same as Deep Groundwater (Table 5-3).

Parameter	Deep Groundwater and Mine Service Water
Ca (mg/L)	307
Mg (mg/L)	80
Na (mg/L)	142
K (mg/L)	38
Cl (mg/L)	22
HCO <sub>3</sub> (mg/L)	90
SO <sub>4</sub> (mg/L)	1287
SiO2 (mg/L)	NA
F (mg/L)	3.1
NO <sub>3</sub> -N (mg/L)	0.2
Al (mg/L)	0.05
Sb (mg/L)	0.0010
As (mg/L)	0.008
Ba (mg/L)	0.027
Be (mg/L)	0.0005
B (mg/L)	NA
Cd (mg/L)	0.0005
Cr (mg/L)	0.0010
Co (mg/L)	0.0033
Cu (mg/L)	0.0037
Fe (mg/L)	0.05
Pb (mg/L)	0.0005
Mn (mg/L)	3.6
Hg (mg/L)	0.0004
Mo (mg/L)	NA
Ni (mg/L)	0.0046
Se (mg/L)	0.0010
Ag (mg/L)	0.0050
TI (mg/L)	0.0005
Zn (mg/L)	0.31
pH (s.u.)	8.15

#### Table 5-3. Water chemistries for the Deep Groundwater and Mine Service Water

NA = not analyzed.





### 5.3.1.5 Apache Leap Tuff (initial water chemistry)

The chemistry of water initially present in the ALT before drainage through the fractured block cave and exposure to oxidation in sulfide ore zones was defined as the average of analyses of samples collected from HRES-01, HRES-02, HRES-03, and HRES-04 (M&A, 2012). The average was calculated using the solution mixing function in PHREEQC with equal mixing proportions for the four samples (Table 5-4).

Parameter	ALT Water
Ca (mg/L)	247
Mg (mg/L)	3.7
Na (mg/L)	55
K (mg/L)	1.2
Cl (mg/L)	6.8
HCO₃ (mg/L)	196
SO <sub>4</sub> (mg/L)	8.2
SiO2 (mg/L)	61.4
F (mg/L)	0.44
NO <sub>3</sub> -N (mg/L)	3.6
Al (mg/L)	0.01
Sb (mg/L)	0.0033
As (mg/L)	0.0086
Ba (mg/L)	0.007
Be (mg/L)	0.0008
B (mg/L)	0.028
Cd (mg/L)	0.0005
Cr (mg/L)	0.0039
Co (mg/L)	0.0034
Cu (mg/L)	0.0060
Fe (mg/L)	0.086
Pb (mg/L)	0.007
Mn (mg/L)	0.02
Hg (mg/L)	0.0001
Mo (mg/L)	0.01
Ni (mg/L)	0.01
Se (mg/L)	0.006
Ag (mg/L)	0.0008
TI (mg/L)	0.0035
Zn (mg/L)	0.065
pH (s.u.)	7.67

#### Table 5-4. Water chemistry for the ALT

#### 5.3.2 Dynamic Chemistries

The dynamic chemistry components of the model are those that are expected to be affected by the processes of sulfide oxidation and metal leaching in the ore zones through which water





from the ALT will drain before being collected in the Lower Level Sump. They also apply to the water comprising ore moisture that will also be affected by sulfide oxidation and metal leaching. These dynamic components are shown conceptually in the box labelled "Block Cave Geochemical Model" in Figure 5-1. The details of the calculation methods for the Block Cave Geochemical Model are described in the following sections.

#### 5.3.2.1 Block Cave Geochemical Model Structure

The structure of the Block Cave Geochemical Model is shown conceptually in Figure 5-5. The vertical movement of ALT flow and chemical release from oxidation and leaching are segmented into the 8 model zones. These zones comprise the vertical discretization of the water and chemical mass balance calculations within the model. The definitions of the depth intervals for the model zones are provided in Section 5.3.2.3.

Each of the model zones are represented as mixing cells in the model. The initial chemical compositions of groundwater in model zones 1 to 3 were assumed to equal to the ALT composition (Table 5-4). The initial chemical compositions of groundwater in model zones 4 to 8 are assumed to be equivalent to the Deep Groundwater composition (Table 5-3).

The ALT inflow is routed sequentially from zone 1 to zone 8 to represent vertical flow through the entirety of the fractured zone of the block cave from the top to the lower levels of the mine (Figure 5-5). Solute release rates for all constituents were applied to zones 5 to 8 based on an aggregation of experimental leaching rates as functions of depth (described below). During mining, the fractured ore will move vertically downward to drawpoints and be removed. As the ore is removed, it will be replaced by ore caving from above it. This effect is accounted for in the model by tracking the rate of removal of material from each model zone over time. At each point in simulation time, the solute release rates for the model zone being removed from drawpoints were multiplied by the panel lateral dimensions, dry bulk density, thickness of the oxidized zone, and a temperature kinetic factor (described below). Oxidation is assumed to occur in a thin zone at the depths of the drawpoints where ventilation system will circulate air. The masses of solute released in each mixing cell were divided by the estimated fractured pore volume for each model zone to yield bulk concentrations for all solutes. Solute release rates were not applied to model zones 1 to 4 because these zones are comprised of mostly ALT, Whitetail Conglomerate, and low-sulfide portions of the upper volcaniclastics, which are comparatively non-reactive, relative to the deeper sulfide-bearing zones 5 to 8. Also, panel excavation never results in the mining of rock from zone 4 and above; hence these zones will not be exposed to oxygen.

The bulk concentrations were used to construct input files for PHREEQC with a specified set of equilibrium constraints. PHREEQC returns the concentrations for solutes after application of the equilibrium constraints. The equilibrated water chemistry was then directed to the next model zone in sequence. The linkage to PHREEQC was done for model zones 5 to 8 for each time step of the simulation (Figure 5-5).

The equilibrated chemistry from the bottommost model zone 8 represents the chemical composition of water entrained in mined sulfide ore as ore moisture. The equilibrated chemistry model zone 8 is also multiplied by the ALT inflow rate (minus the portion lost to ore moisture) and routed to the Lower Level Sump where it is mixed with Mine Service Water, Deep Groundwater, and Blowdown water (Figure 5-5). This mixture is again equilibrated with



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PHREEQC. The equilibrated chemical mass in the Lower Level Sump is then sent to the Upper Level Sump and mixed with an additional inflow of Blowdown water and again equilibrated with PHREEQC. The final equilibrated chemistry in the Upper Level Sump represents the water that is pumped to the process circuit at the West Plant (Figure 5-5).





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#### Figure 5-5. Structure of the Block Cave Geochemical Model (depth intervals are for Panel 2)

#### 5.3.2.2 Panel Mining Sequence

Five panels have been defined by the mine plan. Figure 5-6 shows the orientation of the mine panels in map view. The model discussed in this report considers a sequence of first mining in Panel 2 for 15 years followed by mining in Panel 5 for 30 years. The actual mining sequence may vary from this order in the future and other panels will also be mined over the mine life. Panels 2 and 5 were selected for the modeling effort because they contain the highest sulfide mineral contents among all the panels, providing a conservative depiction of the potential effects of water-rock reactions, such as sulfide mineral oxidation, on water chemistry.

#### 5.3.2.3 Model Zone Delineations

The vertical pathway that will be followed by ALT water traveling downward through the fractured rock of the block cave was segmented into 8 geochemical model zones to provide a way to represent variability in leaching chemistry as a function of mineralogy with depth. The vertical extents of these 8 model zones were developed as follows:

- 1. Output from the three-dimensional Vulcan geologic block model for the deposit was used to calculate the distribution of rock and alteration types at 25-m elevation intervals within the block cave.
- The rock and alteration distributions at each 25-m elevation interval were used to weight the experimentally-derived release rates in proportion to the abundance of each rock and alteration type. The release rates were obtained from the set of longterm kinetic tests conducted on a wide range of samples from the deposit (MWH, 2013).

These calculations produced release rates as a function of depth for Panel 2 and Panel 5. The trends in release rates were assessed to identify geochemical zones where rates were either approximately constant with depth or showed a transition across a certain depth interval. Within each identified geochemical zone, the 25-m interval release rates were averaged to derive one set of solute release rates for each of the 8 model zones.

