Low-temperature weathering (4°C): The leachate pH has remained steady at values of 7.6 ± 0.2 from Week 1 and the measured alkalinity has always exceeded acidity (Figure 6a). The dissolved sulfate concentration appears to decrease with the progress of the experiment except during the final rinse, concomitant with a slight increase in the acidity and conductivity measurements. The noted increase in acidity, dissolved sulfate and conductivity reflects storage of soluble sulfide oxidation products during the antecedent 10-week drying period. The calculated sulfate release rate, however, has definitely followed a decreasing trend throughout the testing (Figure 6b). The waste rock sample contains relatively little As (556 ppm) such that dissolved As has not been detected in most of the leachate samples. In the As time series depicted in Figure 6, concentrations corresponding to half the detection limit for As has been used if As is non-detectable in the leachate analysis. The Zn content of the waste rock is also low (40 ppm). Dissolved Zn concentrations measured in the leachate analysis are either below detection limit (0.01 mg/L) or generally below 0.1 mg/L. The anomalous value of 23 mg/L noted on Week 17 is probably a measurement error, or due to contamination introduced in the laboratory.

Room-temperature weathering (22°C): The leachate pH has generally remained near-neutral with values of 7.3 ± 0.2 (Figure 7a and Appendix III). Observations made on the dissolved sulfate concentration, acidity, conductivity, sulfate production rate for the cold temperature weathering also apply to the room temperature weathering results. However, the amount of sulfate released during the room-temperature weathering is higher than that obtained in the low-temperature experiment. While dissolved As is mostly undetectable, the dissolved Zn concentrations are generally higher than those measured in the low temperature experiment. The measurements are generally erratic and do not follow any definable trend.

