4th INTERNATIONAL CONFERENCE ON ACID ROCK
DRAINAGE

Short Course on:

CHEMICAL PREDICTION TECHNIQUES FOR ARD

MAY 31, 1997
VANCOUVER, BC

Presenters: Rick Lawrence, Ph.D., University of British Columbia
Stephen Day, M.Sc., P.Geo., Norecol Dames & Moore

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PROGRAM

SECTION 1 - INTRODUCTION TO THE PREDICTION OF ARD .... 8:30 - 8:45 (RL)

SECTION 2 - THEORY OF ACID ROCK DRAINAGE PREDICTION .... 8:45 - 9:15 (SD)

SECTION 3 - PREDICTION METHODS
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   3.2 Geological Comparisons .... 9:25 - 9:35 (SD)
   3.3 Field Inspections .... 9:35 - 9:45 (SD)
   3.4 Sampling .... 9:45 - 9:55 (RL)

COFFEE BREAK (9:55 to 10:10)

   3.5 Static Geochemical Methods .... 10:10 - 10:30 (RL)
   3.7 Laboratory Kinetic Tests .... 10:30 - 10:50 (RL)
   3.7 Field Kinetic Methods .... 10:50 - 11:00 (SD)
   3.8 Putting the Methods Together .... 11:00 - 11:10 (SD)

SECTION 4 - CASE STUDIES
   4.1 Dublin Gulch Project, Yukon Territory .... 11:10 - 11:20 (RL)
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1.1 Introduction to ARD
1.2 Management of ARD
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1.4 What objectives can be achieved

1.1 Introduction to ARD

Acid rock drainage, ARD, is the most important environmental issue facing the mining industry. Despite several years of fundamental and applied research carried out to understand its formation, and to prevent and control its impact, ARD generation in waste rock, tailings, underground workings, pit walls and other mine components, continues to pose a significant challenge to mining companies in complying with discharge regulations and in the permitting of new operations.

ARD is very complex and can be very expensive to control and treat. It is only relatively recently that the full implications of its impact has been acknowledged in mine planning. The Equity Silver Mine in northern British Columbia, for example, received permits to operate in 1979 without proper consideration for the potential of ARD and within months became an infamous site of contamination due to the generation of metal-contaminated and acidic drainage from waste rock, tailings, and many structures around the mine site which had been constructed from acid generating rock. Since many of our mines were commissioned well before this date, ARD is a common phenomenon at many abandoned and operating sites in Canada and elsewhere in the world and has been a principal cause for the negative image suffered by the mining industry. Even where some provision for the generation of ARD was made in planning and reclamation activities, approaches for control have often been simplistic and have not proven to be effective in the long term.

ARD can be defined as "contaminated drainage resulting from the oxidation and leaching of sulphide-bearing rocks when exposed to air and water". This simple definition, however, belies the complexity of the reactions that give rise to contaminated water in seeps and drainage emerging from mine wastes and other components. Although acidic and contaminated drainage might form in the microenvironment at the surface of a sulphide mineral grain within a waste, the

ultimate quality of the water will depend on a large number of reactions that can occur as it is transported from the initial site of reaction through the waste and out into the receiving environment. These reactions along the flow path can be combinations of chemical, physical, physico-chemical and biological reactions and can either intensify (e.g. oxidative leaching, acid leaching) or attenuate (e.g. adsorption, neutralization, precipitation, reduction, biosorption, biodegradation) the level of contamination. Some of the fundamental aspects of these reactions will be discussed further in Section 2, Theory of ARD. How these reactions should be taken into account in waste characterization and prediction programs will be discussed in Section 3, Methods of Prediction.

1.2 Management of ARD

Successful management of ARD requires an understanding of the fundamental principals of ARD and the factors affecting water quality to be able to anticipate the formation, extent and impact of ARD before mining and milling operations start. This will allow the development of operating and closure plans to reduce or eliminate impact on the environment. Although the details of a specific waste management plan will vary depending on whether it is designed for an abandoned mine, a mine still in operation, or for a proposed operation, the principal elements can be listed as follows:

- Characterization of all mine components that might be the source of acidic drainage at the site and prediction of the occurrence of ARD and its effect on water quality
- Design and implementation of appropriate ARD control measures
- Design and implementation of water treatment facilities, if required
- Design and implementation of a monitoring program to confirm the effectiveness of the waste management design during operation and after closure

For a new mine, a waste management plan can be designed and implemented to prevent the onset of ARD in many cases. At existing mines, developed before ARD management planning was practiced, the challenge is to be able assess the existing wastes and current mining and disposal plans in order to deal with ARD which might already be present and/or to predict future ARD occurrences so that control and closure plans can be developed. In some cases, an effective mitigation strategy can be put in place at an existing mine to control the ARD already being generated. At other operations, ARD might be difficult to control. If this is the case, remediation efforts will need to focus on a combination of control strategies, including the collection and treatment of contaminated drainage, to ensure satisfactory performance at the end of the mine life and after mine closure.

Accurate prediction potentially offers the most cost-effective means of reducing the impact of

ARD on the environment and the associated costs by allowing advanced planning for prevention and control. In most parts of world, demonstration of rigorous waste characterization and prediction is now a prerequisite for the permitting of new operations or the expansion of existing operations. Failure to appreciate or plan for the potential impact of mining and milling activities will delay the approval process and lead to high costs due to environmental problems during operation and after closure. Since financial assurance or bonding to ensure environmental protection is now a significant line item in the budgets of most projects, thorough and accurate prediction programs can also serve to reduce the amount of money that companies must set aside for this purpose.

1.3 What is Prediction?

The underlying objective of any prediction program for ARD is to assess the environmental and economic liabilities associated with mining during operation and after mine closure. To accomplish this objective, it is essential to identify and, as far as possible, quantify the sources and extent of potential contamination and incorporate effective control ARD measures. Acidic drainage can be generated at or within a number of mine site components. Primary sources usually include waste rock, tailings, open pit walls, underground workings, and heaps and dumps after leach operations have terminated. In addition, secondary sources can include ore stockpiles, rock cuts, structures constructed from waste rock, concentrate loadout areas, concentrate spillage, and emergency ponds.