Figure 5-7a shows the release rates for major cations and major anions as a function of depth for Panel 2 that resulted from the application of the release rate data as a function of depth and model zones. Figure 5-7b shows the percent pyrite and copper for Panel 2 to provide an indication of the change in sulfide mineral content with depth. Figure 5-8a and Figure 5-8b show release rates for metals and sulfide mineral contents with depth for Panel 2, respectively. Figure 5-9 and Figure 5-10 show a similar set of release rate trends and percent pyrite and copper for Panel 5.

In each of these release rate figures, the horizontal colored areas indicate the definitions of the 8 model zones used to represent vertical variability in leaching chemistry in the model. For Panel 2 and Panel 5, release rates for acidity and metals are lowest in the upper zones where sulfide mineral contents are lowest, and increase with depth in zones 6 to 8 in parallel with the increases in sulfide mineral contents.



# **HATCH**



Figure 5-6. Panel orientation for the Resolution Block Cave Mine







Figure 5-7. Panel 2: a) Release rates for major parameters and b) percent pyrite and copper







Figure 5-8. Panel 2: a) Release rates for metals and b) percent pyrite and copper







Figure 5-9. Panel 5: a) Release rates for major parameters and b) percent pyrite and copper







Figure 5-10. Panel 5: a) Release rates for metals and b) percent pyrite and copper





The positions of model zones 1 to 8 relative to the major geological units (RCM, 2014) are shown in Figure 5-11. Zones 1 and 2 are predominantly ALT. Zone 3 is mostly Whitetail Conglomerate. Zone 4 is mostly comprised of Whitetail Conglomerate and volcaniclastics. Zones 5 to 8 are made up mostly of volcaniclastics and the economically mineralized portions of the deposit.

The zone elevations, thicknesses, and physical properties for Panel 2 are given in Table 5-5. Dimensions and properties for Panel 5 are summarized in Table 5-6. The solids densities represent average values calculated from the geologic block model. The dry bulk densities were estimated from the pre-mining porosity and density data and provided by RCM.

# Table 5-5. Model zone elevations and properties used to define mixing cell properties for Panel 2(320 m wide by 1200 m long)

Model Zone	Top Elevation (m)	Bottom Elevation (m)	Layer Thickness (m)	Density of Solids (kg/m³)	Dry Bulk Density (kg/m³)	Pre-mining Porosity (≤3 yrs) (%)	Post-Mining Porosity (> 3 yrs) (%)
1	1262.5	837.5	425	2440	2391	2%	2%
2	837.5	737.5	100	2470	2421	2%	2%
3	737.5	262.5	475	2550	2448	4%	5%
4	262.5	-87.5	350	2580	2554	1%	15%
5	-87.5	-162.5	75	2670	2643	1%	20%
6	-162.5	-362.5	200	2750	2723	1%	27%
7	-362.5	-512.5	150	2780	2752	1%	38%
8	-512.5	-762.5	250	2760	2732	1%	38%

# Table 5-6. Model zone elevations and properties used to define mixing cell properties for Panel 5(200 m wide by 750 m long)

Model Zone	Top Elevation (m)	Bottom Elevation (m)	Layer Thickness (m)	Density of Solids (kg/m³)	Dry Bulk Density (kg/m³)	Pre-mining Porosity (≤ 3 yr) (%)	Post-Mining Porosity (> 3 yr) (%)
1	1312.5	962.5	350	2440	2391	2%	2%
2	962.5	887.5	75	2500	2450	2%	2%
3	887.5	262.5	625	2580	2477	4%	5%
4	262.5	-112.5	375	2710	2683	1%	15%
5	-112.5	-262.5	150	2750	2723	1%	20%
6	-262.5	-387.5	125	2760	2732	1%	27%
7	-387.5	-512.5	125	2760	2732	1%	38%
8	-512.5	-762.5	250	2810	2782	1%	38%









Figure 5-11. Lithologic cross sections with model zones 1-8 for a) Panel 2 and b) Panel 5





## 5.3.2.4 Chemical Release Rates

The chemical release rates shown in the preceding figures for the model zones were based on 54 laboratory column kinetic tests were conducted on a range of lithologies, alteration types, and sulfide contents. Sample sizes for these kinetic tests ranged from 1.5 kg to 20 kg. Test durations ranged from 16 to 74 weeks. MWH (2013) provides a summary of these kinetic tests.

Release rates were calculated using the average concentrations from the final three weeks of the tests multiplied by the recovered water volumes and divided by the sample weight to yield rates in mg/kg/week. The last three weeks of measurements were used because they were assumed to be representative of fully established acid generation and metal leaching rates for the tests that produced acidic leachates. This calculation procedure was followed for parameters that had concentrations greater than detection limits. For chemical parameters that had concentrations less than detection limits for one or more of the last three week's concentrations, those concentrations were set to one half of the detection limit.

A number of parameters had concentrations that were nearly always less than detection levels in the experimental leachates. These include Sb, Be, B, Cr, Hg, Mo, Ag, TI, and V for which 70 to 100% of reported concentrations were less than detection levels in leachates from the last three weeks of testing (Table 5-7). These parameters also typically showed a pattern of a decreased release rate (mg/kg/week) with an increase in the sample weight used in the test. Figure 5-12 shows an example of this pattern for Be, which had a high percentage of non-detects (Table 5-7). The pattern in Figure 5-12 indicates that the calculated release rate for Be is more of an artifact of dividing non-detect concentrations by the sample weight than a function of chemical processes.

As a result of this observation, the following procedure was used to calculate release rate for the parameters with high frequencies of non-detects (Sb, Be, B, Cr, Hg, Mo, Ag, Tl, and V):

- Concentrations less than detection levels were set equal to one half of the detection level.
- Rates were calculated using only data from kinetic tests with sample weights greater than 5 kg. Using these data minimized the effect of the sample weight for skewing the release rates to higher than expected values because the detection level concentrations were divided by a smaller mass of sample compared to other tests.





Cr

Hg

Мо

Ag Tl

V

0.05

0.001

0.05

0.03

0.0005

0.03

95%

100%

70%

94%

79%

87%

Parameter	Number of Analyses	Number < Detection	% Non- Detect	Detection Limit (mg/L)
Sb	957	1101	87%	0.002
Be	1041	1345	77%	0.01
В	825	1100	75%	0.05

1101

1099

1344

1099

1344

1099

1050

1095

933

1036

1068

961

Table 5-7. Summary of non-detects from kinetic tests (54 tests; data from all weeks of testing)



Figure 5-12. Relationship between Be leaching rate and sample weight for the last three samples of leachates from kinetic tests (DL=detection limit)

#### 5.3.2.5 Scaling Factors

The approach for extrapolating the laboratory-measured leaching rates to the block cave involved two key factors:

- Temperature effect
- Oxidized thickness





#### 5.3.2.5.1 Temperature Effect

The rate of oxidation of sulfide minerals is accelerated as temperature increases. Rock temperatures have been measured in the range of 40 to 80°C in drill-holes penetrating to the lowermost depths of the mine. With development and circulation of ventilation air and movement of water from higher, cooler zones, these temperatures will moderate. For the geochemical model, it is assumed that elevated temperatures will persist but will be moderated in zones where mining occurs by cooling and ventilation systems to a range of 45 to 55°C for the lower model zones (Zones 5-8).

The effect of temperature on the rate of  $O_2$  consumption (kg  $O_2/m^3/yr$ ) due to sulfide oxidation in waste rock was reviewed by Eary (2015). Figure 5-13 shows a regression line for the  $O_2$ consumption rate as a function of temperature developed from observations in waste rock storage facilities. Figure 5-13 also shows the range of  $O_2$  consumption rates (5<sup>th</sup> to 95<sup>th</sup> percentiles) calculated from the RCM column kinetic tests from SO<sub>4</sub> concentrations. The median laboratory rate was about 7 times faster than the value indicated by the regression curve at 25°C. To extrapolate the laboratory tests to the temperature conditions of the block cave, the median  $O_2$  consumption rate from the kinetic tests on block cave samples was divided by 7 to make it consistent with observations in waste rock. This factor or 7 is assumed to be an artifact of the small grain size in the laboratory tests compared to particle sizes in the field. To extrapolate the laboratory data to the elevated temperatures of the block cave, the median laboratory rate (after division by 7) was increased with temperature in parallel with the regression line in Figure 5-13.