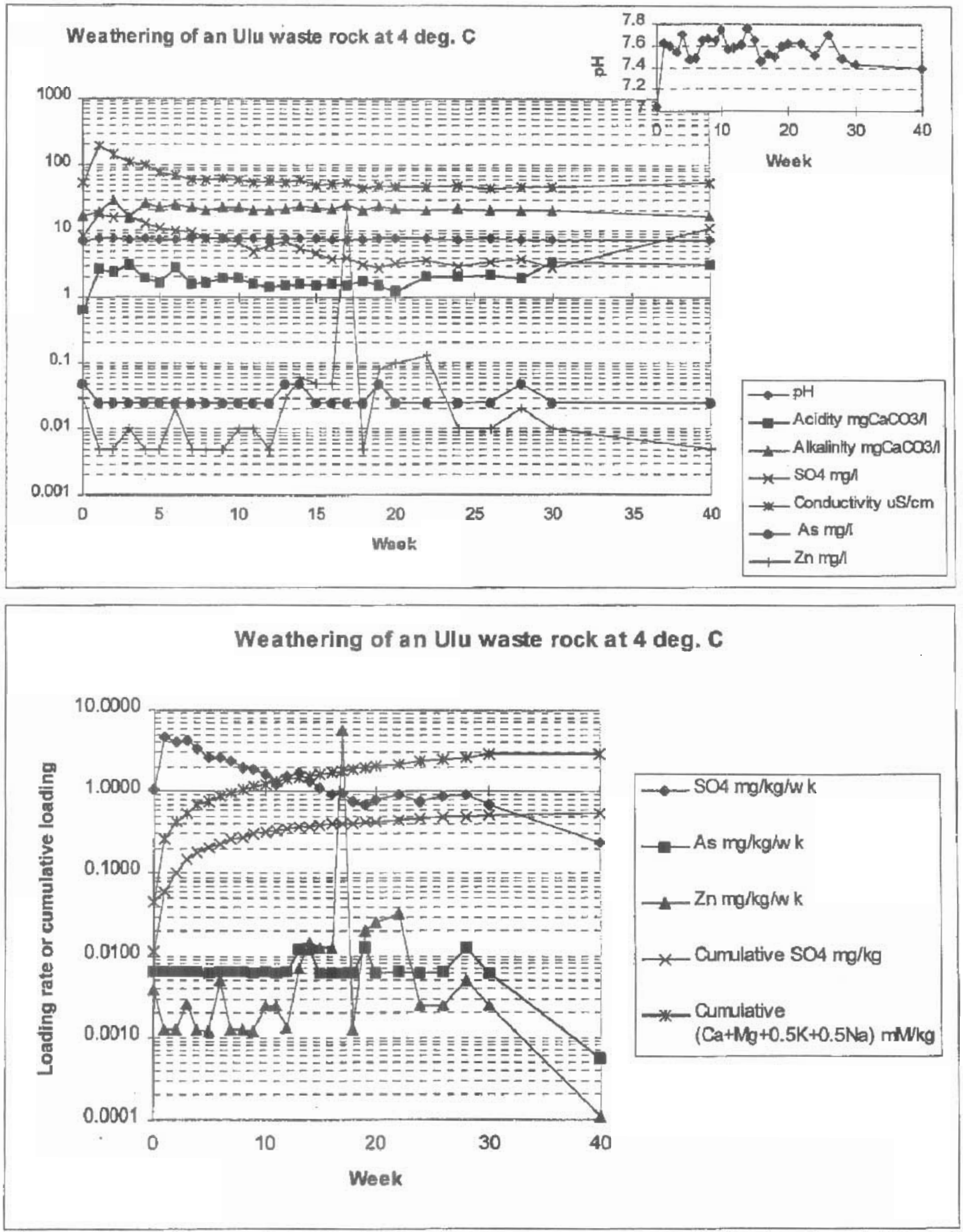


Figure 6 Time series of selected parameters determined during humidity-cell testing of an Ulu waste rock at 4°C.

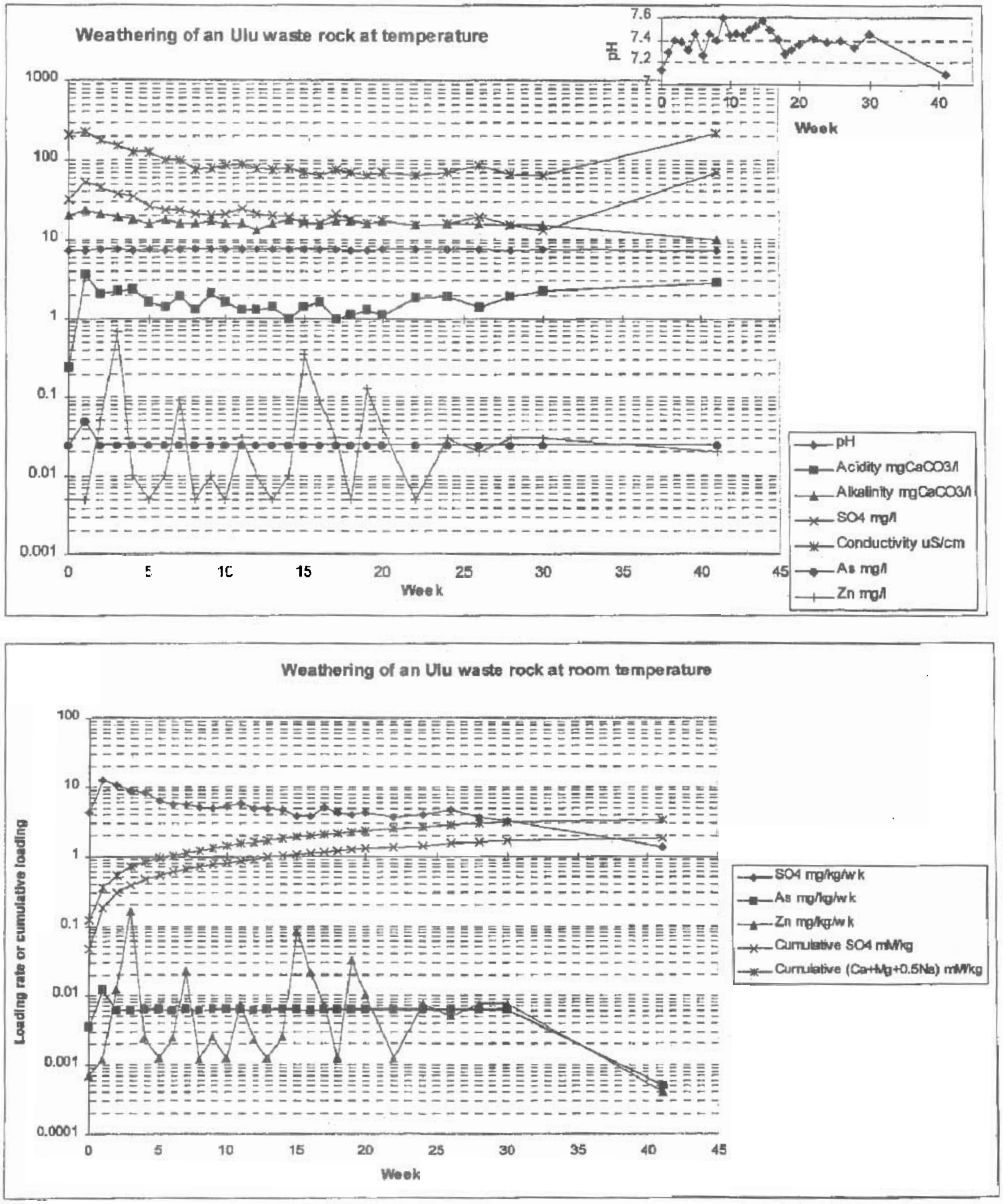


Figure 7 Time series of selected parameters determined during humidity-cell testing of an Ulu waste rock at room temperature.

