FIGURES

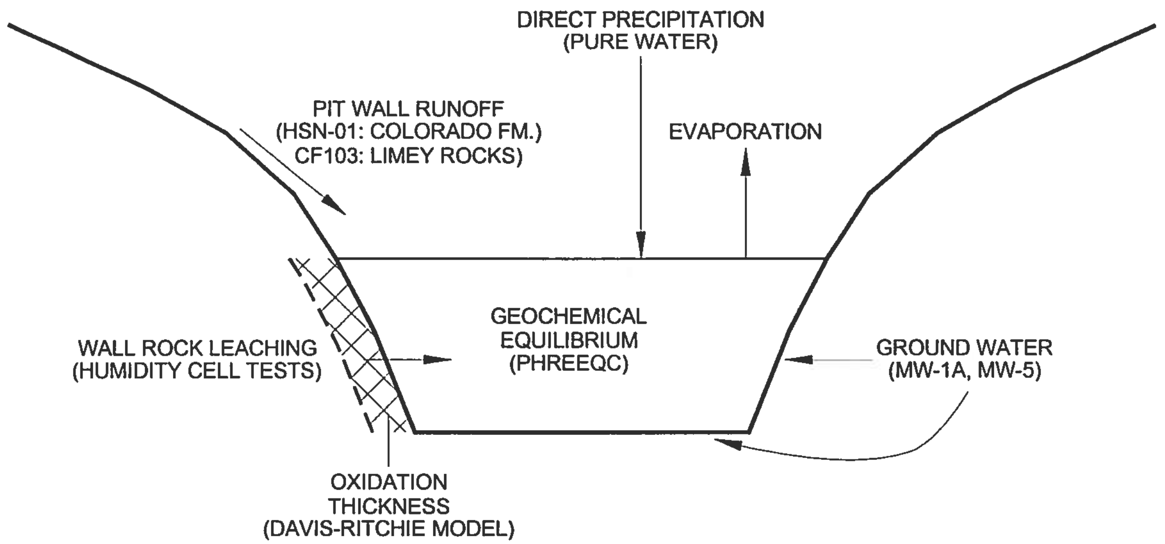

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FIGURE H-1
CONTINENTAL PIT LAKE
CONCEPTUAL MODEL

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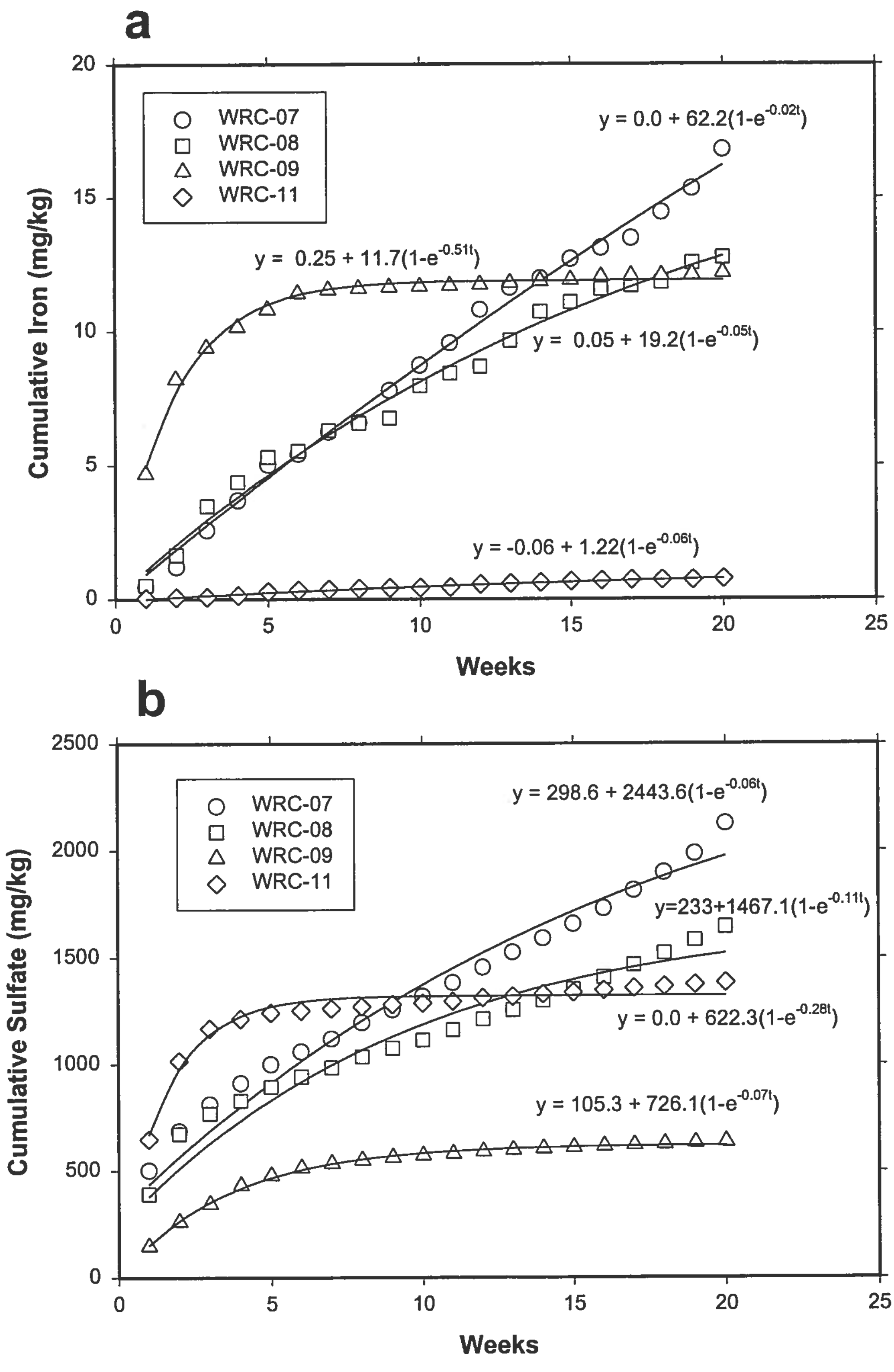

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FIGURE H-2
Examples of Fits (lines) to Cumulative Amounts of (a) Iron and (b) Sulfate Measured (symbols) in Humidity Cell Tests.