The combined effects of the correction of the kinetic test rates to waste rock rates and increase with temperature were applied to the leaching rates of chemical parameters expected to be associated with sulfide mineral oxidation (Table 5-8). The parameters in Table 5-8 were applied as multipliers to the rates obtained from the kinetic tests. For other parameters, such as Si, Na, K, F, and Be, that are contained predominantly in silicate minerals, their leaching rates were accelerated with temperature based on an activation energy of 24.8 kJ/mol, which is average for biotite, muscovite, phlogopite, pyrollphyllite, and kaolinite (Palandri and Kharaka, 2004). No increases in rates were applied to the upper model zones 1-4 because those zones were assumed be at low temperature (20-30°C) not significantly different from laboratory temperature.







Figure 5-13. Oxygen consumption rates and extrapolation method for increased temperature





Parameter	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8
Temperature (°C)	40	45	50	55	55
Са	0.90	1.70	3.17	5.92	5.92
Mg	0.90	1.70	3.17	5.92	5.92
Na	1.60	1.88	2.17	2.50	2.50
К	1.60	1.88	2.17	2.50	2.50
Cl	1.60	1.88	2.17	2.50	2.50
HCO <sub>3</sub>	1	1	1	1	1
SO <sub>4</sub>	0.90	1.70	3.17	5.92	5.92
SiO <sub>2</sub>	1.60	1.88	2.17	2.50	2.50
F	1.60	1.88	2.17	2.50	2.50
NO <sub>3</sub>	1	1	1	1	1
Al	1.60	1.88	2.17	2.50	2.50
Sb	0.90	1.70	3.17	5.92	5.92
As	0.90	1.70	3.17	5.92	5.92
Ва	0.90	1.70	3.17	5.92	5.92
Ве	1.60	1.88	2.17	2.50	2.50
В	1.60	1.88	2.17	2.50	2.50
Cd	0.90	1.70	3.17	5.92	5.92
Cr	1.6	2.2	2.5	2.9	3.3
Со	0.90	1.70	3.17	5.92	5.92
Cu	0.90	1.70	3.17	5.92	5.92
Fe	0.90	1.70	3.17	5.92	5.92
Pb	0.90	1.70	3.17	5.92	5.92
Mn	0.90	1.70	3.17	5.92	5.92
Hg	0.90	1.70	3.17	5.92	5.92
Мо	0.90	1.70	3.17	5.92	5.92
Ni	0.90	1.70	3.17	5.92	5.92
Se	0.90	1.70	3.17	5.92	5.92
Ag	0.90	1.70	3.17	5.92	5.92
TI	0.90	1.70	3.17	5.92	5.92
Zn	0.90	1.70	3.17	5.92	5.92

Table 5-8. Leaching rate acceleration scaling factors

## 5.3.2.5.2 Oxidized Thickness

Oxygen will be consumed as it moves by diffusion and possibly by some amount of advection into mineralized rock and reacts with sulfide minerals. Thus, the entire rock mass in the block cave will not be subjected to oxidation but only a veneer where  $O_2$  penetrates before being consumed. The depth of penetration of  $O_2$  is expected to be limited by the high rate of sulfide oxidation observed in the kinetic tests and the additional rate increase due to elevated temperatures. To estimate, the depth of  $O_2$  penetration, a model of  $O_2$  diffusion, advection, and reaction was developed. The combined transport of  $O_2$  by diffusion and advection and consumption for a first order reaction rate can be described by the following equation:

$$D\frac{d^2}{dx^2}P - \nu\left(\frac{d}{dx}P\right) - k\left(\frac{P}{P^0}\right) = 0 \qquad \text{Eq. 1}$$

In Eq.1, *D* is the O<sub>2</sub> diffusion constant, *P* is the O<sub>2</sub> partial pressure,  $P^0$  is the atmospheric partial pressure of O<sub>2</sub> (0.21 atm), *v* is advective air velocity, *x* is depth, *k* is a the rate constant for O<sub>2</sub> consumption (kg O<sub>2</sub>/kg-s). At steady state, an analytical solution for Eq. 1 is:





$$r = \frac{v - \sqrt{v^2 + 4Dk}}{2D}$$
 such that  $P(x) = P_0 \cdot e^{rx}$  Eq. 2

In Eq. 2, P(x) is the partial pressure of O<sub>2</sub> with distance *x* and  $P_0$  is the ambient partial pressure of O<sub>2</sub> at time zero (0.21 atm). Using, a rate of O<sub>2</sub> consumption of 18.3 kg O<sub>2</sub>/m<sup>3</sup>/yr), temperature = 55°C, advection rate = 0.5 m/d, O<sub>2</sub> diffusion constant = 1 x 10<sup>-6</sup> m<sup>2</sup>/s for moist but drained material, and tortuosity = 0.2, the depth at which O<sub>2</sub> is depleted to 0.01 atm is about 2 m (Figure 5-14). The depth to which O<sub>2</sub> is greater than 0.01 atm or 5% of atmospheric O<sub>2</sub> is assumed to be depth of active oxidation (Wels et al. 2014).



Figure 5-14. Calculation of result for O<sub>2</sub> penetration into sulfidic rock





### 5.3.2.6 Solubility and Adsorption Parameters

The chemical release rates and application of scaling factors described in the above sections yield bulk chemical compositions for the model zones and sumps. These bulk chemical compositions were equilibrated with various mineral solubility and gas partial pressures using PHREEQC. The equilibration parameters are provided in Table 5-9. The O<sub>2</sub>(g) partial pressure is equivalent to ambient air. The partial pressure for CO<sub>2</sub>(g) was set at twice the ambient atmospheric pressure at 10<sup>-3.2</sup> atm, assuming that levels in the oxidizing rock mass would be somewhat elevated due to water-rock reactions and exhausts from machinery. The selections of mineral solubilities were based on temperatures (for example gypsum for model zones with temperatures less than or equal to 40°C and anhydrite for higher temperatures) and assumptions for phases expected to precipitate or dissolve at rates fast enough to approach equilibrium.

Parameter	Zones 1-4	Zones 5-8
Temperature	20-40°C	45-55°C
Partial pressure O <sub>2</sub> (g)	10 <sup>-0.7</sup> atm	10 <sup>-0.7</sup> atm
Partial pressure CO <sub>2</sub> (g)	10 <sup>-3.2</sup> atm	10 <sup>-3.2</sup> atm
Secondary minerals specified as solubility controls (Only allowed to precipitate if oversaturation conditions exist)	Anglesite, PbSO <sub>4</sub> Antlerite, Cu <sub>3</sub> (OH) <sub>4</sub> SO <sub>4</sub> Barite, BaSO <sub>4</sub> Be(OH) <sub>2</sub> (am) Brochantite. Cu <sub>4</sub> (OH) <sub>6</sub> SO <sub>4</sub> Cerargyrite, AgCl Chalcedony, SiO <sub>2</sub> Ferrihydrite, Fe(OH) <sub>3(a)</sub> Fluorite, CaF <sub>2</sub> Gibbsite, Al(OH) <sub>3</sub> Gypsum, CaSO <sub>4</sub> ·2H <sub>2</sub> O Jarosite(ss), (K <sub>0.77</sub> Na <sub>0.03</sub> H <sub>0.2</sub> )Fe <sub>3</sub> (SO <sub>4</sub> ) <sub>2</sub> (OH) <sub>6</sub> Langite, Cu <sub>4</sub> (OH) <sub>6</sub> SO <sub>4</sub> :H <sub>2</sub> O	Alunite, KAl <sub>3</sub> (SO <sub>4</sub> ) <sub>2</sub> (OH) <sub>6</sub> Anglesite, PbSO <sub>4</sub> Antlerite, Cu <sub>3</sub> (OH) <sub>4</sub> SO <sub>4</sub> Barite, BaSO <sub>4</sub> Be(OH) <sub>2</sub> (am) Brochantite. Cu <sub>4</sub> (OH) <sub>6</sub> SO <sub>4</sub> Cerargyrite, AgCl Chalcedony, SiO <sub>2</sub> Ferrihydrite, Fe(OH) <sub>3(a)</sub> Fluorite, CaF <sub>2</sub> Anhydrite, CaSO <sub>4</sub> · $2H_2O$ Jarosite(ss), (K <sub>0.77</sub> Na <sub>0.03</sub> H <sub>0.2</sub> )Fe <sub>3</sub> (SO <sub>4</sub> ) <sub>2</sub> (OH) <sub>6</sub> Langite, Cu <sub>4</sub> (OH) <sub>6</sub> SO <sub>4</sub> :H <sub>2</sub> O ZnSiO <sub>3</sub>
Adsorption/Desorption		Surface Adsorption (mass determined from simulated amount of precipitant formed due to iron sulfide oxidation; surface area equal to 600 m <sup>2</sup> /g; molecular weight of 89 g/mol) Hfo_wOH (week binding sites) 0.2 bindings sites (mol/mol Fe) Hfo_sOH (strong binding sites) 0.005 bindings sites (mol/mol Fe)