A prediction program for ARD involves carrying out a number of integrated and iterative tests, analyses and procedures to assess the future behaviour of mine wastes and other components. Predictive tests vary in complexity of procedure and data interpretation, the time required to achieve a predictive result and in cost. It is highly unlikely that any one test can produce all the information necessary to evaluate all mine wastes. Combinations of tests are required to provide a reliable assessment.

The scope of a prediction program will depend on site specific conditions and factors. Some programs might comprise few simple tests requiring only a relatively short time period and a modest budget. Others can involve extensive testing and analysis lasting several months or even more than 1 or 2 years, with much higher cost. The approach required might include some or all of the following:

- initial assessment and site reconnaissance
- sampling
- chemical, mineralogical and physical analyses
- short-term leaching tests

- geochemical static tests
- geochemical kinetic tests
- mathematical models

In most cases, previous experience and comparisons with other sites and assessments can be very useful in achieving the objectives of a specific prediction program.

Prediction programs are most commonly associated with new mine projects to assist in the development of plans to store wastes and the final close-out of open pit and underground workings in a manner that ARD generation can be prevented or minimized. However, environmental and economic liabilities need to be assessed for existing operations to assess the possible extent of ARD at the site, to implement appropriate control methods into the waste management plan where no or inadequate measures were previously practiced, and to plan for eventual closure. Similarly, prediction can be used at abandoned mines to allow development of plans for control, remediation and final closure.

With these considerations in mind, the key questions to be asked in most prediction programs are:

- Is there a potential for ARD generation?
- Will the potential for acid generation be realized?
- When will ARD be generated
- How much ARD will be generated?
- For how long will ARD be generated?
- What will be the water quality?
- Will control measures work?
- Will the mine remain in compliance?

Prediction tests must be designed and interpreted in a way that the mode of occurrence or deposition of the waste and the mechanism of ARD generation are taken into account when designing a prediction test program and in the interpretation of results. Mechanisms of acid generation and in the controls that affect ultimate water quality can vary significantly. For example, ARD generation and transport in a waste rock pile is different to that in a tailings impoundment. In waste rock, air infiltration can occur at any point at the dump and is relatively rapid due to convection and barometric pumping. In tailings, however, air infiltration occurs only at the surface and is limited by the rate of diffusion. Diffusion rates in tailings are, in turn, dependent on the moisture content of the tailings, with rates being extremely slow in areas of high moisture content or saturation. In contrast, water flow in waste rock piles can be relatively unconfined, with resulting rapid release of seepage. However, several studies have shown that the percentage of rock which actually gets flushed can be quite low for many areas of a pile.

Despite this, the initiation of ARD and appearance of contaminated water can be quite rapid for waste piles. In contrast, the slow displacement of water within a tailings mass often means that the emergence of water of poor quality might not occur until long after mine closure.

A summary of the stages of a typical ARD prediction program which is incorporated into the overall ARD management strategy is shown schematically in Figure 1.1.
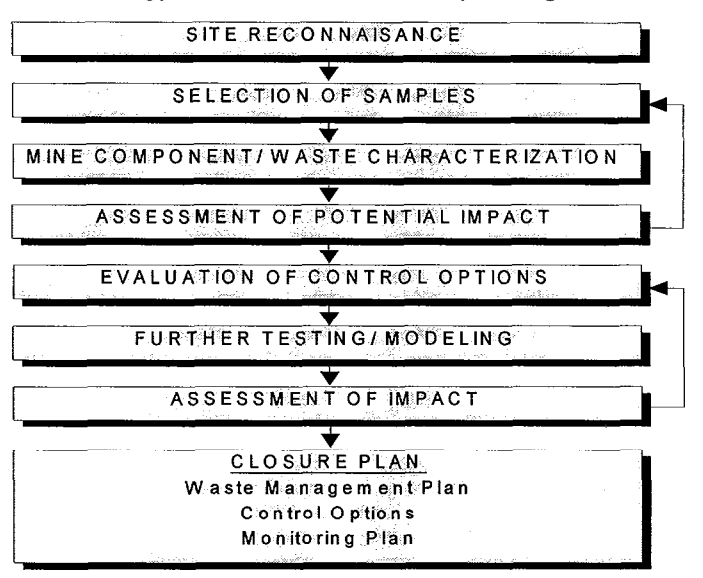

Figure 1.1 Typical Stages of an ARD Prediction Program

1.4 What Objectives can be Achieved by Prediction

Prediction of ARD can be seen to be a short term assessment of a potentially long term phenomenon. For all tests and procedures, therefore, interpretation of data will have a lesser or greater extent of uncertainty associated with it. In general, the level of uncertainty in meeting objectives increases with decreasing size of test (decreasing quantity of material) and with decreasing duration of the test. Both factors are particularly pertinent for a group of procedures known as static tests which are conducted on very small quantities of material and for which no insight into temporal effects (kinetics) is possible. Certainty in the prediction of the occurrence of acid generation and on the resultant water quality is only possible from observation of the behaviour of the full scale waste facility after a period of time which is almost always substantially longer than any test can simulate in a practical time frame (i.e. determination of "what actually happened"). This means that almost all test results have to be interpolated into the future. Significant differences exist between the field and laboratory climate and conditions that are related to both scale and the ability to simulate changes and variations in conditions, particularly for tests that are smaller and shorter in duration. For all tests, therefore, one or more

of the conditions and variables that define, or will define, a particular full scale waste facility will have to be estimated based on experience and/or modeled mathematically.

As will be seen in Section 3, tests vary in scale from simple laboratory procedures conducted on very small samples of material, larger laboratory tests, to field tests. The differences between the laboratory or field tests and prototypes and the actual waste facility as scale is increased can be categorized as follows:

- increasing sample size and material variability
- increasing average and maximum grain size
- increasing variability in seepage and flushing paths
- increasing thermal and convective air effects
- increasing complexity of flow path geochemistry

The following table indicates the extent of the numbers of parameters that cannot be determined using a specific scale of test or physical model and which will have to be estimated or modeled. It can be noted that the sample size difference between the smallest kinetic test shown (1 kg in a humidity cell) and a 5×10^7 t waste pile is 10 orders of magnitude.