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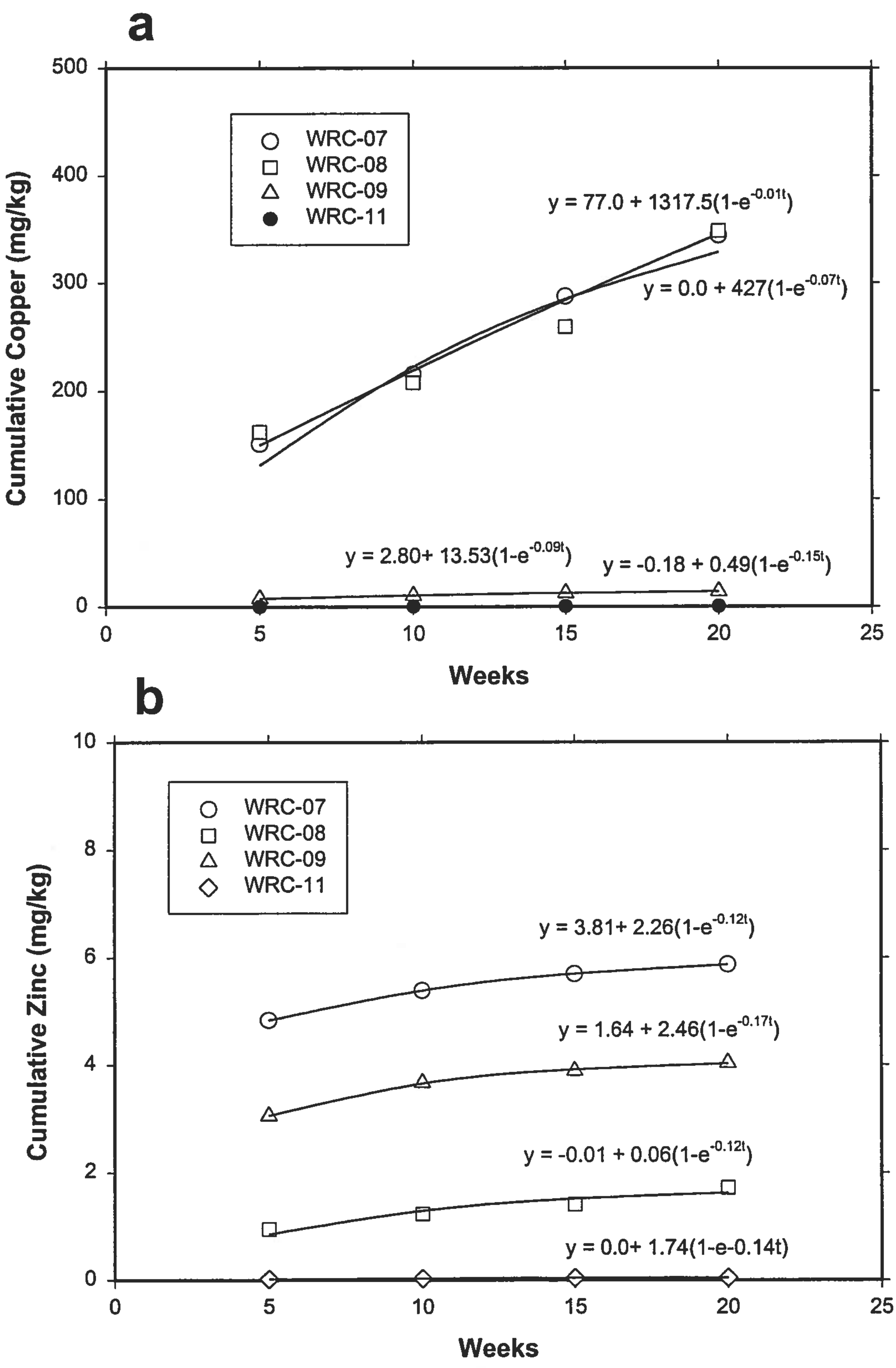

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FIGURE H-3

Examples of Fits (lines) to Cumulative Amounts of (a) Copper and (b) Zinc Measured (symbols) in Humidity Cell Tests.

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TABLES

Table H-1 Summary of the Water Balance for the Hanover Pit Lake

Time (years)	Depth (ft)	Volume (Mgal)	Flow Rate (gpm)				
			Ground Water	Pitwall Runoff	Precipitation	Evaporation	Net
1	47	24.8	32.5	13.5	4.4	10.1	40.3
5	118	76.3	28.8	11.3	19.0	44.1	15.0
10	150	111	27.3	10.3	25.5	59.2	3.9
15	154	117	26.9	10.0	27.1	63.1	0.9
20	155	119	26.8	10.0	27.6	64.1	0.3
30	155.9	119.6	26.8	10.0	27.7	64.5	0
50	155.9	119.6	26.8	10.0	27.7	64.5	0

Table H-2 Summary of Data and Methods Used to Represent Hydrogeochemical Processes in the Pit Lake Model

Factor	Source of Chemical Composition Data	Chemical Representation in Pit Lake Model	Inflow Rate
Ground Water Inflow	MW-1A	Average of monitoring well data for MW-1A	Based on hydrologic model
Pit Wall Runoff	MWMP Tests	Average of results for Colorado Leach Cap, Unoxidized Colorado Formation, and Barringer Fault Zone rocks proportioned to the surfaces areas of these rock types in the pit wall.	Based on hydrologic model
Direct Precipitation	Gila Cliff Dwelling Monitoring Station	Direct addition of water to pit lake	Based on hydrologic model
Evaporation	Distilled Water	Direct subtraction of water from pit lake	Based on hydrologic model
Wallrock Leaching	HCT Results	Average of results for oxidized Colorado Formation, Unoxidized Colorado Formation, and Barringer Fault Zone in terms of release rates per kg of rock	Proportioned to time of exposure and iron sulfide oxidation (Davis-Ritchie Model) and wall rock surface area.
Equilibrium Processes	NA	PHREEQC equilibration of pit lake chemical composition, assuming complete mixing	NA

NA – Not applicable

Table H-3 Water Quality Data Used to Represent the Chemical Composition of Ground Water Inflow for the Pit Lake Model and Precipitation Chemistry