Comparison of the consequences of weathering at different temperatures: The deductions on sulfate oxidation and NP depletion rates for the weathering of the Ulu waste rock under the two temperature conditions are compared in Table 4. Although the waste rock composite does not appear to contain any salt contamination, to be consistent, the same methodology as described above for the Ulu ore is used to calculate the relevant data on release rates and depletion times. Since no significant release of trace elements has been detected in the waste rock leachates, loading rate data are omitted.

Table 4 A comparison of the results of weathering of an Ulu waste rock under different conditions

	Low temperature (4°C)	Room temperature (22°C)
S depletion rate (mM/kg/wk)	0.010	0.044
NP depletion rate (mM $CaCO_3$/kg/wk)	0.079	0.087
Time for complete S depletion (yr)	698	159
Time for total NP depletion (yr)	68	62

Similar to what has been observed in the weathering of Ulu ore samples, temperature does not greatly affect the NP depletion rate but the sulfide-S depletion rate at room temperature is four times as high as that obtained at 4°C. On a molar basis, NP depletion proceeds faster than sulfide oxidation under both temperature conditions. Thus, although the waste rock composite has a neutralization potential ratio (NPR, = NP/MPA) of about 1, sustained weathering will eventually lead to net acid generation. This will occur in about 60 years with weathering at room temperature and about 70 years at 4°C.

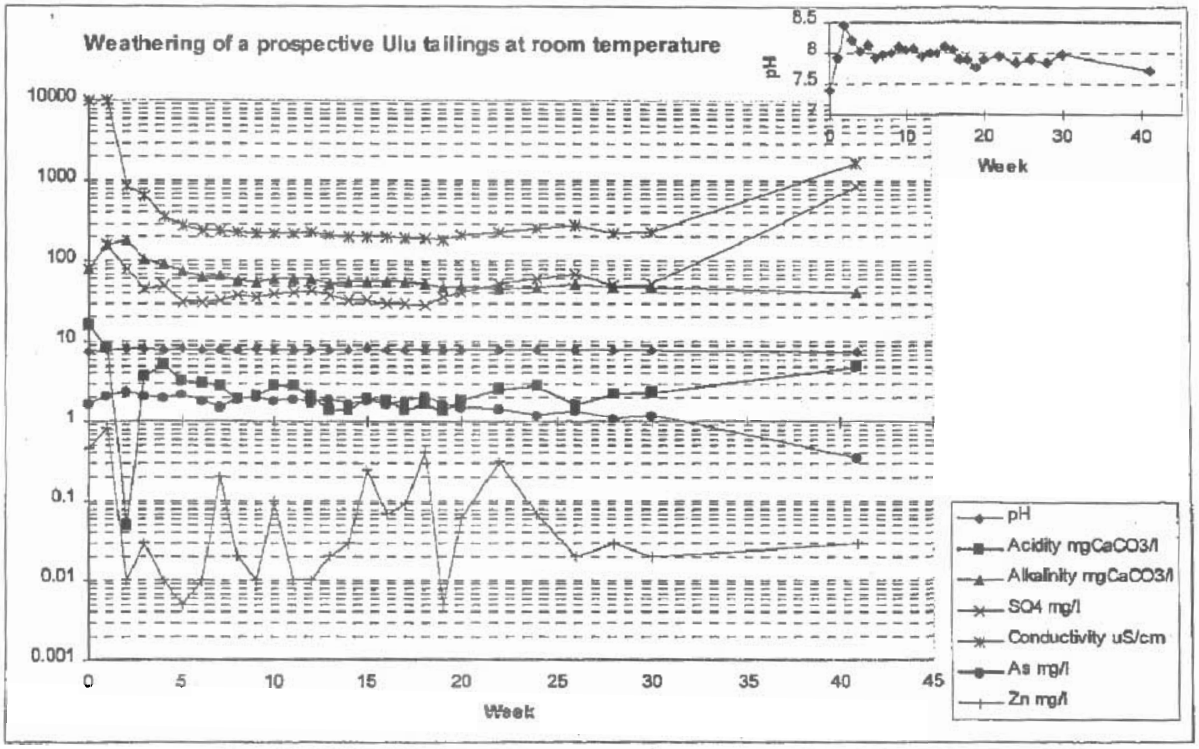
3.2.3 Weathering of Prospective Ulu Tailings

Humidity-cell testing of prospective Ulu tailings has been conducted only at room temperature to serve as the worse case scenario for weathering of geological materials from the Ulu deposit. The test sample represents the fine-grained portion (<1.5 mm) of the bulk ore composite. Its geochemical and mineralogical composition is thus very similar to that of the Ulu ore subsamples subjected to kinetic testing under varied conditions as described above. The major differences are that the tailings contains slightly more total S (1.6 versus 1.1%) and has a higher NP (9 versus 6 kg/t $CaCO_3$) than the ore subsamples tested.