Physical Model or Test	Sample Size	Mathematical Modeling Requirements
Full scale waste rock pile	5×10^7 t	
Field test pile	2×10^3 t	size, thermal. rock variability
Field barrels or test plots	1.0 t	*all the above plus* size distribution, seepage paths
Laboratory kinetic column or large scale humidity cells	5×10^{-2} t	*all the above plus* seepage/flush flows, reaction product storage, climate
Humidity cell test	1×10^{-3} t	*all the above plus* chemical/biological micro-climates
Acid base accounting	2×10^{-6} t	*all the above plus* all reaction kinetics

It is clear, therefore, that predictions of the occurrence, timing, and magnitude of ARD is not precise in many cases. Factors of safety need to be built into any interpretations and in any designs based on them.

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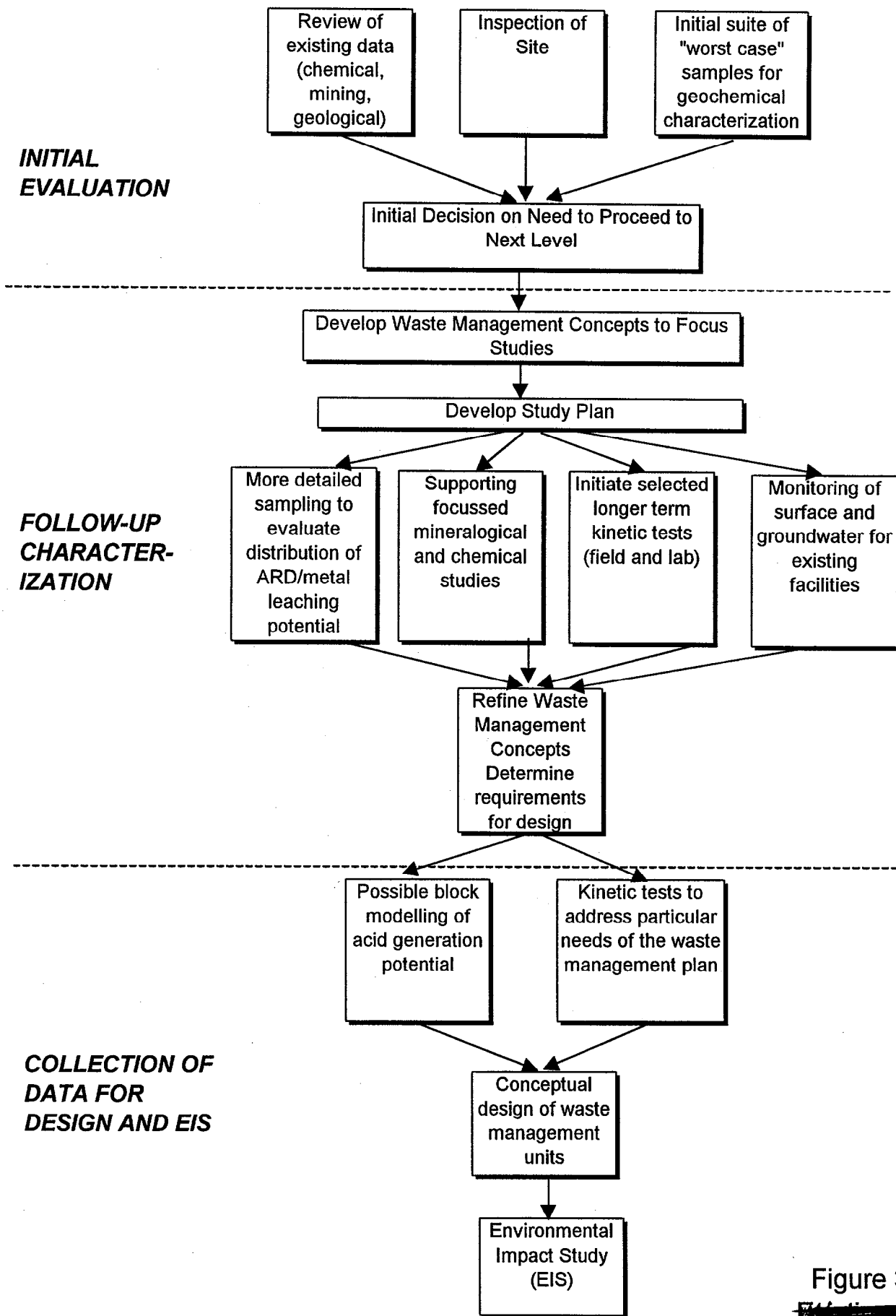
INITIAL EVALUATION

Review of existing data (chemical, mining, geological)

Inspection of Site

Initial suite of "worst case" samples for geochemical characterization

Initial Decision on Need to Proceed to Next Level

Develop Waste Management Concepts to Focus Studies

Develop Study Plan

FOLLOW-UP CHARACTER-IZATION

More detailed sampling to evaluate distribution of ARD/metal leaching potential

Supporting focussed mineralogical and chemical studies

Initiate selected longer term kinetic tests (field and lab)

Monitoring of surface and groundwater for existing facilities

Refine Waste Management Concepts Determine requirements for design

COLLECTION OF DATA FOR DESIGN AND EIS

Possible block modelling of acid generation potential

Kinetic tests to address particular needs of the waste management plan

Conceptual design of waste management units

Environmental Impact Study (EIS)