		Monitoring Well Concentrations (mg/L)						
	Precip.	MW-1	MW-1A					Average
Constituent	Chem.	2/28/96	2/28/96	1/23/97	4/14/97	7/3/97	10/17/97	Groundwater
Aluminum	-	<0.05	<0.05	<0.021	<0.05	<0.05	<0.05	0.024
Antimony	-	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.025
Arsenic	-	<0.005	<0.05	<0.002	<0.005	<0.005	<0.005	0.0046
Bicarbonate	-	120	360	301	343	372	66	204
Cadmium	-	<0.005	<0.005	<0.0001	<0.001	<0.001	<0.001	0.0017
Calcium	0.16	2.8	95	104	100	97.5	104	51
Chloride	0.13	1.0	28	28.8	26.4	27	59	17
Chromium	-	<0.005	<0.005	<0.005	<0.01	<0.01	<0.01	0.0033
Cobalt	-	<0.005	<0.005	<0.01	<0.01	<0.01	<0.01	0.0035
Copper	-	<0.005	<0.005	<0.003	<0.01	<0.01	<0.01	0.0032
Fluoride	-	1.4	<0.5	<0.5	<0.5	<0.5	<0.5	0.83
Iron	-	<0.01	0.26	0.71	0.35	0.79	0.56	0.27
Lead	-	<0.05	<0.05	<0.001	<0.005	<0.005	<0.005	0.016
Magnesium	0.021	0.08	49	57.3	53.7	51.5	56.8	27
Manganese	-	<0.005	0.38	0.47	0.47	0.568	0.543	0.24
Mercury	-	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.00005
Molybdenum	-	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	0.0025
Nickel	-	<0.02	<0.02	<0.017	<0.01	<0.01	<0.01	0.0084
Nitrate (as N)	0.88	0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.025
Potassium	0.022	1.4	4.2	4.34	4.35	3.9	3	3
Selenium	-	<0.05	<0.05	<0.04	<0.005	<0.005	<0.005	0.018
Silicon	-	4.9	9.3	9.3	9.3	9.3	9.3	7.1
Sodium	0.098	65	28	31.3	30.4	27.9	29.6	47
Sulfate	0.88	18	160	201	188	183	181	153
Zinc	-	<0.005	0.014	0.006	<0.025	<0.02	<0.025	0.007
pH	4.8	9.28	7.27	7.51	7.4	6.86	7.26	7.52
Temperature (C)	-	13.4	14.9	14.9	14.9	14.9	14.9	14.2
Charge-Balance (%)[1]	-15.0	7.06	3.23	8.99	4.92	5.44	31.17	-

1- 100*(Cations - |Anions|)/(Cations + |Anions|))

Table H-4 Leachate Compositions from MWMP Tests Used to Define a Mixed Composition for Representation of Pit Wall Runoff in the Pit Lake Model

	Concentration (mg/L)			
	Unoxidized Colorado Formation	Colorado Formation Leach Cap	Barringer Fault Zone	Mixed Composition*
Portion of Pit Wall Area	89%	8%	3%	-
MWMP Test Number	WRC-07	WRC-09	WRC-09	-
Aluminum	59.4	37	37	57
Antimony	<0.002	<0.002	<0.002	0.001
Arsenic	<0.04	<0.04	<0.04	0.020
Barium	0.026	0.051	0.051	0.029
Beryllium	0.002	<0.002	<0.002	0.0019
Bicarbonate	<1	<1	<1	0
Cadmium	0.004	0.002	0.002	0.0038
Calcium	5.99	7.27	7.27	6
Chloride	4	16.8	16.8	5
Chromium	0.016	0.011	0.011	0.015
Cobalt	2.5	0.234	0.234	2.22
Copper	175	11.3	11.3	157
Fluoride	<0.5	<0.5	<0.5	0.25
Iron	13.6	5.6	5.6	12.73
Lead	<0.010	<0.001	<0.001	0.0045
Magnesium	2.66	2.15	2.15	2.61
Manganese	0.268	0.171	0.171	0.26
Mercury	<0.0002	<0.0002	<0.0002	0.0001
Molybdenum	0.006	<0.003	<0.003	0.0055
Nickel	0.627	0.069	0.069	0.57
Phosphorous	3.86	0.22	0.22	3.46
Potassium	6.5	14.8	14.8	7
Selenium	<0.048	<0.048	<0.048	0.024
Silicon	2.67	8.99	8.99	1.57
Silver	<0.005	<0.005	<0.005	0.0025
Sodium	4.63	9.89	9.89	5.21
Sulfate	681	263	263	606
Thallium	<0.001	<0.001	<0.001	0.0005
Zinc	5.25	1.84	1.84	4.88
pH	4.08	3.66	3.66	4.03

* Mixing calculations performed with PHREEQC using percentages of pit wall surface area.

Table H-5 Values of Parameters Input to the Davis-Ritchie Model of Sulfide Oxidation

Parameter	Value	Source
Sulfide-Sulfur Content	1.29%	ABA Data
Rock Specific Gravity	2.52 g/cm^3	Estimated
Rock Porosity	5%	Estimated
Rock Moisture Content	3%	Estimated
Coefficient for Oxygen Diffusion through into Sulfidic Rock	2.7 x 10^{-11} m^2/s	Braun and others, 1974
Coefficient for Oxygen Diffusion through Water-Filled Pore Spaces	2.4 x 10^{-7} m^2/s	Braun and others, 1974

Table H-6 Results of the Davis-Ritchie Modeling as Thickness and Mass of Oxidized Wallrock as a Function of Time

Time (years)	Oxidized Zone Thickness (m)	Pit Wall Surface Area (m^2)	Oxidized Mass (kg)
1	0.26	4159	2,717,670
5	0.30	3860	2,904,020
10	0.35	1984	1,726,590
20	0.43	248	270,098
30	0.51	33	42,693

Table H-7 Release Rates of Constituents from Leaching of Wall Rock Calculated from the Results of Humidity Cell Test