The time series for selected parameters measured and derived in the humidity-cell testing of the prospective tailings sample are depicted in Figure 8. The leachate pH is slightly basic with values generally measured at 8.0 ± 0.3 and the net difference between the corresponding alkalinity and acidity measurements is much higher than that observed in the weathering of the Ulu ore at room temperature. After consistent decreases in the first five weeks, the sulfate concentration measured in the leachates appear to increase with further weathering culminating in a significant jump during the final rinse (Figure 8 a). The sulfate production rate also follows the same trend (Figure 8b). Apparently, the fine grain size of the test sample has led to the retention of intergranular moisture that has sustained significant sulfide oxidation during the non-flushing period of Weeks 30 to 41.

The time variation curves for acidity and conductivity generally mimic that of dissolved sulfate. The apparently low acidity measurement in Week 2 (<0.1 mg $CaCO_3$ /L) is compatible with the measured pH of 8.4, which reflects the reactivity of the acid-neutralizing minerals during the early stage of the weathering experiment.

The leaching of As appears to decrease slightly with the progress of the weathering while Zn leaching appears to be slightly enhanced with time. Similar to that observed in the weathering of Ulu ore and waste rock, the Zn measurements are generally more erratic than the As measurements.



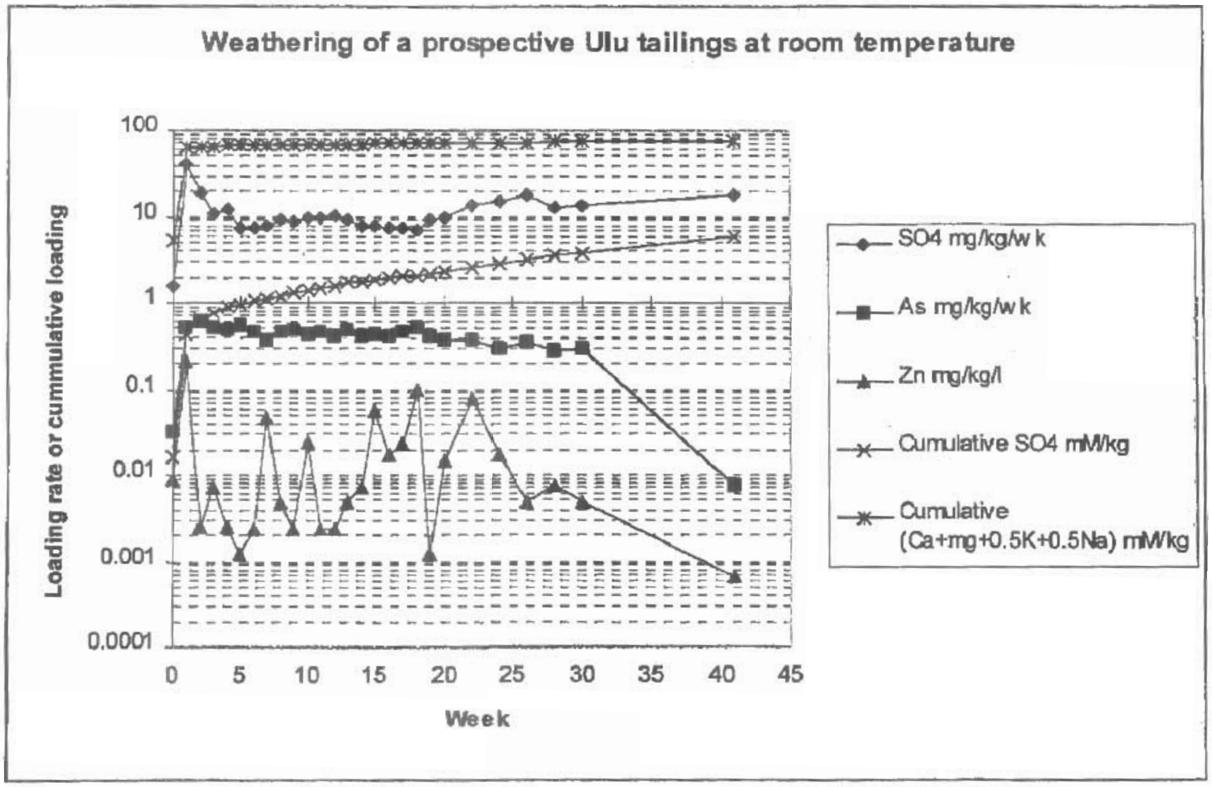


Figure 8 Time series of selected parameters measured or derived in the humidity-cell testing of a prospective Ulu tailings sample at room temperature.