#### Table 5-9. Parameters used for equilibrium chemical processes simulated with PHREEQC





# 6. Model Predictions of Water Chemistry

## 6.1 Time Trends

A series of time-trend charts of mean annual concentrations of selected parameters are shown in this section for the simulation period. The selected parameters in the charts are illustrative of other parameters included in the model but not shown in charts. Numerical simulation results for mean annual concentrations for ore moisture and the Upper Level Sump are given in Table 6-1 and Table 6-2.

Time trends for pH and SO<sub>4</sub> for model zones 5 to 8 and the Upper Level Sump are shown in Figure 6-1 and Figure 6-2. Results are not shown for zones 1 to 4 because no reactions are specified for those zones and the water chemistries are unchanged from their initial conditions. The model zone results provide a depiction of the progressively increasing effects of sulfide oxidation and metal leaching as ALT water moves vertically downward through the block cave. The following conclusions are made from the model zone results:

- Figure 6-1: The pH decreases with depth as shown by comparison of results for model zones 5 to 8. The pH for the upper zones 5 and 6 are predicted to remain at pH > 5 whereas the lower zones 7 and 8 are predicted to decrease to 4.5 to 5.0 after an initial period of higher values. The length of time for neutral pH values is longer for model zones 5 and 6 than 7 and 8 because they are not exposed to air until later in the mine life. The pH value for the Upper Level Sump ranges from a near-neutral range for an initial period of about 7 years before decreasing to about 5.0. The initial period of near-neutral pH water is due to the relatively higher proportion of slightly alkaline Deep Groundwater entering the sumps at that time compared to ALT water, which is acidic due to sulfide oxidation in the ore zones (Figure 5-2 and Figure 5-3). As Deep Groundwater flow to the sumps decreases over time and ALT flow increases, the pH is predicted to increase. The result is an acidic chemistry even after mixing with near-neutral Mine Service water, Blowdown water, and Deep Groundwater.
- Figure 6-2: Sulfate shows patterns that are consistent with pH. The highest concentrations up to about 3800 mg/L are predicted for zone 8, which would be representative of ore moisture. Sulfate concentrations for the Upper Level Sump are lower at about 2200 to 2400 mg/L due to mixing with Deep Groundwater, Mine Service Water, and Blowdown water all of which have lower SO<sub>4</sub> concentrations compared to zone 8. Sulfate concentrations in zones 5 and 6are lower than for the sump or zones 7 and 8 because the rocks in the upper zones are not exposed to O<sub>2</sub> until later years.

A series of example charts for pH, SO<sub>4</sub>, Al, Fe, Cu, Zn, As, and Se are shown in the following set of figures. These results are for ore moisture, which is obtained from the model zone 8 results, and the Upper Level Sump, which is representative of water pumped to the process circuit at the West Plant.

• Figure 6-3 (pH). Predictions for pH show values for ore moisture starting at about 6.5 and then decreasing to 4.4 at about year 15 and then increasing slightly to 4.5. The small increase at year 15 is due to the switch from Panel 2 to Panel 5, which has





slightly lower release rates for acidic constituents than Panel 2. The pH values for the Upper Level Sump are greater than 6.0 for an initial period and then decrease to about 5.0. The pH values for the Upper Level Sump are a function of changes in mixing proportions of different water types entering the sump over time relative to the inflow of acidic ALT water from zone 8.

- Figure 6-4 (Sulfate). Sulfate concentrations are predicted to follow a similar pattern • as pH. Higher concentrations are predicted for ore moisture compared to the Upper Level Sump. The lower concentrations for the Upper Level Sump are a result of dilution by input of other water sources with lower SO<sub>4</sub> concentration to that sump. Solubility limits for anhydrite and gypsum are predicted to occur for both ore moisture and the Upper Level Sump, causing SO<sub>4</sub> concentrations to be lower than would be predicted in the absence of considering secondary precipitates. Solubility limits for alunite, jarosite/Fe(OH)<sub>3</sub>(a), and barite are also reached. These have a smaller controlling effect on SO<sub>4</sub> concentrations, but control the concentrations of Fe, Al, and Ba, respectively. Some solutions with the highest Cu, Pb, and SO<sub>4</sub> concentrations also reach the solubilities of copper and lead sulfates, depending on the pH.
- Figure 6-5 and Figure 6-6 (Fe and AI): Iron and AI concentrations show increases over the first 15 years as the pH slowly decreases. After 15 years, Fe and Al concentrations are predicted to decrease by a small amount as the pH increases slightly with the switch to Panel 5. Concentrations predicted for the Upper Level Sump are lower than for ore moisture due to its predicted higher pH caused by mixing with slightly alkaline Deep Groundwater, Mine Service Water, and Blowdown water. Solubility limits for alunite, jarosite/Fe(OH)<sub>3</sub>(a) are reached for most of time period of simulation resulting in Al and Fe concentrations that are lower then what would occur for conservative mixing.
- Figure 6-7 and Figure 6-8 (Cu and Zn): Predictions for Cu and Zn for ore moisture and the Upper Level Sump show increases over the first 15 years as Panel 2 is mined. After 15 years, the concentrations of Cu and Zn are predicted to decrease. The concentrations of Cu and Zn are functions of both the pH, which affects solubilities, and dilution; hence, their patterns are similar to AI, Fe, and SO<sub>4</sub>.
- Figure 6-9 and Figure 6-10 (As and Se): Predictions for As and Se show patterns that are generally similar to those predicted for SO<sub>4</sub>, Cu, and Zn. Concentrations for ore moisture and the Upper Level Sump increase up to year 15 and then decrease slightly or level out. Arsenic concentrations of about 0.3 to 0.4 mg/L are predicted for ore moisture and about 0.2 to 0.25 for the Upper Level Sump. Selenium concentrations are predicted to range up 3.3 mg/L for ore moisture and about 1.0 mg/L for the Upper Level Sump. There are no solubility controls for As and Se under the expected solution conditions. Also, adsorption is limited because much of the Fe is precipitated as jarosite(ss) under the predicted pH and high SO<sub>4</sub> concentrations rather than Fe(OH)<sub>3</sub>(am).