	Colorado Unoxidized (89%) (mg/kg)				Leach Cap (8%) (mg/kg)	Barringer Fault (3%) (mg/kg)		Release Rate (mg/kg)
Test	WRC-07	WRC-08	WRC99-2	WRC99-3	WRC-09	WRC-11	WRC99-1	-
Humidity Cell	HC-7	HC-8	HC-13	HC-14	HC-9	HC-10	HC-12	-
Aluminum	22.5	12.0	10.0	47.9	31.2	0.14	3.8	45.3
Antimony	0.0035	0.0045	0.011	0.0035	0.0055	0.0055	0.0055	0.010
Arsenic	0.02	0.02	0.02	0.02	0.02	0.02	<0.04	0.020
Barium	0.99	0.96	0.09	0.06	4.73	0.85	0.09	1.29
Beryllium	0.001	0.001	0.031	0.001	0.001	0.001	0.014	0.028
Alkalinity	0	0	0	0	0	422.7	712.4	13.95
Cadmium	0.0212	0.001	0.001	0.001	0.001	0.001	0.001	0.019
Calcium	64.6	396.7	54	25.3	13.3	1159.7	120.8	392.4
Chloride	20.6	8.3	2.6	7.6	15.3	5.6	9.8	19.90
Chromium	0.004	0.004	0.025	0.0165	0.0205	0.004	0.017	0.024
Cobalt	3.85	1.07	0.26	0.28	0.05	0.013	0.12	3.43
Copper	1395	427	4.23	11.4	16.3	0.31	1.78	1242.9
Fluoride	0.25	<0.2	1.65	2.25	0.2	1.5	1.05	2.07
Iron	62.2	19.3	14.3	7.77	12	1.16	1.32	56.37
Lead	0.29	0.22	0.051	0.052	0.13	0.002	0.08	0.271
Magnesium	8.1	8.5	23	9	3.4	90.5	57.2	23.73
Manganese	0.94	0.57	5.4	0.67	0.42	0.44	1.47	4.89
Mercury	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Molybdenum	0.025	0.0195	0.03	<0.008	0.0205	0.0525	0.033	0.030
Nickel	1.011	0.445	0.166	0.182	0.144	0.063	0.1205	0.92
Phosphorus	0.29	0.216	0.473	0.498	0.13	<0.1	0.665	0.48
Potassium	10.4	12.5	27.1	22.1	19.4	13	19.1	26.32
Selenium	0.146	0.122	0.114	<0.048	0.142	0.112	0.104	0.15
Silica	39.44	46.5	46.12	-	40.97	28.2	34.37	45.84
Silver	0.0035	0.0035	0.0035	0.0035	0.0035	0.0035	0.0035	0.0035
Sodium	11.5	7.6	30.9	22.8	13.7	76.1	27.2	31.12
Sulfate	2742.2	1700.1	840.6	947	622.3	1321	831.4	2534.6
Thallium	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
Zinc	6.07	1.74	2.055	3.46	4.1	0.05	0.807	5.76

Table H-8 **Predicted Water Quality for the Hanover Pit Lake Over Time for $K_h = K_v/10$. Concentrations in mg/L.**

Constituent	Time (years)									
	5	10	15	20	25	30	35	40	45	50
Aluminum	0.66	2.63	1.37	1.78	2.20	2.63	3.07	3.52	3.98	4.44
Antimony	0.025	0.094	0.050	0.064	0.079	0.094	0.110	0.125	0.140	0.156
Arsenic	0.012	0.042	0.023	0.029	0.035	0.042	0.049	0.055	0.062	0.068
Barium	0.017	0.013	0.015	0.014	0.014	0.013	0.013	0.013	0.013	0.012
Beryllium	0.0005	0.0008	0.0006	0.0007	0.0007	0.0008	0.0009	0.0010	0.0011	0.0012
DIC*	1.4	1.3	1.4	1.4	1.3	1.3	1.3	1.3	1.3	1.3
Cadmium	0.004	0.013	0.007	0.009	0.011	0.013	0.014	0.016	0.018	0.020
Calcium	71	224	129	160	192	224	256	289	322	355
Chloride	20	74	39	51	62	74	85	97	109	121
Chromium	0.010	0.035	0.019	0.024	0.030	0.035	0.040	0.046	0.051	0.057
Cobalt	0.001	0.002	0.001	0.001	0.002	0.002	0.002	0.002	0.002	0.003
Copper	85.5	172.9	122.6	139.3	156.0	172.9	189.9	207.0	224.1	241.4
Fluoride	1.0	3.5	1.9	2.4	3.0	3.5	4.1	4.6	5.2	5.8
Iron	0.08	0.12	0.10	0.11	0.11	0.12	0.12	0.13	0.14	0.14
Lead	0.009	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
Magnesium	27.9	104.6	55.7	71.6	88.0	104.6	121.3	138.1	155.1	172.1
Manganese	0.001	0.004	0.002	0.003	0.003	0.004	0.004	0.005	0.006	0.006
Mercury	0.0001	0.0003	0.0002	0.0002	0.0003	0.0003	0.0004	0.0004	0.0005	0.0005
Molybdenum	0.006	0.019	0.011	0.013	0.016	0.019	0.022	0.024	0.027	0.030
Nickel	0.28	0.89	0.50	0.63	0.76	0.89	1.02	1.15	1.28	1.42
Phosphorus	0.81	3.19	1.66	2.16	2.68	3.19	3.71	4.22	4.73	5.25
Potassium	6.8	22.1	12.5	15.6	18.8	22.1	25.4	28.7	32.0	35.3
Selenium	0.034	0.109	0.062	0.077	0.093	0.109	0.125	0.141	0.157	0.173
Silicon	4.5	4.0	4.3	4.1	4.1	4.0	4.0	4.0	4.0	4.0
Silver	0.001	0.004	0.002	0.003	0.003	0.004	0.004	0.005	0.005	0.006
Sodium	49	184	98	126	155	184	214	243	273	304
Sulfate	497	1532	886	1097	1313	1532	1753	1975	2199	2424
Thallium	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Zinc	2.2	7.3	4.1	5.1	6.2	7.3	8.4	9.5	10.6	11.7
pH	5.1	5.0	5.1	5.0	5.0	5.0	5.0	5.0	5.0	4.9

*Dissolved inorganic carbon

Table H-9 Predicted Water Quality for the Hanover Pit Lake Over Time for $K_h = K_v$. Concentrations in mg/L.

Constituent	Time (years)									
	5	10	15	20	25	30	35	40	45	50
Aluminum	0.19	0.00	0.03	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Antimony	0.030	0.111	0.061	0.077	0.094	0.111	0.128	0.146	0.163	0.181
Arsenic	0.009	0.000	0.011	0.002	0.000	0.000	0.000	0.000	0.000	0.000
Barium	0.018	0.014	0.015	0.014	0.014	0.014	0.013	0.013	0.013	0.013
Beryllium	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
DIC*	1.7	8.8	2.9	4.4	6.5	8.8	11.0	13.2	15.4	17.7
Cadmium	0.004	0.012	0.007	0.009	0.011	0.012	0.014	0.016	0.018	0.019
Calcium	85	250	148	182	216	250	284	318	353	388
Chloride	23	83	46	58	71	83	96	109	122	135
Chromium	0.009	0.024	0.017	0.021	0.023	0.024	0.026	0.027	0.028	0.030
Cobalt	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Copper	9.4	0.2	1.4	0.5	0.2	0.2	0.1	0.1	0.1	0.1
Fluoride	1.1	2.8	2.2	2.8	2.9	2.8	2.8	2.7	2.7	2.7
Iron	0.02	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lead	0.002	0.003	0.001	0.001	0.002	0.003	0.003	0.003	0.003	0.003
Magnesium	33.5	122.1	66.7	85.0	103.5	122.1	140.8	159.7	178.6	197.6
Manganese	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mercury	0.0001	0.0003	0.0002	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004	0.0004
Molybdenum	0.006	0.018	0.011	0.013	0.016	0.018	0.021	0.023	0.026	0.028
Nickel	0.21	0.67	0.39	0.48	0.58	0.67	0.77	0.87	0.96	1.06
Phosphorus	0.51	0.01	0.24	0.05	0.02	0.01	0.01	0.00	0.00	0.00
Potassium	6.6	21.1	12.1	15.0	18.0	21.1	24.1	27.1	30.2	33.3
Selenium	0.036	0.112	0.065	0.080	0.096	0.112	0.128	0.144	0.160	0.177
Silicon	5.3	4.4	4.7	4.5	4.5	4.4	4.4	4.4	4.4	4.4
Silver	0.001	0.003	0.002	0.002	0.002	0.003	0.003	0.004	0.004	0.004
Sodium	58	214	117	149	182	214	247	281	314	348
Sulfate	445	1405	806	1004	1204	1405	1608	1812	2017	2223
Thallium	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Zinc	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
pH	5.8	7.0	6.4	6.7	6.9	7.0	7.1	7.2	7.3	7.3