Rate-related data derived from the weathering of the tailings sample are summarized in Table 5. Compared to the weathering of Ulu ore under the same conditions, the sulfate depletion rate is twice as fast and the NP depletion rate nearly three times faster. Thus, even though the tailings contains more sulfides and has a higher NP than the Ulu ore, it takes less time for the tailings to exhaust its sulfide content and NP than the coarser-grained ore. It is estimated that net acid generation will occur in about 30 years if the tailings is subjected to weathering at room temperature. The calculated As loading rates are at least four times higher than those calculated for the Ulu ore while the erratic Zn release rates are only about two time higher. Evidently, grain size plays a significant role in mineral weathering and the associated metal leaching.

Table 5 **Deduced rate data from the weathering of an Ulu tailings at room temperature**

Sulfide-S depletion rate (mM/kg/wk)	0.119
NP depletion rate (mM $CaCO_3$/kg/wk)	0.305
Time required for total S depletion (yr)	82
Time for complete NP depletion (yr)	31
As loading rate (mg/kg/wk)	0.28 - 0.61
Zn loading rate (mg/kg/wk)	0.001 - 0.209

4. DISCUSSION

The kinetic test program for the Ulu Project described above has been designed to elucidate the climatic controls on mineral weathering and metal leaching. Based on the acquired data, two important environmental issues related to the proposed ore stockpiling at the Ulu site can be addressed. These topics are briefly discussed below. Recommendations for further work to complement the current investigation are also made.

4.1 Climatic controls of mineral weathering

From the perspective of acid rock drainage prediction, the most important aspects of mineral weathering are sulfide oxidation and alkali removal. Sulfide oxidation can lead to acid generation if the sulfides are iron-rich or have a metal to sulfur ratio of less than one (Kwong, 1993). The sulfide oxidation rate can be estimated directly from the sulfate production rate if a test sample does not contain any soluble sulfate minerals. This is the case for the Ulu test samples. From the humidity-cell testing of the ore and waste rock composites, it is evident that the contained sulfide minerals oxidized about four times faster at room temperature than at 4°C. The different sulfide mineralogy in the test samples (mainly pyrrhotite and arsenopyrite in the ore and pyrite in the waste rock) does not seem to affect the sulfate production rate. Evidenced by significant changes in leachate chemistry during the final rinse, however, the length of antecedent drying period greatly affects the overall sulfide oxidation rate. Generally speaking, a longer antecedent drying period will allow a greater accumulation of oxidation products, resulting in higher concentrations of dissolved constituents in the leachate. Nevertheless, the overall oxidation rate on a per mass basis is reduced with a longer antecedent period between flushing events unless sufficient intergranular moisture is maintained to sustain rigorous oxidation. It is due to the dual effects of an overall lower mean temperature and less frequent flushing that the weathering of the Ulu ore in the field columns has given rise to a much lower sulfide oxidation rate compared to controlled weathering in the laboratory.

The acid neutralization process essentially involves the replacement of alkali (e.g. Na, K) and alkali earth (e.g. Mg, Ca) elements occurring in an acid-neutralizing mineral by hydrogen with or without concomitant complete dissolution of a solid and/or evolution of a gaseous phase. Thus, the release rate of alkali and alkali earth metals expressed in terms of equivalent moles of calcite (i.e., Ca+Mg+0.5Na+0.5K) during weathering can be used to represent the rate of NP depletion in a test sample. Both the laboratory humidity-cell testing of the Ulu ore and waste rock and field-column testing of the Ulu ore indicate that the NP depletion rate is higher than the sulfide oxidation rate. In addition, temperature appears to have a less dominant effect on NP depletion than on sulfide oxidation. At room temperature, the NP depletion rate is slightly less than threefold the sulfide oxidation rate. Thus, only geologic materials with an NPR of equal to or greater than 3 will not give rise to acid rock drainage upon weathering. Under colder conditions, an NPR of about 7 is required. However, in the latter case, the amount of acid generated is so small (e.g., 0.2 moles of H_2SO_4 per tonne of rock per year for the weathering of the Ulu ore under field conditions) that it will not have a significant environmental impact or that it can readily be remedied.