Figure 6-1. Predicted yearly mean pH values for zones 5-8 and the Upper Level Sump



Figure 6-2. Predicted yearly mean SO<sub>4</sub> concentrations for zones 5-8 and the Upper Level Sump







Figure 6-3. Predicted pH values for ore moisture and the Upper Level Sump



Figure 6-4. Predicted SO<sub>4</sub> concentrations for ore moisture and the Upper Level Sump







Figure 6-5. Predicted Fe concentrations for ore moisture and the Upper Level Sump



Figure 6-6. Predicted AI concentrations for ore moisture and the Upper Level Sump



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Figure 6-7. Predicted Cu concentrations for ore moisture and the Upper Level Sump



Figure 6-8. Predicted Zn concentrations for ore moisture and the Upper Level Sump







Figure 6-9. Predicted As concentrations for ore moisture and the Upper Level Sump



Figure 6-10. Predicted Se concentrations for ore moisture and the Upper Level Sump



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Parameter	рН	Са	Mg	Na	К	Cl	HCO₃	SO <sub>4</sub>	SiO <sub>2</sub>	F	NO <sub>3</sub> -N	Al	Sb	As	Ва	Ве	В	Cd	Cr	Со	Cu	Fe	Pb	Mn	Hg	Мо	Ni	Se	Ag	Tİ	Zn
Year	s.u.	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
1	6.67	512	86	144	41	27	11	1881	4.2	3.2	0.3	0.1	0.005	0.001	0.028	0.001	0.05	0.020	0.027	0.30	5	0.01	0.005	5.3	0.002	0.02584	0.3	0.1	0.071	0.002	0.3
2	5.17	614	99	149	44	36	0	2284	15.4	7.5	0.3	2.5	0.015	0.007	0.028	0.008	0.16	0.064	0.098	0.94	58	0.07	0.031	8.9	0.007	0.00018	0.9	0.4	0.215	0.004	2.7
3	4.91	606	111	154	50	45	0	2456	26.6	16.4	0.4	7.4	0.024	0.009	0.028	0.020	0.26	0.107	0.168	1.58	137	0.13	0.056	12.4	0.012	0.00008	1.5	0.7	0.358	0.006	5.1
4	4.77	598	124	159	57	54	0	2634	34.1	27.2	0.4	13.2	0.033	0.011	0.027	0.032	0.37	0.149	0.235	2.22	218	0.18	0.079	16.0	0.017	0.00005	2.1	0.9	0.497	0.008	7.6
5	4.69	592	137	163	63 70	63 72	0	2813	34.4	38.5	0.4	19.4 25.4	0.042	0.012	0.027	0.043	0.47	0.191	0.299	2.84	298	0.23	0.102	19.5	0.021	0.00004	2.7	1.2	0.528	0.011	11.5
7	4.03	581	140	108	76	80	0	3144	34.3	49.0 60.6	0.5	31.4	0.058	0.013	0.027	0.066	0.66	0.250	0.338	3.98	445	0.27	0.124	25.8	0.023	0.00004	3.8	1.4	0.496	0.015	19.8
8	4.54	576	135	172	81	87	0	3298	34.3	71.2	0.6	37.2	0.066	0.013	0.027	0.076	0.75	0.302	0.469	4.50	512	0.34	0.164	28.7	0.033	0.00003	4.3	1.9	0.486	0.016	24.0
9	4.52	573	179	179	86	94	0	3425	34.3	80.0	0.6	41.9	0.072	0.014	0.026	0.085	0.82	0.331	0.514	4.93	567	0.37	0.180	31.1	0.036	0.00003	4.7	2.1	0.480	0.018	27.6
10	4.50	571	187	182	82	100	0	3504	34.2	86.6	0.6	45.5	0.079	0.017	0.026	0.098	0.90	0.358	0.579	5.35	597	0.38	0.198	33.4	0.040	0.00003	5.1	2.2	0.474	0.020	29.6
11	4.49	570	196	185	76	107	0	3562	34.2	92.4	0.7	48.7	0.086	0.020	0.026	0.112	0.98	0.384	0.657	5.77	614	0.39	0.216	35.7	0.043	0.00003	5.5	2.4	0.468	0.021	30.8
12	4.49	569	205	189	70	114	0	3619	34.2	98.2	0.7	51.8	0.093	0.025	0.026	0.129	1.06	0.408	0.740	6.19	631	0.40	0.236	38.0	0.047	0.00003	5.9	2.6	0.464	0.023	32.0
13	4.48	569	213	193	65	122	0	3676	34.2	104.0	0.7	54.9	0.101	0.030	0.026	0.146	1.15	0.431	0.827	6.60	647	0.41	0.255	40.2	0.051	0.00003	6.3	2.8	0.460	0.025	33.1
14	4.48	568	221	196	61	129	0	3727	34.2	108.8	0.8	57.5	0.109	0.036	0.026	0.162	1.24	0.450	0.911	6.97	660	0.41	0.273	42.1	0.055	0.00003	6.7	3.0	0.458	0.027	34.0
15	4.47	568	229	200	58	137	0	3774	34.2	113.3	0.8	59.9	0.118	0.043	0.026	0.179	1.33	0.467	0.997	7.33	672	0.42	0.291	43.9	0.059	0.00003	7.0	3.2	0.456	0.029	34.9
10	4.48	569	235	203	59 67	143	0	3791	34.2	101.0	0.8	59.0	0.123	0.048	0.026	0.188	1.40	0.468	1.049	7.48	639	0.41	0.300	44.5	0.062	0.00003	7.2	3.3	0.454	0.030	34.0
18	4.50	570	237	204	76	148	0	3730	34.2	91.9	0.8	48.2	0.124	0.047	0.026	0.170	1.40	0.424	0.995	7.05	613	0.39	0.232	41.1	0.062	0.00003	6.8	3.1	0.453	0.030	30.7
19	4.51	571	236	204	86	148	0	3684	34.2	84.0	0.8	43.9	0.121	0.037	0.026	0.157	1.38	0.402	0.944	6.80	589	0.37	0.270	39.3	0.061	0.00003	6.5	2.9	0.453	0.030	29.1
20	4.52	572	234	203	95	148	0	3648	34.2	77.5	0.7	40.4	0.118	0.031	0.026	0.142	1.36	0.381	0.886	6.53	568	0.36	0.257	37.4	0.060	0.00003	6.3	2.8	0.453	0.029	27.7
21	4.53	572	232	201	104	146	0	3614	34.2	72.4	0.7	37.6	0.115	0.027	0.026	0.128	1.33	0.363	0.828	6.28	551	0.36	0.244	35.7	0.058	0.00003	6.1	2.6	0.453	0.028	26.6
22	4.53	573	230	198	112	145	0	3587	34.2	68.4	0.7	35.4	0.111	0.023	0.026	0.118	1.30	0.351	0.778	6.09	537	0.35	0.233	34.2	0.056	0.00003	5.9	2.5	0.453	0.027	25.6
23	4.54	574	228	195	120	144	0	3563	34.2	65.2	0.7	33.7	0.108	0.020	0.026	0.108	1.28	0.343	0.732	5.96	525	0.34	0.224	33.0	0.055	0.00003	5.7	2.4	0.453	0.027	24.9
24	4.55	574	225	191	127	142	0	3537	34.2	62.5	0.6	32.2	0.105	0.017	0.027	0.099	1.25	0.339	0.687	5.85	516	0.34	0.216	31.8	0.053	0.00003	5.6	2.3	0.453	0.026	24.3
25	4.55	575	223	187	132	140	0	3515	34.2	60.4	0.6	31.1	0.102	0.015	0.027	0.092	1.22	0.339	0.651	5.78	508	0.33	0.210	30.9	0.052	0.00003	5.5	2.1	0.453	0.025	23.7
26	4.56	576	220	182	133	138	0	3469	34.2	57.4	0.6	29.5	0.099	0.014	0.027	0.088	1.20	0.341	0.629	5.73	489	0.32	0.205	30.1	0.051	0.00003	5.5	2.0	0.453	0.025	22.6
27	4.57	580	210	170	133	137	0	3422	34.2	52.1	0.5	26.0	0.097	0.014	0.027	0.080	1.10	0.345	0.600	5.71	471	0.32	0.202	29.4	0.043	0.00003	5.4 5.4	1.9	0.453	0.024	21.4
29	4.59	582	210	1/0	132	133	0	3305	34.3	49.1	0.5	25.0	0.091	0.011	0.027	0.080	1.13	0.352	0.581	5.65	431	0.30	0.195	28.0	0.046	0.00004	5.3	1.7	0.454	0.022	18.9
30	4.60	585	206	155	127	129	0	3246	34.3	46.7	0.4	23.7	0.088	0.013	0.027	0.077	1.11	0.355	0.566	5.61	412	0.29	0.191	27.3	0.045	0.00004	5.3	1.6	0.454	0.022	17.8
31	4.61	587	202	147	125	127	0	3201	34.3	44.8	0.4	22.7	0.085	0.012	0.027	0.075	1.10	0.360	0.554	5.60	399	0.28	0.189	26.8	0.044	0.00004	5.3	1.5	0.454	0.021	17.0
32	4.62	588	201	142	125	126	0	3177	34.3	43.9	0.4	22.2	0.084	0.012	0.027	0.075	1.09	0.366	0.548	5.64	392	0.28	0.188	26.7	0.043	0.00004	5.3	1.5	0.454	0.021	16.6
33	4.62	589	201	136	126	126	0	3162	34.3	43.3	0.3	21.9	0.083	0.012	0.027	0.074	1.09	0.374	0.546	5.70	389	0.27	0.189	26.7	0.043	0.00004	5.3	1.4	0.454	0.021	16.4
34	4.62	590	201	132	127	127	0	3158	34.3	43.2	0.3	21.8	0.083	0.012	0.027	0.075	1.10	0.383	0.547	5.78	389	0.27	0.190	26.8	0.043	0.00004	5.4	1.4	0.454	0.021	16.4
35	4.62	590	202	127	128	127	0	3152	34.3	43.0	0.3	21.7	0.082	0.011	0.027	0.075	1.10	0.392	0.548	5.87	389	0.27	0.192	26.9	0.042	0.00004	5.5	1.4	0.454	0.020	16.4
36	4.62	591	201	122	128	127	0	3139	34.3	42.7	0.3	21.6	0.082	0.011	0.027	0.075	1.11	0.400	0.548	5.94	387	0.27	0.193	27.0	0.042	0.00004	5.5	1.3	0.454	0.020	16.3
3/	4.62	591	203	118	129	128	0	3145	34.3	43.1	0.3	21.7	0.082	0.011	0.027	0.076	1.12	0.410	0.552	6.05	300	0.28	0.195	27.3	0.042	0.00004	5.0	1.3	0.453	0.020	16.5
39	4.60	590	200	110	132	130	0	3195	34.3	43.8	0.2	22.2	0.083	0.011	0.027	0.080	1.15	0.422	0.570	6.35	409	0.28	0.203	27.7	0.043	0.00004	5.9	1.3	0.453	0.021	17.5
40	4.60	590	214	112	140	136	0	3229	34.3	46.1	0.2	23.4	0.085	0.011	0.027	0.082	1.18	0.449	0.582	6.53	420	0.29	0.208	28.9	0.044	0.00004	6.0	1.3	0.452	0.021	18.2
41	4.59	589	219	111	144	139	0	3268	34.3	47.5	0.2	24.1	0.087	0.011	0.027	0.085	1.21	0.463	0.596	6.72	433	0.30	0.214	29.7	0.045	0.00003	6.2	1.3	0.452	0.022	18.9
42	4.58	588	225	110	148	143	0	3312	34.3	49.0	0.2	24.9	0.089	0.011	0.027	0.088	1.24	0.479	0.611	6.92	448	0.30	0.220	30.4	0.046	0.00003	6.4	1.3	0.451	0.022	19.8
43	4.57	586	231	109	153	147	0	3360	34.3	50.7	0.2	25.8	0.091	0.011	0.027	0.091	1.27	0.495	0.626	7.13	463	0.31	0.226	31.3	0.047	0.00003	6.6	1.4	0.451	0.023	20.7
44	4.56	585	238	109	158	151	0	3411	34.3	52.5	0.2	26.8	0.093	0.011	0.027	0.094	1.31	0.512	0.643	7.36	479	0.32	0.233	32.1	0.048	0.00003	6.8	1.4	0.451	0.023	21.7
45	4.56	584	244	109	160	155	0	3452	34.2	53.6	0.2	27.4	0.095	0.012	0.027	0.100	1.35	0.529	0.672	7.59	489	0.32	0.241	33.1	0.050	0.00003	7.0	1.4	0.451	0.024	22.4