*Dissolved inorganic Carbon

APPENDIX H

UPDATED PREDICTION OF WATER QUALITY FOR THE HANOVER PIT LAKE, GRANT COUNTY, NEW MEXICO

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APPENDIX H

PREDICTION OF WATER QUALITY FOR THE PROPOSED HANOVER PIT LAKE, GRANT COUNTY, NEW MEXICO, COBRE MINING COMPANY, INC.

TABLE OF CONTENTS

1.0 INTRODUCTION 1

2.0 CONCEPTUAL MODEL 2

3.0 MODEL INPUTS 3

3.1 Ground water Inflow 3

3.2 Pit Wall Runoff 5

3.3 Direct Precipitation 6

3.4 Evaporation 6

3.5 Wallrock Leaching 6

3.5.1 Davis-Ritchie Model 7

3.5.2 Constituent Release Rates 8

4.0 MODELING PROCEDURES 10

4.1 Geochemical Equilibria 10

5.0 RESULTS FOR PREDICTED WATER QUALITY 12

6.0 CONCLUSIONS 14

7.0 REFERENCES 16

LIST OF TABLES

Table H-1 Summary of the Water Balance for the Hanover Pit Lake

Table H-2 Summary of Data and Methods Used to Represent Hydrogeochemical Processes in the Pit Lake Model

Table H-3 Water Quality Data Used to Represent the Chemical Composition of Ground water Inflow for the Pit Lake Model and Precipitation Chemistry

Table H-4 Leachate Compositions From MWMP Tests Used to Define a Mixed Composition for Representation of Pit Wall Runoff in the Pit Lake Model

Table H-5 Values of Parameters Input to the Davis-Ritchie Model of Sulfide Oxidation

Table H-6 Results of the Davis-Ritchie Modeling as Thickness and Mass of Oxidized Wallrock as a Function of Time

Table H-7 Release Rates of Constituents from Leaching of Wall Rock Calculated from the Results of Humidity Cell Test

Table H-8 Predicted Water Quality for the Hanover Pit Lake Over Time for $K_h = K_v/10$. Concentrations in mg/L.

Table H-9 Predicted Water Quality for the Hanover Pit Lake Over Time for $K_h = K_v$. Concentrations in mg/L.

LIST OF FIGURES

Figure H-1 Hanover Pit Lake Conceptual Model

Figure H-2 Examples of Fits (lines) to Cumulative Amounts of (a) Iron and (b) Sulfate Measured (symbols) in Humidity Cell Tests.

Figure H-3 Examples of Fits (lines) to Cumulative Amounts of (a) Copper and (b) Zinc Measured (symbols) in Humidity Cell Tests.

1.0 INTRODUCTION

The planned expansion of the Continental Mine will involve development of a new surface mine at Hanover Mountain. Based on the results of hydrologic modeling, a lake is expected to form in the Hanover Pit after dewatering operations cease and the local ground water table fills to a static level (Appendix E). The study described herein provides the results of predictions of the water quality of the future Hanover Pit Lake.

The predictions of water quality were made with a numerical model of the pit lake hydrogeochemistry. The model contains two major components including:

- A water balance model used to describe the bulk chemical composition of the lake water based on rates of chemical influx to the pit lake
- A model of solution equilibria used to describe the effects of geochemical processes on the composition of the pit lake water under expected conditions.

The inputs to the model are derived from available information on the mine geology, geochemical properties, experimental testing results on rock reactivity, hydrologic predictions of filling rate of the pit lake, and knowledge of geochemical equilibrium processes that generally have been found to control water chemistry in existing pit lakes. The methods used to define inputs to the model and operation of the models themselves are described in this report, as well as, the predictions of future water quality made with the models.

2.0 CONCEPTUAL MODEL

The main hydrogeochemical factors that will affect the water quality of the Hanover Pit Lake include (Figure H-1):

- Ground water inflow, including the effects of variabilities in vertical and horizontal hydraulic conductivity
- Pit wall runoff
- Direct precipitation to the lake surface
- Evaporation
- Wallrock leaching
- Geochemical processes.

The first four factors involve the main components of the water balance for the pit lake. In general terms, their hydrogeochemical influences on the pit lake composition are represented by the rates of chemical flux input to the lake for each component of the water balance, as determined from the hydrologic model of the pit lake (see Appendix E), and representative chemical compositions for each component. The water balance determined by hydrological modeling for the pit lake is summarized in Table H-1.

The remaining two factors involve primarily geochemical processes. Wallrock leaching reflects releases of constituents from the wallrock by oxidation and dissolution reactions. Geochemical processes include precipitation, dissolution, aqueous speciation, redox, and adsorption. The geochemical processes are assumed to take place at equilibrium and their effects on water quality were calculated with the PHREEQC geochemical model (Parkhurst, 1995).

Each of these main factors was explicitly incorporated into the pit lake prediction model. A summary of the methods used to represent these factors is provided in Table H-2 and described in more detail in the following sections.

3.0 MODEL INPUTS

The methods used to define chemical compositions of inflows to the pit lake are described in this section.