Figure 3.6-1

Stage of ARD Prediction

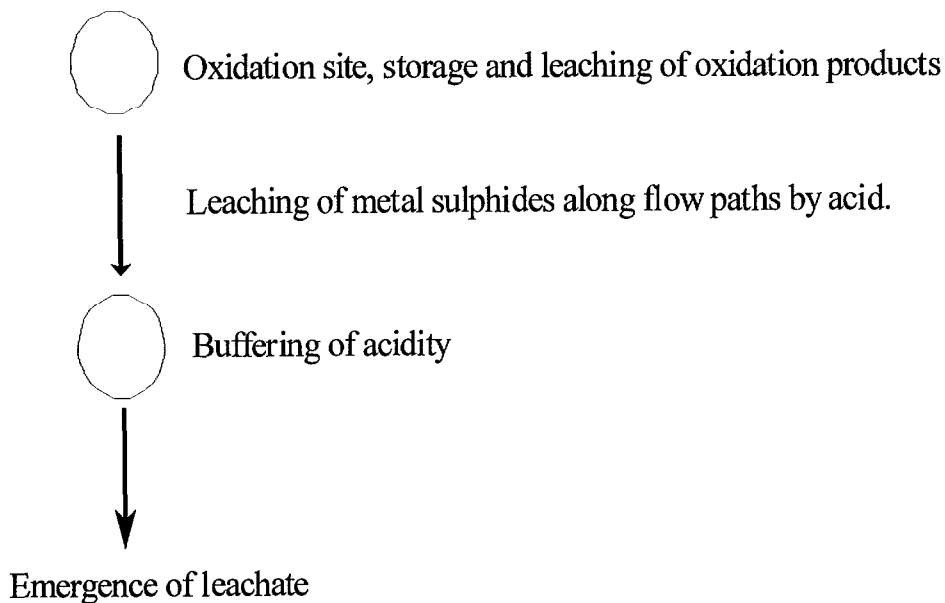# SECTION 2 - THEORY OF ACID ROCK DRAINAGE PREDICTION

Aspects Covered in this Section

2.1   The pyrite oxidation reaction.

2.2   Sulphur-containing minerals that can and cannot produce acid.

2.3   Leaching of heavy metal sulphides by acid leachate metals

2.4   pH buffering

2.5   The importance of mineral availability and reaction rates

Introduction

This section presents the basics of acid generation as it relates to chemical prediction studies. Particular emphasis is placed on the importance of mineralogy in predicting the composition of drainage.

The composition of mine drainage, including its acidity depend on a series of processes illustrated conceptually as follows:

Oxidation site, storage and leaching of oxidation products

Leaching of metal sulphides along flow paths by acid.

Buffering of acidity

Emergence of leachate

Sections 2.1 to 2.5 discuss these processes in more detail. Sections 2.1 to 2.4 refer to reactions without reference to reaction rate and availability of minerals.

2.1 The Pyrite (FeS_2) Oxidation Reaction

Pyrite, composed of ferrous iron (Fe^{2+}) and disulphide (S_2^{2-}) is oxidized to ferric iron (Fe^{3+}) and sulphate (SO_4^{2-}). Under well-oxygenated atmospheric conditions, the ferric iron precipitates as iron hydroxide ($Fe(OH)_3$). The overall reaction releases acidity expressed as H^+.

$$FeS_2 + 15/4O_2 + 5/2H_2O \rightarrow Fe(OH)_3 + 2SO_4^{2-} + 4H^+;$$
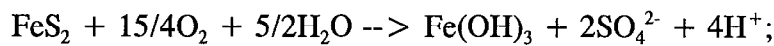
For most laboratory and field prediction studies, this is the fundamental reaction. In reality, nuermous complicating factors need to be considered, such as incomplete oxidation, oxidation potential, other oxidants and auto-oxidation.

The most important implications of the reaction to prediction studies are that:

 ♣ acid production requires minerals composed of sulphur as sulphide and usually ferrous iron.
 ♣ oxidation is catalyzed by bacteria.
 ♣ oxidation of 1 part (mole) of pyrite produces 4 moles of acidity.

## 2.2 Sulphur-containing minerals that can and cannot produce acid

The pyrite oxidation reaction shows that understanding the sulphur content is an important aspect of prediction studies. However, not all sulphur minerals can produce acid therefore understanding the sulphur mineralogy is extremely important. In nature, there are major two types of sulphur-containing minerals: sulphides and sulphates. The acid producing potential of minerals within these groups are presented below.
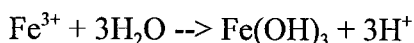
Sulphide Minerals

As noted above, acid production usually requires minerals composed of sulphur as sulphide and ferrous iron (for example, pyrite (FeS_2)). The oxidation of pyrite can be represented as three steps. Firstly, sulphide oxidizes to sulphate (2 moles of acid for every mole of pyrite):

$$S_2^{2-} + 7/2O_2 + H_2O \dashrightarrow 2SO_4^{2-} + 2H^+$$
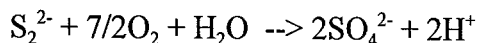
then ferrous iron oxidizes to ferric iron (then 1 mole of acid consumed for every mole of pyrite):

$$Fe^{2+} + \blacksquare O_2 + H^+ \dashrightarrow Fe^{3+} + \blacksquare H_2O$$
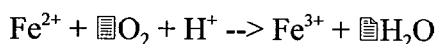
Finally, ferric iron is hydrolyzed to produce ferric hydroxides (releasing three moles of acid for every mole of pyrite):

$$Fe^{3+} + 3H_2O \dashrightarrow Fe(OH)_3 + 3H^+$$

On balance four moles of acidity are released for each mole of pyrite (two moles of acidity for each mole of sulphur).

Similarly, the mineral troilite produces two moles of acid for each mole of sulphur:

$$FeS + 9/4O_2 + 5/2H_2O \dashrightarrow Fe(OH)_3 + SO_4^{2-} + 2H^+$$
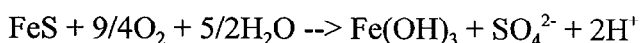
Common iron-containing sulphide minerals capable of producing acidity (when completely oxidized) are:

- Pyrite (FeS_2)
- Marcasite (FeS_2)
- Pyrrhotite ($Fe_{1-x}S$)
- Chalcopyrite ($CuFeS_2$)
- Bornite (Cu_3FeS_4)
- Arsenopyrite ($FeAsS$)

It should be noted that if conditions are not strongly oxidizing (ie only sulphur is oxidized), oxidation of minerals composed of sulphide rather than disulphide and metals which are not hydrolyzed except at high pH, will not result in acidic conditions.

$$FeS + O_2 \dashrightarrow Fe^{2+} + SO_4^{2-}$$
$$ZnS + O_2 \dashrightarrow Zn^{2+} + SO_4^{2-}$$
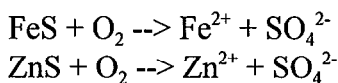
Common sulphide minerals which cannot produce acidity include:

- Sphalerite (ZnS)
- Galena (PbS)

This does not mean that these sulphide-containing minerals do not oxidize to release the associated metals (Pb, Zn). It does however illustrate that when considering acid potential, it is important to understand the sulphide mineralogy because not all sulphide minerals will contribute to the acid potential.
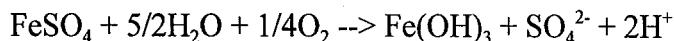
Sulphate Minerals

Sulphate is the most completely oxidized form of sulphur, therefore it cannot be oxidized further. Common natural sulphate minerals are:

- Gypsum $(CaSO_4 \cdot 2H_2O)$
- Anhydrite $(CaSO_4)$
- Barite $(BaSO_4)$
- Anglesite $(PbSO_4)$

The first two minerals dissolve readily in water releasing calcium and sulphate to solution. They do not contribute acidity to leachate.