4.2 Environmental Issues Related to Ore Stockpiling at Ulu

The possible formation of acid rock drainage and metal leaching are two important environmental issues of concern for ore stockpiling at the Ulu site. Both the laboratory and field weathering results have shown that the lag time for net acid generation with natural weathering of the Ulu material is long. Even for the worst case of weathering the relatively sulfide-rich tailings at room temperature with frequent flushing, the material will not turn acid in 30 years. Thus, temporal storage of the ore material on site for a few years waiting for transport to Lupin for processing should not pose a problem as far as acid generation is concerned.

The results of leachate analysis show that no potentially deleterious trace elements are leached from the weathering of the Ulu waste rock under any of the test conditions. Dissolved As and Zn, however, have been detected from the weathering of the Ulu ore composite. The leaching rates for both elements are extremely low under the field conditions (averaged about 0.002 mg/kg/wk for As and <0.0009 mg/kg/wk for Zn). Nevertheless, because of the possibility of enhanced leaching of these trace elements from pulverized materials particularly at higher temperatures (Table 5), it is recommended that the ore should not be pulverized to <1.5 mm for stockpiling on site or for transport to Lupin. This will help to prevent potential metal leaching problems from occurring at the Ulu site or from accidental spillage during transport.

4.3 Recommended Further Work

While the current study has furnished valuable data on the acid generation and metal leaching potential of the Ulu materials under different conditions, there are two apparent short-comings that require further complementary work for ratification. These are briefly discussed below:

1) The field-column testing has been operated for one complete cycle of changing seasons yielding three data points, which are insufficient to define any long-term trend. In addition, the leachate volume has not been measured accurately during two of the three sampling events. Thus the resultant loading rates calculated are only rough estimates. Since the operation of the test column does not require much maintenance and the costs associated with the subsequent leachate analyses are relatively low, it is recommended that the field-column testing be extended for at least two more years.

2) The kinetic test work described in this report has been conducted with samples collected from the upper levels of the Ulu deposit. If the composition of either the orebody or the associated waste rock changes with depth, then more samples must be collected and tested accordingly.

5. CONCLUSIONS

The kinetic test program with selected Ulu ore, waste rock and prospective tailings composites under different conditions have been conducted to facilitate further mine development at the Ulu site and substantiate conclusions on acid generation and metal leaching potential drawn previously based on field observations and static geochemical analyses. The results of the current test work lead to the following conclusions:

1) Given the low sulfide oxidation and metal leaching rates occurring under field conditions, stockpiling of coarse ore at the Ulu site up to 50 years is unlikely to give rise to acid drainage or intensive metal leaching.

2) Temperature affects the rate of sulfide oxidation to a greater extent than the rate of depletion of neutralization potential in a sample. Since the latter occurs faster than the former under all conditions for the weathering of test composites from Ulu, only geologic materials with a neutralizing potential ratio of greater than 3 will not lead to net acid generation with prolonged weathering at room temperature. Under colder conditions, the ratio required can be as high as 7. However, in this latter case, the annual production of acid is too small to cause any significant impact.

3) The relatively low sulfide oxidation and metal leaching rates observed in the field-column testing of the Ulu ore compared to those observed in the humidity-cell experiments are the results of both a lower average annual temperature and a lower frequency of flushing events occurring at the site.

4) Metal leaching with the Ulu waste rock tested is insignificant but variable amounts of As and Zn may be leached from the ore composite depending on grain size, the ambient temperature and the frequency of flushing. To avoid unnecessary metal leaching problems, it is recommended that ore stockpiled at the Ulu site or for winter-road transport to Lupin should be as coarse as practical. They should definitely not be pulverized to generate a large proportion of grains finer than 1.5 mm in diameter.

5) Since insufficient data have been collected from the field columns to establish long-term trends and that kinetic testing has been conducted only with samples collected from the shallow parts of the Ulu deposit, it is recommended that the field testing program be extended for another two years and more samples be collected from the deeper parts of the deposit for complementary testing as the Ulu Project progresses.

Yours truly,

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APPENDIX I

Glossary

APPENDIX I

GLOSSARY

Antecedent drying period: Time elapsed prior to flushing of the weathering products.

Archean: Early Precambrian, describing the age of the oldest rocks of the Precambrian.

Arsenopyrite: A tin-white metallic mineral with a chemical formula of FeAsS.

Concomitant: Occurring at the same time.

Discordant: A term used to describe an igneous contact that cuts across the bedding or foliation of adjacent rocks.

Efflorescence: Surface encrustation produced by evaporation.

Epigenetic: That formed near the surface of the earth.

Excursion: A deviation from the norm.

Galvanic sulfide oxidation: Preferential oxidative dissolution of a sulfide mineral resulting from the formation of a galvanic cell between two sulfide minerals with differing electrode potentials.

Iron oxyhydroxide: A precipitate containing iron oxide and an hydroxyl (OH) ion.

Lode: A tabular deposit of valuable mineral(s) between definite boundaries.