3.1 Ground Water Inflow

Hydrologic modeling has indicated that ground water will comprise the majority of the inflow to the Hanover Pit Lake (see Table H-1 and Appendix E). Water enters the pit through a horizontal component of flow through the pit wall and a vertical component of flow through the bottom of the pit. The hydraulic conductivity in the vertical (K_v) and horizontal (K_h) directions play an important role in the pit water quality because they control the amount of groundwater that flows into the pit lake relative to other inflow sources. The groundwater is characterized by chemical compositions with high alkalinity, hence its proportion of inflow to the pit lake has a large effect on the predictions of alkalinity and pH for the pit lake. To bracket the effects of hydraulic conductivity on the pit lake chemical composition, two sets of values were examined in the modeling calculations; one where $K_v = K_h$, and the other where $K_v = K_h /10$.

In the pit lake geochemical model, the chemical composition of the influent ground water is represented by the combined average of water compositions determined for monitoring wells MW-1 and MW-1A for samples collected in 1996 and 1997 (Table H-2).

Both of these monitoring wells are completed in the Colorado Formation in areas that will be upgradient of the proposed pit after mining ceases. Monitoring well MW-1 is screened at a depth of 210 to 230 ft in the basal shale member of the Colorado Formation (Appendix A) and produces dilute water with an alkaline pH and sodium-bicarbonate-sulfate composition with low alkalinity (Table H-3). Monitoring well MW-1A is screened at 40 to 70 ft in a sandstone unit and produces water with a neutral to alkaline pH and calcium-magnesium-bicarbonate-sulfate composition and high alkalinity (Table H-3).

The Colorado Formation will comprise the majority of the ultimate pit wall surface. Hence, the data for monitoring wells MW-1 and MW-1A are expected to provide the best available representation of the composition of the ground water that will flow into the Hanover Pit Lake after closure. For the pit lake model, it was assumed that the ground water entering the pit lake would have a chemical composition comprised of equal portions of water with compositions characterized by those determined for MW-1 and MW-1A. This assumption is conservative in that the sandstone portions of the Colorado Formation, which are represented by the high alkalinity water from MW-1A, might be expected to yield proportionately more water than the shale portions, which are represented by low alkalinity water from MW-1.

The following procedure was followed to obtain an average chemical composition of the ground water influent to the pit lake. Five chemical compositions for water samples from well MW-1A collected in 1996 and 1997 were mixed in equal proportions using the solution mixing option in the PHREEQC to yield an overall average composition (Table H-3). The PHREEQC model was used to calculate the average because its mixing formulations allowed for preservation of hydrogen ion and alkalinity for mixed solutions. In the mixing calculations, a minor amount of either sulfate or sodium was automatically added by PHREEQC to charge-balance individual solution analyses.

A single composition for a sample from MW-1 was available from a sample collected in 1996. The MW-1 composition was mixed with the average from MW-1A, assuming equal proportions, to yield a composite average composition from both monitoring wells (Table H-3). The average ground water composition was characterized by a slightly alkaline pH with a major element composition dominated by calcium, magnesium, bicarbonate, and sulfate. Metal concentrations are low.

In developing the chemical composition data for averaging, dissolved concentrations were used whenever they were available. In cases where analytical protocols changed over time and dissolved concentrations were not available for a specific analyte, the concentration determined for the previous sampling event was used. Metals that were determined to exist at concentrations less than detection levels were entered into the averaging calculations at one-half of the detection level.

3.2 Pit Wall Runoff

Precipitation that falls on pit walls will run across exposed rock surfaces, potentially dissolving constituents and transporting them into the pit lake. As the pit fills, the proportion of water entering the lake from pit wall runoff will decrease (Table H-1).

The surface area of the Hanover Pit wall will be comprised of two major rock types, including the Colorado Leach Cap (89%) and unoxidized Colorado Formation (8%). A very small portion of the pit wall is comprised of Barringer Fault Zone (3%). In the pit lake model, the chemical composition of the pit wall runoff was represented empirically by the results obtained from Meteoric Water Mobility Procedure (MWMP) tests (Table H-4) proportioned to the relative areas of the two major rock types.

One MWMP test was conducted on a sample of Colorado Leach Cap (sample WRC-09) from Hanover Mountain. Hence, the leachate composition from this test was used to represent runoff from the Colorado Leach Cap (Table H-4). This leachate composition was also used to represent runoff from the Barringer Fault Zone. The Barringer Fault Zone shows wide variability in its acid/base characteristics, depending on its sulfide content (Appendix D). A single MWMP test on Barringer Fault Zone sample WRC-11, which produced an NNP value of +40.4 T $CaCO_3$/kT, yielded a neutral pH. However, the average net neutralizing potential (NNP) for samples from the Barringer Fault Zone is –30.5 T $CaCO_3$/kT, implying that sample WRC-11 is not a representative sample for the Barringer Fault Zone. Consequently, the results from the MWMP test on sample WRC-09 from the Colorado Leach Cap, which produced an acidic leachate, was also used to represent the Barringer Fault Zone.

Two MWMP tests were conducted on samples of the unoxidized Colorado Formation (samples WRC-07 and WRC-08). The results from the test on sample WRC-07 were used to represent the composition from the unoxidized Colorado Formation in the pit lake model (Table H-4). Sample WRC-07 produced a higher mineral acidity than WRC-08, hence was assumed to represent a conservative estimate of the chemical composition of the pit wall runoff in the pit lake model.

In the pit lake model, the leachate compositions from the three rock types were mixed in proportion to their relative surface areas in the pit wall, assuming that those proportions do not change significantly over time (Table H-4). The mixing calculations were conducted with PHREEQC. Similar to the procedures used for ground water mixing, constituents that were less than detection levels were entered into the model at one-half of the detection level. Either sulfate or sodium were used to charge-balance solutions.

3.3 Direct Precipitation

As the pit lake fills with water and becomes larger in surface area, an increasing portion of the inflow will result from precipitation that falls directly on the lake surface (Table H-1). In the pit lake model, the chemical make-up of precipitation water was obtained from the 1994 edition of the Annual Summary produced by the National Atmospheric Deposition Program (NADP). The closest site was for the Gila Cliff Dwellings which had a pH = 4.8 and low concentrations of major cations and anions (Table H-3).

3.4 Evaporation

Additionally, as the pit lake surface increases, evaporation becomes an increasingly more important component of the water balance (Table H-1). In the pit lake model, evaporation was represented by the removal of pure water.