## Table 6-2. Predicted mean annual concentrations for the Upper Level Sump

Parameter	рН	Са	Mg	Na	K	Cl	HCO <sub>3</sub>	SO <sub>4</sub>	SiO2	HCO <sub>3</sub>	SO <sub>4</sub>	Al	Sb	As	Ва	Ве	В	Cd	Cr	Со	Cu	Fe	Pb	Mn	Hg	Мо	Ni	Se	Ag	Tİ	Zn
Year	s.u.	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
1	6.87	309	78	149	37	26	5	1364	1.4	2.7	0.6	0.004	0.001	0.006	0.019	0.000	0.00	0.002	0.002	0.02	0.1	0.00	0.001	3.5	0.000	0.00202	0.02	0.01	0.008	0.001	0.02
2	6.90	342	85	163	40	28	4	1504	1.9	2.9	0.6	0.004	0.002	0.006	0.021	0.000	0.01	0.004	0.006	0.05	0.2	0.00	0.002	4.0	0.001	0.000016	0.1	0.02	0.016	0.001	0.02
3	6.90	345	88	174	41	32	4	1540	3.5	2.9	0.8	0.004	0.002	0.006	0.021	0.001	0.01	0.006	0.010	0.08	0.4	0.00	0.004	4.2	0.001	0.000005	0.1	0.04	0.023	0.001	0.01
4	7.07	354	92	190	43	30	/	1604	4.0	2.9	1.1	0.006	0.002	0.006	0.021	0.001	0.01	0.004	0.006	0.05	0.3	0.00	0.003	4.2	0.001	0.000001	0.1	0.02	0.017	0.001	0.01
6	5.84	303	103	203	43	41	1	1807	6.4	4.3	1.1	0.004	0.002	0.011	0.021	0.001	0.01	0.020	0.008	0.29	18	0.00	0.004	4.4 5.8	0.001	0.000001	0.1	0.03	0.018	0.001	1.5
7	7.03	390	103	217	48	42	10	1793	4.9	3.2	1.3	0.2	0.002	0.009	0.020	0.001	0.01	0.005	0.007	0.06	4	0.01	0.003	4.6	0.001	0.000001	0.1	0.03	0.014	0.001	0.3
8	5.74	408	110	215	51	46	2	1922	7.3	5.9	1.2	1.7	0.007	0.012	0.020	0.007	0.07	0.029	0.045	0.42	34	0.04	0.017	6.6	0.004	0.000003	0.4	0.18	0.051	0.002	2.5
9	5.38	413	112	216	52	48	0	1969	8.0	7.3	1.2	2.4	0.009	0.013	0.020	0.010	0.09	0.038	0.059	0.56	48	0.05	0.022	7.4	0.005	0.000003	0.5	0.23	0.060	0.003	3.4
10	5.35	415	114	218	52	49	0	1995	8.3	8.1	1.3	2.9	0.010	0.013	0.020	0.012	0.11	0.043	0.070	0.64	55	0.05	0.025	7.9	0.005	0.000003	0.6	0.27	0.063	0.003	3.9
11	5.30	417	117	218	52	51	0	2024	8.6	9.3	1.3	3.5	0.012	0.014	0.020	0.015	0.13	0.051	0.087	0.76	63	0.06	0.030	8.5	0.006	0.000004	0.7	0.32	0.068	0.003	4.4
12	5.28	417	118	219	51	52	0	2038	8.7 9.4	9.9	1.3	3.8 5.0	0.013	0.015	0.020	0.017	0.14	0.055	0.099	0.83	67 80	0.06	0.033	8.9 9.8	0.007	0.000004	0.8	0.35	0.068	0.004	4.0
14	5.13	427	121	220	50	59	0	2164	10.5	16.7	1.3	7.6	0.022	0.017	0.020	0.022	0.17	0.087	0.125	1.34	108	0.07	0.040	11.7	0.000	0.000004	1.3	0.43	0.094	0.004	6.9
15	5.17	424	126	222	49	59	0	2132	9.9	14.5	1.3	6.3	0.021	0.018	0.020	0.030	0.22	0.079	0.166	1.23	95	0.08	0.050	11.1	0.010	0.000005	1.2	0.54	0.082	0.005	6.2
16	5.04	439	139	221	50	68	0	2299	12.3	24.0	1.3	11.6	0.032	0.022	0.020	0.048	0.35	0.120	0.267	1.91	147	0.11	0.077	14.7	0.016	0.000007	1.8	0.84	0.120	0.008	9.1
17	5.02	445	143	222	53	72	0	2339	13.1	24.5	1.3	11.9	0.035	0.023	0.020	0.051	0.39	0.125	0.288	2.04	153	0.11	0.083	15.2	0.018	0.000008	2.0	0.89	0.131	0.009	9.4
18	5.02	448	145	222	56	74	0	2355	13.5	23.7	1.2	11.4	0.037	0.022	0.020	0.050	0.41	0.125	0.291	2.06	152	0.11	0.084	15.2	0.018	0.000008	2.0	0.90	0.136	0.009	9.3
19	5.02	452	147	222	59	76	0	2377	14.0	23.3	1.2	11.2	0.038	0.021	0.020	0.049	0.42	0.125	0.293	2.10	154	0.11	0.085	15.2	0.019	0.000009	2.0	0.91	0.143	0.010	9.3
20	5.04	453	146	222	62	75	0	2364	13.9	21.4	1.2	10.2	0.037	0.019	0.020	0.044	0.41	0.117	0.273	2.00	146	0.10	0.080	14.6	0.019	0.000009	1.9	0.85	0.142	0.009	8.7
21	5.05	454	143	222	67	73	0	2339	14.0	18.1	1.2	9.5 8.4	0.030	0.018	0.020	0.040	0.41	0.112	0.230	1.93	141	0.10	0.070	13.2	0.018	0.000009	1.9	0.81	0.143	0.003	
23	5.05	458	146	220	71	76	0	2371	14.4	19.3	1.2	9.0	0.036	0.016	0.020	0.035	0.41	0.110	0.237	1.91	130	0.10	0.073	13.7	0.018	0.000010	1.8	0.77	0.149	0.009	8.2
24	5.06	458	145	219	74	75	0	2363	14.4	18.5	1.2	8.6	0.034	0.015	0.020	0.032	0.40	0.109	0.222	1.87	137	0.10	0.070	13.3	0.017	0.000010	1.8	0.72	0.149	0.009	8.0
25	5.07	458	144	218	75	75	0	2350	14.3	17.6	1.2	8.1	0.033	0.014	0.020	0.030	0.39	0.107	0.207	1.82	132	0.10	0.067	12.9	0.017	0.000010	1.7	0.68	0.147	0.008	7.7
26	5.05	465	147	215	79	77	0	2391	15.3	18.8	1.2	8.8	0.035	0.014	0.020	0.031	0.42	0.119	0.220	1.99	142	0.10	0.073	13.4	0.018	0.000011	1.9	0.71	0.161	0.009	8.2