Mafic: Composed mainly of the magnesian rock-forming silicates.

Metagabbro: A metamorphosed, coarse-grained dark igneous rock.

Pyrrhotite: A magnetic iron sulfide with the general formula of $Fe_{1-x}S$ where x varies from 0 to 0.2.

APPENDIX II

Test Procedures and Sampling Protocols

INTERNATIONAL METALLURGICAL AND ENVIRONMENTAL INC.

Modified Acid Base Accounting

OBJECTIVES:

- to determine the balance between acid producing and acid consuming components of a mine waste.

PRINCIPLES OF TEST:

The fundamental principles of the modified acid base accounting procedure are essentially the same as for the standard procedure, and involve: (1) determination of the neutralization potential (NP) of a sample and (2) calculation of the acid potential (AP) of the sample. The difference between the two values, the net neutralization potential (Net NP), allows classification of the sample as potentially acid consuming or producing. A positive value for the Net NP indicates that the sample is a net consumer of acid. To facilitate comparison of values, NP, AP, and Net NP are all expressed in units of tonnes $CaCO_3$ equivalent per 1000 tonnes.

In the modified method, the neutralization potential is determined by treating a sample with excess standardized hydrochloric acid at ambient, or slightly above (25-30 C) ambient temperatures for 24 hours. Acid is added as required during the acid-treatment stage to maintain sufficient acidity for reaction. After treatment, the unconsumed acid is titrated with standardized base to pH 8.3 to allow calculation of the calcium carbonate equivalent of the acid consumed. The sample is analyzed for total sulphur and sulphate sulphur, and sulphide sulphur is calculated by difference. AP is determined from the calculated sulphide sulphur analysis, assuming (1) total conversion of sulphide to sulphate, and (2) production of 4 moles H+ per mole of pyrite oxidized. In some cases, other sulphur species might be determined.

The modified acid base accounting test is still under development, although the test as described herein has been in use essentially since 1986.

A. Reagents

1. Distilled and deionized water.

2. Certified grade, 1.0 N hydrochloric acid, for standardization of bases.

3. Certified grade, 1.0 N sodium hydroxide for standardization of acids.

4. *0.1 N hydrochloric acid* - using a 100 ml burette, dispense 16.5 ml of concentrated HCl into a 2000 ml volumetric flask and bulk to the mark with deionized water.

5. *0.5 N hydrochloric acid* - using a 250 ml burette, dispense 82.5 ml of concentrated HCl into a 2000 ml volumetric flask and bulk to the mark with deionized water.

6. *0.1 N sodium hydroxide* - measure 8.0 grams of granular NaOH into a plastic weighing boat and transfer the NaOH into a 1000 ml beaker containing 500 ml of deionized water. Place on magnetic stirrer until

dissolved. Transfer into a 2000 ml volumetric flask and bulk to volume with deionized water.

7. *0.5 N sodium hydroxide* - measure 40 grams of granular NaOH into a plastic cup and transfer the NaOH into a 1000 ml beaker containing 500 ml of deionized water. Place on a magnetic stirrer until dissolved. Transfer into a 2000 ml volumetric flask and bulk to volume with deionized water.

NOTE: granular NaOH should only be handled and measured with a plastic spatula and weighing boat. Take extra care not to allow contact with metal.

8. *Phenolphthalein Indicator* - dissolve 0.5g. Phenolphthalein in 50 ml. ethyl or isopropyl alcohol and bulk to 100 ml. with distilled water.

B Reagent Standardization Method:

-Pipette 20 ml of 0.1 N HCl (4.) into a 50 ml beaker. Add 4 to 5 drops phenolphthalein indicator and place on a magnetic stirrer. Titrate with a certified 1.0 N NaOH standard solution from a conditioned 50 ml burette until the endpoint (from a clear to a pink color) is reached. Approximately 2 ml. (lets say 2.1 ml NaOH was used for the example equation).
Duplicate this step to standardize the 0.5 N HCl (5.). The endpoint should take approximately 1.0 ml of the certified 1.0 N NaOH standard solution.

-Pipette 20 ml of 0.1 N NaOH (6.) into a 50 ml beaker. Add 4 to 5 drops phenolphthalein indicator and place on a magnetic stirrer. Titrate with a certified 1.0 N HCl standard solution from a conditioned 50 ml burette until the endpoint (from a pink to a clear solution) is reached. Approximately 2 ml.
Duplicate this step to standardize the 0.5 N NaOH (7.). The endpoint should take approximately 10 ml of the certified 1.0 N HCl standard solution.