3.5 Wallrock Leaching

Prior to the filling of the pit lake, rocks exposed in the pit surface will weather and oxidize. The most important weathering process that affects water quality in mine pit lakes is generally the oxidation of sulfide minerals. Depending on the sulfide content, oxidation reactions can result in the accumulation of acidic constituents in an oxidized zone within the pit walls when the pit walls are exposed to weathering. After mine closure and dewatering ends, the water table will rise and ground water that flows into the pit lake will leach soluble constituents from the oxidized (weathered) zone in the pit walls and transport them to the pit lake. As the elevation of the pit lake rises, the leached zones will become increasingly submerged, thereby essentially ending the oxidation of sulfide minerals and concomitant release of constituents to the pit lake.

For the pit lake model, the processes of sulfide oxidation and constituent release from oxidized rocks were represented by the Davis-Ritchie model and the results of humidity cell tests, respectively, as described below.

3.5.1 Davis-Ritchie Model

The wallrock for the Hanover Pit will be comprised primarily of the unoxidized Colorado Formation rocks with small amounts of oxidized Colorado Formation, and Barringer Fault Zone rocks. Hence, sulfide minerals are assumed to be present in all of the wallrock that will be exposed to weathering and eventually submerged in the pit lake.

The Davis-Ritchie model of sulfide oxidation was used to represent the rate of oxidation of the sulfide minerals in the wallrock. Additionally, it was used to obtain an estimate of the thickness of the oxidized zone in the pit walls as a function of time (Davis and Ritchie, 1986; Davis and others, 1986; Davis and Ritchie, 1987). For input to the Davis-Ritchie model, the average sulfide-sulfur content was calculated to be 1.29% based on the average of acid base accounting results for Hanover Mountain (Appendix D), weighted for the surface areas of the different rock types. Values for other parameters input to the Davis-Ritchie model were either estimated or taken from Braun and others (1974) (Table H-5).

Based on the hydrologic model, the pit lake is expected to fill to a static depth of approximately 156 ft around 20 years after closure (Table H-1). It is estimated that the portion of the pit that will be eventually submerged by water will be exposed to weathering for 10 years while mining operations occur. This time estimate may be conservative in that the mine-life is expected to be 10 years, hence the time between the end of mining and closure may be less than 10 years.

Using the 10-year period as the starting point for time of oxidation of the pit wallrocks, the Davis-Ritchie model was used to calculate the thickness of the oxidized zone for times after mine closure and infilling of the pit with water. Model results show that the oxidized zone (that is, the oxide rind thickness) ranges from 0.35 m after the initial time period of 10 years, to 0.51 m after 30 years, when the water level in the pit lake is expected to stabilize (Table H-6).

Using the calculated thickness for the oxidized zone, circumference of the pit wall, and an estimated rock density of 2.65 g/cm^3 the masses of oxidized rock as a function of time were also calculated (Table H-6). Multiplication of these masses by the release rates of constituents from the oxidized zone yields the rates of chemical influx to the pit lake. The method for determining the constituent release rates is described in the next section.

3.5.2 Constituent Release Rates

Rates of constituent release were obtained from the results of humidity cell tests conducted on rock samples from Hanover Mountain (Appendix D). Data from the weekly and 5-week composite water samples from the humidity cell tests were converted to cumulative amounts of constituents released as a function of time. The cumulative amounts for each constituent (C_i) were then used to fit a curve defined by:

$$C_i = y_0 + a(1 - \exp^{-bt}) \qquad (1)$$

In this expression, y_0, a, and b are constants determined by the least-squares curve fitting and t is time in weeks, consistent with the humidity cell test data. In general, Equation (1) provides a good description of the asymptotic increase in the cumulative release of a constituent with time of leaching that is often observed in humidity cell tests.

Examples of measured rates of cumulative releases of iron and sulfate compared to curve-fits based on Equation (1) are shown in Figure H-2. These two constituents were measured on a weekly basis in the humidity cell tests. A similar comparison is shown in Figure H-3 for copper and zinc, whose concentrations were determined in 5-week composite samples. In general, the rates of cumulative release observed in the humidity cells are described by Equation (1).

The utility of Equation (1) for representing the release rates lies in the fact that as time increases to a large value, Equation (1) is approximated by:

$$C_i(\max) = y_0 + a \qquad (2)$$

where $C_i(\max)$ is the maximum amount of release of a constituent from a mass of rock in units of mg/kg rock. Thus, for constituents that did not reach a plateau in cumulative release by the end of the humidity cell tests, such as iron and sulfate in WRC-07 (Figure H-2), Equation (2) was used to calculate the plateau and estimate the maximum rate of release. For a few constituents that were not well represented by Equation (1), the cumulative amount of release at the end of the humidity cell test (20 to 23 weeks) was used in place of the value determined from Equation (2).

The curve-fitting procedure was conducted for each humidity cell to obtain release rates for each constituent (Table H-7). For Hanover Mountain, humidity cell tests were conducted on four samples of the unoxidized Colorado Formation, one sample of the Colorado Leach Cap, and two samples from the Barringer Fault Zone. To calculate a composite release rate for each constituent, the maximum rate determined for each rock type was selected and then averaged together in proportion to the relative surface areas of each rock type in the pit wall (Table H-7). Inherent in this calculation is the assumption that the proportions of the pit wall comprised of the different rock types is constant over the time of the pit lake filling.

In the pit lake model, the release rates listed in Table H-7 were multiplied by the mass of oxidized rock (as determined with the Davis-Ritchie model) to obtain the total mass of constituents entering the pit lake as a function of time. The division of the constituent masses by the volume of the lake (L) yielded the concentrations of the different constituents released to the pit lake as a result of wallrock leaching.

4.0 MODELING PROCEDURES

The predicted composition of the pit lake water was calculated in two steps. In the first step, the bulk water composition was calculated using the rates of chemical influx into the lake based on hydrologic inflow rates and chemical compositions for ground water, wallrock runoff, and wallrock leaching. The bulk compositions were calculated using a dynamics system model. In the second step, a bulk composition from the first step was equilibrated with various reactions expected to affect water compositions in pit lakes (Eary, 1999). To predict changes in the concentrations of constituents in the pit lake over time, these two steps were repeated in a stepwise manner.

4.1 Geochemical Equilibria

In the equilibrium step of the modeling, the bulk chemical compositions were equilibrated with atmospheric oxygen at the ambient partial pressure of 0.2 atm using controls in the PHREEQC geochemical model. Preliminary predictions of pit lake chemistry indicated that the pH would likely range from 4 to 7.0. Data from existing pit lakes with pH less than 7.0 indicate that $CO_2(g)$ levels are generally 10 to 100 times the standard atmospheric level of $10^{-3.5}$ atm (Eary, 1999). Based on this range, a $CO_2(g)$ gas pressure of $10^{-2.5}$ atm was used for all model runs.