27	5.10	459	142	216	75	73	0	2319	14.2	15.6	1.2	7.0	0.031	0.014	0.020	0.027	0.37	0.107	0.191	1.77	120	0.09	0.064	12.2	0.016	0.000010	1.7	0.60	0.144	0.008	6.9
28	5.04	472	149	209	81	79	0	2409	16.2	18.6	1.1	8.7	0.037	0.014	0.020	0.032	0.44	0.133	0.229	2.16	144	0.10	0.077	13.8	0.019	0.000013	2.1	0.70	0.166	0.009	8.0
30	5.07	474	147	207	80	78	0	2392	16.5	16.9	1.1	7.7	0.035	0.014	0.020	0.031	0.44	0.133	0.223	2.17	133	0.10	0.075	13.0	0.018	0.000013	2.1	0.64	0.171	0.009	7.0
31	5.11	470	141	204	76	74	0	2313	15.5	14.5	1.1	6.4	0.031	0.013	0.020	0.027	0.39	0.126	0.196	1.97	116	0.09	0.068	12.4	0.016	0.000013	1.9	0.55	0.162	0.008	6.2
32	5.16	464	137	205	73	71	0	2258	14.4	12.5	1.1	5.3	0.027	0.013	0.020	0.024	0.34	0.115	0.173	1.77	100	0.08	0.060	11.5	0.014	0.000012	1.7	0.47	0.147	0.007	5.5
33	5.16	464	137	204	73	70	0	2251	14.3	12.3	1.1	5.2	0.027	0.013	0.020	0.024	0.34	0.117	0.171	1.78	98	0.08	0.060	11.4	0.014	0.000011	1.7	0.45	0.146	0.007	5.4
34	5.22	456	133	207	70	67	0	2195	13.1	10.3	1.2	4.1	0.023	0.013	0.020	0.020	0.29	0.103	0.147	1.55	82	0.07	0.052	10.5	0.012	0.000010	1.4	0.38	0.126	0.006	4.7
35	5.15	467	139	199	75	72	0	2266	14.7	12.8	1.1	5.5	0.028	0.013	0.020	0.025	0.36	0.128	0.179	1.91	103	0.08	0.064	11.8	0.014	0.000012	1.8	0.45	0.152	0.007	5.6
36	5.18	463	136	201	/3	/0	0	2232	14.1	11.6	1.1	4.8	0.026	0.013	0.020	0.023	0.33	0.120	0.166	1.79	93	0.07	0.059	11.3	0.013	0.000011	1./	0.41	0.141	0.007	5.2
37	5.18	454	134	194	72	69	0	2187	13.7	11.9	1.1	5.0	0.025	0.013	0.020	0.023	0.33	0.122	0.165	1.80	93	0.07	0.059	11.2	0.013	0.000011	1.7	0.39	0.139	0.008	5.1
39	5.14	442	133	181	74	70	0	2151	14.1	14.1	1.0	6.2	0.027	0.012	0.020	0.024	0.37	0.138	0.182	2.02	105	0.08	0.065	11.5	0.014	0.000011	1.9	0.42	0.148	0.007	5.8
40	5.12	436	134	177	75	72	0	2143	14.6	15.2	1.0	6.8	0.029	0.012	0.020	0.027	0.39	0.147	0.191	2.13	111	0.09	0.069	12.1	0.015	0.000012	2.0	0.43	0.152	0.007	6.1
41	5.10	430	135	174	77	74	0	2136	15.2	16.7	1.0	7.6	0.030	0.012	0.020	0.029	0.41	0.157	0.202	2.27	119	0.09	0.073	12.5	0.016	0.000012	2.1	0.45	0.157	0.008	6.6
42	5.07	433	139	174	80	79	0	2182	16.4	18.4	1.1	8.5	0.033	0.012	0.020	0.032	0.45	0.173	0.222	2.50	131	0.10	0.081	13.4	0.017	0.000012	2.3	0.49	0.167	0.008	7.3
43	5.05	437	144	176	84	83	0	2228	17.1	19.5	1.2	9.2	0.035	0.012	0.020	0.034	0.48	0.185	0.235	2.66	140	0.10	0.086	14.0	0.018	0.000013	2.5	0.51	0.167	0.009	7.9
44	5.04	436	146	179	85	84	0	2244	17.2	19.9	1.2	9.4	0.035	0.012	0.020	0.035	0.48	0.189	0.238	2.71	142	0.10	0.087	14.2	0.018	0.000012	2.5	0.51	0.166	0.009	8.2
45	5.05	434	147	181	85	85	0	2247	17.0	19.9	1.3	9.3	0.035	0.013	0.020	0.036	0.48	0.190	0.241	2.72	141	0.10	0.088	14.2	0.018	0.000012	2.5	0.50	0.165	0.009	8.2





## 6.2 Sensitivities

The model contains several key input parameters. The sensitivity of predictions of water chemistry for the Upper Level Sump to these parameters was examined by varying the parameters over ranges expected to encompass reasonable outer bounds and observing the responses in the predictions. The key parameters included in the sensitivity analysis were:

- Oxidized thickness
  - Base case = 2 m
  - Minimum = 1 m
  - Maximum = 4 m
- Temperature effect
  - Base case = 100%
  - Minimum = 50%
  - Maximum = 200%
- Water balance
  - Base case = expected inflow rates for Deep Groundwater and ALT
  - Deep Groundwater Minimum = Deep Groundwater inflow rate at 50% of expected rate and no change to ALT inflow
  - Deep Groundwater Maximum = Deep Groundwater inflow rate at 200% of expected rate and no change to ALT inflow
  - ALT Minimum = ALT inflow rate at 50% of expected rate and no change to Deep Groundwater inflow
  - ALT Maximum = ALT inflow rate at 200% of expected rate and no change to Deep Groundwater inflow
- A combination of the above factors designed to create a Maximum Reasonable worst case water chemistry

The sensitivity analysis was mostly focused on the effects to pH and SO<sub>4</sub> because these are the two primary indicators of water quality of the Upper Level Sump in the block cave model.