Normality (NaOH/HCl) : V(base) X N(base) = V(acid) X N(acid)
e.g.: 20 ml of ? N HCl ,2.1 ml of 1.0 N NaOH was used. Then;

$$(2.1 \text{ ml NaOH})(1.0 \text{ N NaOH}) = (20 \text{ ml HCl})(\ ?\ \text{N HCl})$$

$$\text{Therefore: ? N HCl} = \frac{(2.1 \text{ ml})(1.0 \text{ N})}{20 \text{ ml}}$$

NOTE: Record Normality to 3 decimal places.

C. Procedure

a) Weigh 2.00 grams of sample into a 250 ml Nalgene wide mouth bottle, and add 40 ml (using a 100 ml burette) of 0.1 N standardized HCl.

b) Cover with a film of saran wrap and secure with a punctured lid.

c) Agitate the contents for 24 hours by placing on a mechanical shaker.

d) After 6 hours check the pH of the pulp.

d.i) If the pH of the pulp is below 1.0 at this point, the sample must be rerun starting with a smaller amount of 0.1 N HCl.

d.ii) If the pH of the pulp is above 1.3 at this point, carefully add 0.5 N HCl until the pH drops to 1.2-1.25. Return it to the shaker and continue shaking for the remainder of the test period.

NOTE: The Normality of the hydrochloric acid added at this point should be of the same strength originally added. However, the volume of the bottles may not accommodate the added amount of HCl , therefore, you can use 0.5 N HCl at this point as long as it is accounted for in the final equation.

d.iii) If the pH of the pulp is between 1.0 and 1.3 return it to the shaker and continue for the remainder of the test period.

e) At the end of the shaking period, check the pulp pH. If the total volume and strength of acid was appropriate, the end pH will be in the range 1.0 - 1.5. If the pH is above this range, the amount of acid added is judged to be insufficient for the reaction. If the pH is below the range, the amount of acid added is judged to be too high, causing over- reaction. In either case, repeat the test using the next higher or lower volume or strength of HCl as required.

f) If the pH is within the 1.0-1.5 range titrate the contents using 0.5 N NaOH until a pH of 8.3 is reached. Titrate with NaOH until a *constant reading* of 8.3 remains for at least 30 seconds.

NOTE: The Normality of the sodium hydroxide added at this point should be of the same strength originally added. However, if additional acid of 0.5 N was added at the 6 hour mark then it is best to titrate with 0.5 N NaOH at this point as long as it is accounted for in the final equation.

h) All samples must be run in duplicate.

i) The NBM-1 CANMET standard is run with each set of samples to insure the accuracy of the procedure.

D. Calculations:

1. The neutralization potential, NP, of the sample given by:

$$NP = \frac{50a\,[x - (b/a)y]}{c}$$

where:NP = neutralization potential in tonnes $CaCO_3$ equivalent per 1000 tonnes of material
a = normality of HCl
b = normality of NaOH
c = sample weight in grams
x = volume of HCl added in ml
y = volume of NaOH added to pH 8.3 in ml

2. Different concentrations :

2.1) e.g. If you started with 40 ml 0.1 HCl and 6 ml of 0.489 N HCl was added at the 6 hour mark then the following calculation would be used to determine:

a: $\frac{0.489\ \text{N}}{5} = 0.098\ \text{N}$

$\frac{0.098\ \text{N} + 0.1\ \text{N}}{2} = \underline{0.099\ \text{N HCl}}$

x: $6\ \text{ml} \times 5 = 30\ \text{ml}$

$40\ \text{ml} + 30\ \text{ml} = \underline{70\ \text{ml of .099N HCl}}$

2.2) e.g. con't At the end of the test period 8.6 ml of 0.498 N NaOH was added, then the following calculation would be used to determine:

y: $8.6\ \text{ml} \times 5 = 43\ \text{ml}$

b: $0.498\ \text{N} / 5 = 0.100\ \text{N NaOH}$

Therefore, the NP would be: $\frac{50(0.099\ \text{N})\,[70\ \text{ml} - (0.100\ \text{N} / 0.099)\ 43\ \text{ml}]}{2.00\ \text{grams}} = 65.75$

3. The acid potential , AP, of the sample in tonnes $CaCO_3$ equivalent per 1000 tonnes, is given by:

AP = Percent sulphide sulphur X 31.25

where sulphide sulphur = total sulphur - sulphate sulphur

4. The net neutralization potential, Net NP, in tonnes $CaCO_3$ equivalent per 1000 tonnes of material is given by:

Net NP = NP - AP

E. Interpretation of Results

Interpretation of the Net NP value requires judgment, since although a negative value indicates the theoretical potential of a sample to produce ARD, some samples with this classification are not confirmed as acid producers in kinetic testing or in actual field experience. Of course, this does not imply the ARD will not be produced at some future time. Similarly, samples with positive Net NP values might, under specific circumstances, produce ARD.