Barite and anglesite are relatively insoluble and contribute small amounts of sulphate, and barium and lead, respectively to leachate.

Other types of sulphates are a result of sulphide oxidation and are stored in oxidized rock because leaching water was insufficient to completely remove the products as they formed. There are numerous sulphate minerals in this group. When dissolved these minerals can be a source of acidity. For example, ferrous iron sulphate:

$$FeSO_4 + 5/2H_2O + 1/4O_2 \rightarrow Fe(OH)_3 + SO_4^{2-} + 2H^+$$

2.3 Leaching of Heavy Metal Sulphides by Acid Leachate

The leachate produced by oxidation of pyrite is strongly acidic and oxidizing. Ferric iron in solution is a strong oxidizing agent and oxidizes pyrite without oxygen:

Minerals such as sphalerite, galena and chalcopyrite are oxidized in the acidic environment releasing zinc, galena and copper to the leachate:

$$ZnS + 2O_2 \rightarrow Zn^{2+} + SO_4^{2-}$$
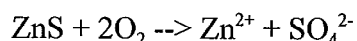
The mobility of the metals liberated depends on the solubility of the metal sulphate minerals. Zinc and copper are readily mobilized since zinc and copper sulphates are highly soluble. Lead sulphate is by contrast highly insoluble. Much of the lead released by oxidation of galena remains at the oxidation site as lead sulphate which occurs as a non-metallic grey coating.

These reactions do not in themselves result in major changes in pH.

2.4   pH Buffering

Acidic leachates also attack other more common minerals that result in increases in pH. These minerals include:

- carbonates.
- hydroxides and oxides.
- silicates.

pH buffering refers to the stable pH resulting from interaction of a leachate with a mineral. Minerals buffer at a variety of pH's ranging from strongly acidic to strongly alkaline according to the relationship between mineral solubility and pH. The buffer pH of a mineral is not constant but depends on overall solution chemistry, the gas composition in contact with the solution and whether the system is open (ie having an infinite supply of reactants) or closed.

Contact time of solutions with minerals is a very important factor not discussed in this section. If the contact time is short, equilibrium conditions will not develop and the true buffering capacity will not be realized. The following discussion assumes that equilibrium conditions occur.

Carbonate Minerals

The most common example is calcite which buffers pH to near 7. Depending on the pH, acidity is consumed by a combination of two reactions to produce bicarbonate (HCO_3^-) or carbonic acid ($H_2CO_3^\circ$):

$$CaCO_3 + H^+ \rightarrow Ca^{2+} + HCO_3^-$$

$$CaCO_3 + 2H^+ \rightarrow Ca^{2+} + H_2CO_3^\circ$$
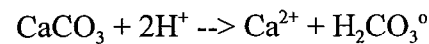
The former reaction is important in weakly acidic to alkaline environments whereas the latter occurs when conditions are very strongly acidic.

Other common carbonates are capable of buffering pH to 6 or 7. These include:

- Dolomite ($CaMg(CO_3)_2$)
- Magnesite ($MgCO_3$)

Siderite ($FeCO_3$) is also quite common in mineralized systems and sedimentary rocks associated with coal deposits. Under well-oxidized conditions siderite is not a useful buffering agent because oxidation of ferrous to ferric iron and subsequent precipitation of ferric iron hydroxide produces as much acidity as is consumed by the carbonate. Under non-oxidizing conditions (such as flooding), siderite is an effective neutralizing agent because the ferrous iron does not oxidize to ferric iron.

Hydroxide and Oxide Minerals

Common hydroxide and oxide minerals buffer solutions at lower pH than the carbonate minerals. Examples are iron hydroxide which buffers pH between 3.0 and 3.5, and aluminum hydroxide which buffers pH between 4.5 and 5.0.

Silicates

Silicates are the largest mineral group and comprise a huge variety of minerals composed of silicon combined with other common elements such as iron, aluminum, potassium, sodium, calcium and magnesium. The buffering pH of these minerals depends on the solubility of the metals released by interaction between the mineral and acidity.

For example, the buffering capacity of a relatively simple calcium silicate such as wollastonite ($CaSiO_3$) would be controlled by the solubility of calcium carbonate minerals assuming buffering occurs in equilibrium with the atmosphere. pH would be expected to be buffered at near neutral conditions.

$$CaSiO_3 + H_2O + 2H^+ \rightarrow Ca^{2+} + H_4SiO_4$$
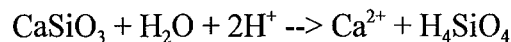
A similar conclusion would be expected for magnesium silicate minerals.

Alumino-silicates release aluminum when interacting with acid. For example, kyanite

$$Al_2Si_2O_5(OH)_4 + 6H^+ \rightarrow 2Al^{3+} + 2H_4SiO_4 + H_2O$$
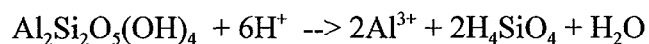
However, aluminum solubility is controlled by the solubility of aluminum hydroxide which buffers pH around 4.5:.

$$Al^{3+} + 3H_2O \longrightarrow Al(OH)_3 + 3H^+.$$
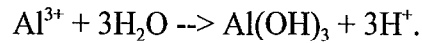
The foregoing demonstrates the importance of mineralogy when understanding buffering capacity.