#### 6.2.1 Oxidized thickness

The sensitivity to the oxidized thickness is shown in Figure 6-11. The oxidized thickness is the depth to which  $O_2$  is predicted to penetrate before being consumed by reactions with sulfide minerals. The predicted depth is 2 m (Figure 5-14), which represents the Base Case. Simulations were run at 1 m and 4 m to assess the sensitivity to the oxidized thickness.

The pH is predicted to be about 0.2 to 0.3 units higher for the 1 m case and 0.2 units lower for the 4 m case when compared to the expected thickness of 2 m for the Base Case (Figure 6-11). The degree of sensitivity of pH to oxidized thickness is controlled of pH by equilibrium



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with the solubility of iron and aluminum minerals  $(Fe(OH)_3(am)/jarosite(ss))$  and  $Al(OH)_3/alunite)$ .

The sensitivity of SO<sub>4</sub> concentrations to the oxidized thickness is also shown in Figure 6-11. The SO<sub>4</sub> concentration is sensitive to the O<sub>2</sub> penetration depth because the mass of SO<sub>4</sub> release is proportional to the mass of rock exposed to O<sub>2</sub>. A decrease in the thickness to 1 m results in about a 6% lower concentration of SO<sub>4</sub> at 15 years compared to the Base Case. An increase to 4 m is predicted to result in about a 10 to 11% increase at 15 years compared to the Base Case. The response is not a strictly linear function of the oxidized thickness because SO<sub>4</sub> concentrations are also affected by the solubilities of SO<sub>4</sub> minerals (anhydrite, gypsum, jarosite(ss) and alunite).



Figure 6-11. Sensitivity pH and SO4 at the Upper Level Sump to the oxidized thickness

## 6.2.2 Temperature effect

The effect of temperature on leaching rates is a key scaling parameter in the model. These scaling factors are given in Table 5-8. To examine the sensitivity of model predictions of pH and SO<sub>4</sub> concentration on these factors, they were collectively multiplied by a percentage amount expected to cover the range of probable variability. These percentage factors were 100%, that is, no changes to the values in Table 5-8, which provides Base Case. The minimum case was a factor of 50%, that is, the values in Table 5-8 were multiplied by 50% for all constituents. The maximum case was 200%, where the values in Table 5-8 were doubled.





The results are shown in Figure 6-12. The magnitude of the sensitivity is the same as for the oxidized thickness in that leaching rates are linearly dependent on both the temperature scaling factor and oxidized thickness. A decrease by the 50% factor results in an increase in pH by about 0.2 to 0.3 units and about a 6% decrease in SO<sub>4</sub> at 15 years compared to the Base Case. An increase to a factor of 200% is predicted to result in decrease in pH of about 0.2 units and about a 10 to 11% increase in SO<sub>4</sub> concentration at 15 years compared to the Base Case.



Figure 6-12. Sensitivity of pH and SO<sub>4</sub> at the Upper Level Sump to the temperature scaling factor

#### 6.2.3 Water Balance

#### 6.2.3.1 Deep Groundwater Inflow

The sensitivity of the chemistry predictions to inflow rates from Deep Groundwater are shown for pH and SO<sub>4</sub> in Figure 6-13 and Cu in Figure 6-15. The sensitivity analyses indicate that the pH is not strongly sensitive to Deep Groundwater inflow (Figure 6-13) because of solubility controls that buffer the pH to the 4.9 to 5.1 range. The concentrations of SO<sub>4</sub> (Figure 6-13) and Cu (Figure 6-14) show limited sensitivity to Deep Groundwater with concentrations lower for higher inflow rates and lower concentrations for lower inflow rates due to dilution, although the relationships are not linear because SO<sub>4</sub> and Cu concentrations are also affected by calcium sulfate (gypsum and anhydrite) and Cu sulfate solubility. The Deep Groundwater enters the Lower Level Sump with generally lower concentrations that





those predicted for ALT inflow; hence, Deep Groundwater has primarily a dilution effect on concentrations in the sumps (Figure 5-1).



Figure 6-13. Sensitivity of pH and SO<sub>4</sub> at the Upper Level Sump to inflow from Deep Groundwater



Figure 6-14. Sensitivity of Cu at the Upper Level Sump to inflow from Deep Groundwater





# 6.2.3.2 Apache Leap Tuff Inflow

The sensitivity of the chemistry predictions to inflow rates from ALT are shown for pH and SO<sub>4</sub> in Figure 6-15 and Cu in Figure 6-15. The ALT flow is the primary recipient of acid generation reactions expected to occur in the block cave due to sulfide oxidation; hence changes to its flow rate affects both the mixing proportions of acidic and non-acidic solutions in the sumps and the rates of chemical transfers to the sumps. Figure 6-15 shows that a decrease in ALT flow to 50% of the expected value results in a longer initial time period of near-neutral pH, but eventually the pH decreases to values approximating the Base Case. This result is a combined effect of the decreased inflow from the Deep Groundwater and increase in flow from the ALT, which over time produce an acidic composition for the sumps. An increase of 200% of the ALT flow decreases the initial time period of near neutral pH, but over time, the pH is predicted to be approximately the same as predicted for the Base Case. Sulfate concentrations do not show much sensitivity to the ALT inflow rate (Figure 6-15) due to solubility control by gypsum and anhydrite in the model zones through which the ALT is conceptually routed to the sumps.

Copper concentrations show a more complex sensitivity to ALT inflow (Figure 6-16). At the lower bound of 50% of expected ALT flow, Cu concentrations are predicted to be less than the Base Case as expected for less flow of acidic water entering the sumps. At the upper bound of 200% of expected ALT flow, Cu concentrations are initial greater due to more acidic water entering the sump. But, after about year 15, Cu concentrations decrease to less than the Base Case. This result is due to the increase in SO<sub>4</sub> entering the sumps that accompanies the increased ALT flow, which shifts the solubility of Cu sulfates to result in lower Cu concentrations under equilibrium conditions.



Figure 6-15. Sensitivity pH and SO4 at the Upper Level Sump to inflow from the ALT







Figure 6-16. Sensitivity of Cu at the Upper Level Sump to inflow from the ALT

#### 6.2.4 Maximum Reasonable Worst Case Chemistry

An additional simulation was made to include values of each of the sensitivity parameters that expected to produce the poorest water quality. These are:

- Oxidized thickness = 4 m
- Temperature effect factor = 200%
- Deep Groundwater inflow equal to 50% of expected rate
- ALT inflow equal to 200% of the expected rate

Example results for predictions of water chemistry parameters for the Upper Level Sump from this simulation are shown in Figure 6-17 and Figure 6-18. For the Maximum Reasonable worst case conditions, the pH is predicted to decrease sooner and more rapidly and ultimately reach lower pH values in the range of 4.5 to 4.7 compared to about 5.0 for the Base Case conditions (Figure 6-17). The SO<sub>4</sub> concentrations are predicted reach over 4000 mg/L for the Maximum Reasonable worst case, which are about 1000 to 1500 mg/L higher than the more realistic Base Case (Figure 6-17).

Predictions for Cu and Se also indicate much higher concentrations for the Maximum Reasonable worst case compared to the more realistic Base Case. Copper concentrations are about 200 to 500 mg/L higher for the Maximum Reasonable worst case conditions compared to the Base Case (Figure 6-18). Selenium concentrations are from 1 to 5 mg/L higher for the Maximum Reasonable worst case conditions compared to the Base Case (Figure 6-18).







Figure 6-17. Simulations of pH and SO<sub>4</sub> for the Upper Level Sump for Maximum Reasonable worst case conditions



Figure 6-18. Simulations of Cu and Se for the Upper Level Sump for Maximum Reasonable worst case conditions



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# 7. Limitations of Water Quality Predictions

The predictions of water chemistry provided in this report are based on information available at the time of development of the input data and modeling approach and are focussed on the period of time covering the operational mine life. While this information is thought to provide a reasonable depiction of geochemical processes and effects on water chemistry, ongoing and future studies that will be completed through the development of the Environmental Impact Statement (EIS) will likely result in refinements of many aspects of the project.







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