Controls in the PHREEQC model were also used to equilibrate the pit lake water with the solubilities of certain mineral precipitates if conditions of oversaturation were reached. The minerals considered for equilibration included those known to form in low-temperature solutions and which have been found to be likely solubility controls for different constituents in pit lakes (Eary, 1999). According to the PHREEQC results, the bulk compositions predicted for the pit lake were oversaturation with barite [$BaSO_4$], birnessite [MnO_2], brochantite [$Cu_4(OH)_6SO_4$], chloropyromorphite [$Pb_5(PO_4)_3Cl$], ferrihydrite [$Fe(OH)_3$], gibbsite [$Al(OH)_3$], heterogenite [$CoOOH$], hydroxyapatite [$Ca_5(PO_4)_3OH$], malachite [$Cu_2(OH)_2CO_3$], and hydrozincite [$Zn_5(OH)_6(CO_3)_2$]. Hence, in the geochemical equilibration step, the water compositions were equilibrated with the solubilities of these minerals.

An additional step in the geochemical modeling involved calculation of the effect of the adsorption of dissolved constituents to ferrihydrite [$Fe(OH)_3$]. The adsorbed constituents included Ag, As, Ba, Be, Ca, Cd, Cr, Cu, Co, F, H, Mn, Mo, Ni, Pb, PO_4, Sb, Se, SO_4, and Zn. In the Hanover Pit Lake model, the PHREEQC model was run for a bulk water composition to determine the mass of ferrihydrite precipitated per liter of water. The PHREEQC model was then run a second time with the ferrihydrite mass specified as an adsorbent. The surface of the ferrihydrite was assumed to have the following standard properties: strong binding sites of 0.005 mol/mol Fe, weak binding sites of 0.2 mol/mol Fe, and specific surface area of 600 m^2/g (Dzomback and Morel, 1990).

5.0 RESULTS FOR PREDICTED WATER QUALITY

The results of the predictions of water quality for the Hanover Pit Lake are provided in Table H-8 where $K_v = K_h/10$ and Table H-9 where $K_v = K_h$. The results indicate that the lake water will initially have a pH from 5.1 to 5.8, depending on the relative ratios of hydraulic conductivity. The pH levels for the prediction with $K_v = K_h/10$ decrease slightly over time to a value of 4.9. For the prediction with $K_v = K_h$, the pH is predicted to increase over time to a value of 7.3.

The trends in predicted compositions for the pit lake are caused by changes in the relative amounts of chemical influx from different inflows over time and by chemical reactions. During the first years of infilling of the lake, the rates of release of constituents from wallrock runoff are at their highest levels because the bulk of the pit wall is exposed. Additionally, the surface area for wallrock runoff is at its maximum extent. Based on the results of humidity cell and MWMP tests, the processes of wallrock runoff and wallrock leachates have the potential to release metals and sulfate to the pit lake. At the same time, the volume of water in the pit is initially low. This combination of events is manifested in the pit lake model results as lower pH and elevated concentrations of some metals during the initial 5 to 10 years of pit infilling (Tables H-8 and H-9).

As the pit fills with water, increasingly larger portions of the wallrock are submerged, causing a decrease in the release of constituents to the pit from wallrock leaching and wallrock runoff. At the same time, the proportion of water entering the pit from ground water inflow increases relative to wallrock runoff. The ground water has a high alkalinity. In the case of $K_v = K_h$ (Table H-9), the relative proportion of ground water that enters the pit is large, and the pit lake model predicts an increase in pH to a value of 5.8 to 7.3 after 50 years. In the case $K_v = K_h/10$ (Table H-8), the relative proportion of groundwater entering the pit is lower. Hence, the prediction shows an approximate constant pH over time. These trends for the different ratios of vertical and horizontal conductivity illustrate the sensitivity of the predictions to the hydrologic parameters used to describe the process of infilling of the pit lake with water.

Accompanying the increase in pH for the case of $K_v = K_h$, the concentrations of aluminum, copper, iron, and zinc reach and exceed the solubility limits of probable mineral precipitates, whose solubilities are generally decreased as the pH rises under equilibrium conditions. Hence, the concentrations of copper, iron, and zinc are predicted to decrease over time as the pH rises (Table H-8). The other metals and most other constituents, which do not reach the solubility limits of potential mineral precipitates, continue to increase over time because of the concentrating effects of evaporation, which are not fully compensated by adsorption. Pit lake evaporation is predicted to increase as the lake fills and increases in surface area.

For both cases described in Tables H-8 and H-9, certain metals, such as antimony, cadmium, chromium, mercury, molybdenum, selenium, silver, and thallium, are also predicted to increase over time. These metals were either never or rarely found at concentrations above detection levels in experimental tests. However, in the model, the concentrating effects of evaporation are applied to all constituents. Hence, the concentrations of certain metals that may not have been actually found at detectable levels in experimental tests are predicted to increase over time as a result of evaporation.

6.0 CONCLUSIONS

In summary, the Hanover Pit Lake is predicted to have an initial pH between 4.8 and 5.9 and a composition dominated by sodium, calcium, magnesium, and sulfate. The pH is expected to increase or stay approximately constant over time, depending on the ground water flow system. Certain metals are also predicted to have elevated concentrations, namely aluminum, copper, and zinc because of releases to the pit lake by the processes of wallrock runoff and wallrock leaching.

The predictions of pit lake water quality were based on a number of conservative assumptions. The most important of these include:

- The ground water composition was specified as a 50:50 mix of waters characterized by compositions from MW-1A and MW-1. This approach reduced the amount of alkalinity flowing into the pit lake from the ground water system.
- The maximum rates of constituent release that were determined in humidity cell tests were used to represent the process of wallrock leaching. This approach maximized the rates of constituent flux to the pit lake.
- The pit walls were assumed to be exposed to weathering for a 10-year period before closure and filling of the pit with water. This approach resulted in a buildup of leachable constituents in the wallrock because of oxidation processes, which are then released to the pit lake in the model as the pit fills with water.

The assumptions listed above make it likely that the predictions for the Hanover Pit Lake represent a reasonably conservative depiction of future water quality.

Importantly, the pit chemistry is controlled by the balance of water that inflows from acidic sources, such as the pit walls, and alkaline sources, such as the ground water, predictions of the future chemical composition are highly dependent on the representation of the groundwater hydrologic system. However, the relative proportion of high alkalinity ground water flowing into the pit lake is predicted to increase over time. Consequently, the pH of the lake is also predicted to increase slowly. With increase in pH, the concentrations of many metals can be expected to decrease over time because of precipitation and adsorption reactions.

7.0 REFERENCES

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