Progress of Buffering

An assumption of buffering is that a particular mineral component is available in infinite amounts at a particular moment in time. As a mineral becomes exhausted, excess acidity is available and is buffered by a mineral at a lower pH. In situations where calcite is the only mineral available to buffer at higher pH's, the pH of the leachate very rapidly decreases from near 7 (buffered by calcite) to near 3 (buffered by ferric hydroxide) (see Figure below).

Theoretically, steep transitions followed by pH plateaus should be a result of buffering by calcium carbonates, iron carbonates, alumino-silicates and ferric hydroxide. In reality, where many different minerals are capable of buffering, the transition from near neutral pH to ferric hydroxide buffered does not occur sharply but steadily over a long period as different minerals buffer the leachate pH.
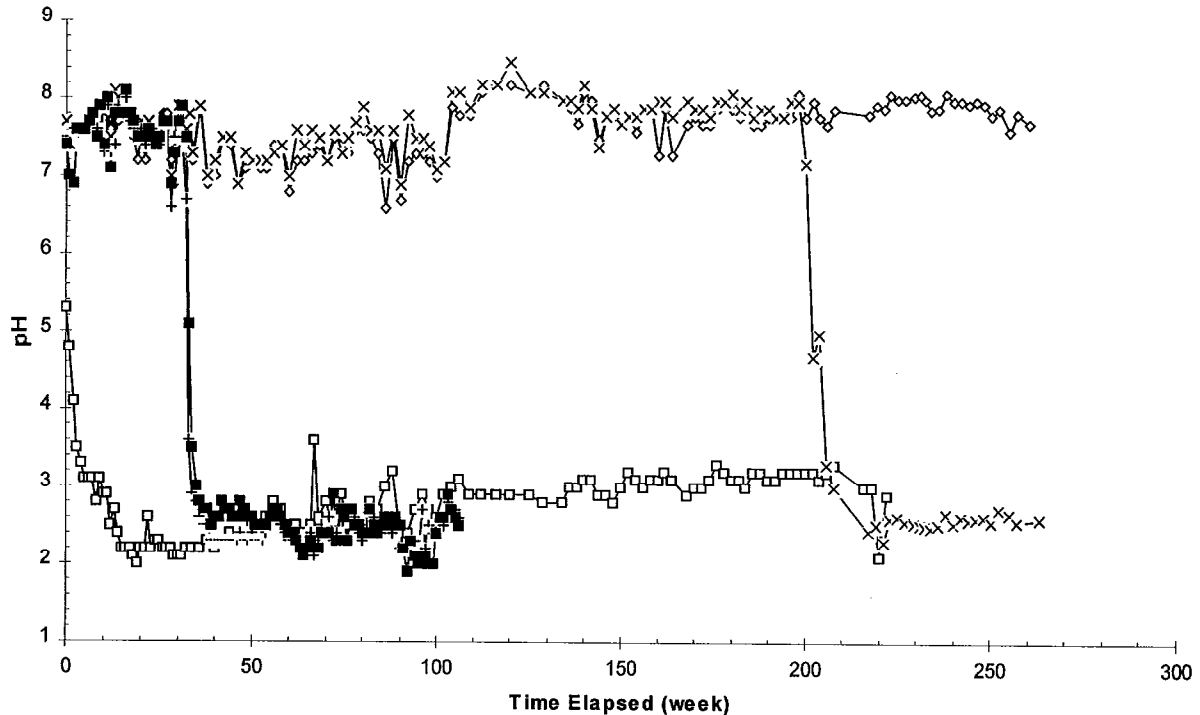
2.5 The importance of mineral availability and reaction rates

The above discussions address the relevant chemical reactions without referring to the availability of minerals and the reactions rates. There are two important aspects to consider:

1.   The exposure of a mineral may make it more or less available for reactions.

2.   The rate of oxidation of sulphide minerals and the ability of acid neutralizing minerals to meet demand.

These are discussed further in the following sections.

Mineral Exposure

Mineral exposure is relevant to the availability of both acid generating and acid consuming minerals. Natural exposures of mineral deposits often contain small quantities of pyrite despite possibibly thousands of years of weathering. These minerals grains are often found to be encapsulated in slow-weathering silicates (eg quartz). In mine wastes, the prerential exposure of minerals can lead to greater availability. For example:

1.   Pyrite may occur as fracture coatings which when exposed due to mining are exposed on fractures faces and also more readily broken down and become reactive fines.

2.   Likewise, calcite often occurs as a fracture fillings and partings.

3.   Calcite is sometimes formed as a low-grade metamorphic alteration product and may be encapsulated by resistant silicates such as feldspars.

Mineral exposure is very unlikely to be constant for a mineral property. Different rock properties lead to different mineral occurrences. For example, a brittle rock type would be more likely to have openings (fractures) which fill with minerals whereas ductile rock types may not have the same mineral occurrence.

Mineral exposure is very difficult to quantify however, it is relative factor that needs to be quantified.

Reaction Rates

Reaction rates is a complex area which will only be briefly be addressed for the relevance to prediction studies.

Sulphide Minerals

The rate of acid production by sulphide minerals can depend on numerous factors which include:

- pH
- Eh
- temperature
- surface area
- cystallinity
- chemistry of pore waters
- types of oxidants
- humidity
- frequency of leaching
- types of minerals.
- trace element content of minerals

Due to the number of factors, few generalizations can be made on reactions. It is commonly though that pyrrhotite is more readily oxidized by pyrite though is not always the case. Pyrite occurs in a variety of forms some of which are know to render it highly reactive. For example, pyrite associated with coal wastes sometimes occurs as framboids which are more reactive than coarse cubic crystalline pyrite.

Acid Neutralizing Minerals

The rate at which acid neutralizing minerals can consume acidity is important when considering factors such as lag times for storage of potentially acid generating wastes. It is commonly observed for acid producing wastes that initially strongly acid consuming minerals (such as,carbonates) remain in the wastes even after acid production has begun. Mass accounting for kinetic tests on acid producing wastes indicate that only a portion of the neutralizing minerals are available to neutralize acid prior to the onset of acid leaching but these minerals continue to be leached agressively once acidity is being generated. Several factors can effect the reactivity of acid consuming minerals. These include:

- The type of acid neutralizing minerals.
- Particle surface area.
- pH
- Eh
- Contact times
- Leachate chemistry
- Precipitates formed by neutralization.

Contact time and particle surface area are probably the most significant factors. In strongly reactive materials, the acid release typically quickly overwhelms the available carbonate resulting in acidic conditions. However, a significant amount of carbonate may remain.

There has been considerable discussion about the availability of silicates to buffer acid solutions. The main limitation of silicates is that many of the minerals are chemically resistant and react slowly. Though they may in theory provide neutralizing capacity, contact times may be too short. Silicates are likely to offset acidity under strongly acid generating conditions but they are unlikely to significantly delay the onset of acidity. The exceptions to these comments may include the soft layer silicates such as chlorite.

SECTION 3 - PREDICTION METHODS

Aspects Covered in this Section

3.1 Introduction and Definitions

The prediction of ARD is facilitated by carrying out a combination of field observations, and a number of analyses and tests. A thorough prediction study draws from all information sources including geological knowledge, natural weathering conditions and testwork at various scales. A range of different types of tests are available and which are intended to determine specific characteristics and parameters based on the fact that drainage water quality from a waste facility or mine component depends on a number of factors including:

- waste rock characteristics
- rate of mineral oxidation and acid generation
- rate of metal leaching
- rate of acid neutralization
- solubility of metal species (pH)
- accumulation of oxidation products
- reactions along the flow path

The procedures that will be described in the following sub-sections attempt to provide insights and, where possible, values for the above factors.

The terminology of prediction testing is not standard throughout the industry and some confusion in the terms used can arise when reports by different authors or from different parts of the world are compared. The following list is by no means the "official list" but it presents some of the most commonly accepted terms and their definitions:

Paste pH	the pH of a paste made from mixing finely ground sample with water
AP, acid potential	the potential of a sample to generate acid based on the total sulphur content. $AP = S\% \times 31.25$
SAP, sulphide acid potential	the potential of a sample to generate acid based on the sulphide sulphur content. $SAP = Sulphide \% \times 31.25$
NP, neutralization potential	the capacity of a sample to consume acid
Carbonate NP, or Carb-NP	the capacity of a sample to consume acid due to carbonate minerals
Field NP (or available NP)	the effective NP or the NP actually available in the field
Net NP (or NNP), net neutralization potential	the difference between NP and AP, Net NP = NP - AP
NPR, neutralization potential ratio	the ratio of NP:AP
NAP, or NAG	net acid potential, or net acid generation derived in a peroxide test

AP, NP and other parameters are usually expressed in units of either kg $CaCO_3$ equivalent per tonne of material or tonnes $CaCO_3$ equivalent per 1000 tonnes of material.

3.2   Geological Comparisons

Geological comparisons can be used as an initial screening tool when assessing a new deposit or mine.   The main assumption in such comparisons is that there are common factors in the formation of mineral deposits. The main limitation is that almost every desposit of a commodity amenable to mining has different characteristics.

Example from the Appalachian Coal Mining Region

The earliest example of using comparisons between deposits describes attempts to understand the potential for acid drainage at coal mines based on observed conditions at other nearby coal mines (EPA-600/7-77-067). It is also a good example of the principles involved.

In the Appalachian region, many of the seams are continuous regionally and are exploited at many different locations. It was observed that mines in certain seams are prone to acid mine drainage.

The explanation for these observations was found in the paleoenvironment of formation of the

seams. Seams formed in salty paleo-environments are observed to have sulphur in a reactive form than seams formed in brackish environment. On a broader scale, coals formed in freshwater environments would be expected to have lower sulphur content due to the generally low sulphate concentrations in these environments.

Such comparisons require care and cannot be used without supporting information from other studies. For example:

♦   geological depositional environments can change over short distances both laterally and vertically;

♦   post-formation factors can affect the composition of the coal and host rocks;

♦   mining methods can make a significant difference to the potential for acid generation.

Application to Metal (Hardrock) Mining

Coal deposits represent a relatively simple depositional environment (ie low temperature and low pressure) and a defined mechanism for controlling acid generation potential.

Metal mines (hardrock deposits) represent a much more complex depositional environment because the mineralization is formed under extreme conditions of temperature and pressure usually by hot fluids interacting with rocks and other fluids.

The first step in a geological comparison is to classify the deposit according to standard genesis based systems. The geologist most familiar with the geological environment and the deposit should be responsible for the classification. Secondly, general information should be assembled.

This could include:

♦   the age of the mineralization and host rocks;
♦   main rock types expected to be exposed during mining;
♦   the types and proportions of reactive minerals in each rock type;
♦   the occurrence of the reactive minerals;
♦   the physical weatherability of the rock;
♦   the likely mining method; and
♦   climatic information (ie, temperature range, precipitation patterns).

Having assembled this information it can then be compared with data for similar projects. Table

3.2-1 summarizes existing knowledge of the classification of genetic deposit types according to acid rock drainage susceptibility.

TABLE 3.2-1

CLASSIFICATION OF COMMON MINERAL DEPOSIT TYPES ACCORDING TO AMD SUSCEPTIBILITY

DEPOSIT TYPE	SUSCEPTIBILITY RANGE		
	HIGH	MEDIUM	LOW
Volcanogenic massive sulphide, any type.	A/M		
Coal formed in saltwater environment	A	M	
Coal formed in freshwater environment			A/M
Skarn		A/M	
Limestone-hosted lead and zinc		M	A
Epithermal vein - volcanic hosted		A/M	
Epithermal vein - sediment hosted		A/M	
Geologically oxidized ore deposits, any type		M	A
Magmatic sulphide deposits	A/M		
Mesothermal vein		M	A
Porphyry (calc-alkalic)		A/M	
Porphyry (alkalic)			A/M

Note:
A = Acid drainage
M = Metals/metalloids, regardless of acidity

MEND Project 1.32.1 resulted in a simple classification scheme for mineral deposits based on their mineral composition

Examples of potential situations where geological comparisons are not likely to be successful include:

♦ The two deposits are in the same geological system but one is epithermal gold mineralization whereas the other is porphyry copper mineralization;

    ❀   One deposit is an existing underground mine whereas the proposed mine is a large open pit; and

    ❀   One deposit is hosted by sedimentary rocks and the other is hosted by intrusive igneous rocks.

3.3   FIELD INSPECTIONS

Background

Determination of the weathering characteristics of rock in the field is usually the objective of predictive test work, therefore examination of existing waste rock piles and natural accumulations of broken rock can provide valuable information regarding the longer term behaviour of waste rock without conducting extended testing under laboratory or field conditions. The main limitation of this approach is that the initial characteristics of the test materials cannot easily be determined except at the local grain scale where larger rock fragments may have characteristics indicative of initial conditions. The composition of larger rock piles can not generally be reliably determined and related to drainage conditions.

Old Mine Workings

Examination of old waste rock piles can provide weathering information relevant to time scales varying from a few years to several centuries (in historical mining areas). These provide an obvious analog to proposed or newer piles. The main limitations to be considered are the similarities of the various piles being compared. Variations in ore source, mining methods, including extraction methods, scale and efficiency can have significant effect on the composition of rock piles.

Natural Exposures

Examination of naturally weathered rock can provide information over time scales varying from centuries to several millenia, depending on local climatic conditions, physiography and geology. Possible sources of information are weathered outcrops, talus, glacial moraines, soils and gossans. However, comparison of natural accumulations of broken rock to artificial waste rock piles requires care since the conditions of formation are dissimilar mainly with respect to rates of physical and chemical processes. Some limitations in applications are presented below.

Limitations

Observations of existing site conditions should, if possible be a part of ARD prediction projects. The main requirement for such studies is that the geology of the older waste pile or natural rock exposure should be relevant to the proposed mine. In the case of comparing old mine workings to proposed or existing newer mines, comparisons may not be relevant if the new mine will be an open pit exploiting lower grade mineralization but the old mine used underground methods to follow high grade zones. Nonetheless, even in such cases, examination of individual samples of oxidized wastes can be used.

When attempting to use natural weathering features to predict behaviour in waste rock piles, the following differences between natural and artificial piles should be considered:

 ❧ Physical breakage by natural processes (freeze-thaw, heating-cooling, gravity) compared to use of equipment and explosive. These will relate to rate of release of reactive minerals and the mineralogical composition of size fractions;

 ❧ Availability of Oxygen and Moisture. In fractured rock masses, oxygen and moisture may be less available due to tighter fractures.

 ❧ Intimacy of Mineralogical Contact. Contact between conductive minerals in particular is greater in natural outcrops than would be expected in rock piles resulting in stronger and larger galvanic cells.

 ❧ Degree of Mixing. Mining tends to result in mixing of rock from different sources. Natural features may not show the same degree of mixing.

Methods

In general, methods applicable to assessment of rock piles and natural exposures can include:

 ❧ Description of rock mineralogy in field hand samples, including reactivity of carbonates determined by fizz reaction with dilute hydrochloric acid;

 ❧ Observation of preferential exposure of minerals along exposed fractures and other zones of weakness;

 ❧ Observation of large and small-scale weathering features on rock fragments including oxidation coatings (colour and type) and efflorescent minerals (Table 3.3-1 provides

some examples of common coatings.)

    Measurement of paste pH on rock fines (1:1 (v/v) water:solid mixture) determined to assess the availability and acidity of soluble oxidation products. A paste pH less than 5 (reached rapidly) indicates the presence of acidity. The pH of the water used in the test should be determined beforehand;

    Measurement of pH and TDS for seepage, observations of precipitates and rock corrosion by seepage;

    Description of presence or absence of vegetation cover; and

    Observation of variations in snow cover as an indication of heat production

There are no standard methods for incorporating data from such studies into larger prediction studies. The studies provide supporting information in a variety of very site specific applications.

TABLE 3.3-1
INTERPRETATION OF OXIDATION COATINGS

COATING DESCRIPTION	MINERAL OR CHEMICAL COMPOUND	INTEPRETATION
Yellow associated with iron sulphide	Jarosite	Strongly acidic oxidation products
Orange and dark brown associated with iron sulphide	Limonite	Iron sulphide weathering
Light orange as a coating on carbonates	Limonite	Formed from iron carbonate.
Light brown on rock surfaces	Limonite	Formed by slow weathering of silicates
White associated with pyrite	Iron sulphate	Strongly acidic coating
Green or blue	Basic copper carbonate or copper sulphate	Formed by weathering of copper minerals in alkaline or acidic conditions.

Note: Limonite is a term used to describe a mixture of the minerals geothite, lepidocrocite and jarosite.

3.4   Sampling

Poor sampling techniques and inadequate sample selection can contribute more to excessive variance, difficulties in data interpretation and incorrect assessment than other factor in a prediction program. A sampling program should include or attention paid to the following:

- consultation with geologists to assess the number and type of lithological units which should be sampled and evaluated
- consultation with the mine planners to determine mining sequence and options for waste disposal
- selection of an appropriate sampling method
- samples should be fresh and be handled, labeled, transported and stored carefully
- all lithological units should be represented
- the size and number of samples should be appropriate to the mine plan
- number and type of samples will be site specific
- caution must be taken with respect to composite samples; spatial variations should be considered if composites are to be tested.
- rigorous laboratory procedures for sample preparation must be followed
- chain-of-custody records should be maintained

3.5   Static Geochemical Methods

Elemental and Other Analyses

Waste characterization programs should include analysis and measurement of a number of chemical, physical and mineralogical properties of samples for use in the interpretation of the results of static and kinetic tests.

Chemical tests which can be carried out include:

- metals by ICP, AA, and/or XRF. Digestion procedures used (aqua regia, HF, fusions) should be specified in reporting.
- sulphur species, including total, sulphate, and sulphide sulphur. In addition, if barite is known to be present, sulphur associated with this mineral should be determined as it is not analyzed in standard sulphate analysis. Typically sulphide-sulphur is determined by difference between total sulphur and sulphate-sulphur.
- inorganic carbon for assessment of carbonate content (see section 3.5.3)

Physical parameters that can be determined include:

- particle size/surface area. Size analysis usually can be performed using screens. Separation procedures for very fine fractions can be used for specific applications.
- bulk and particle density
- porosity and permeability of a rock mass or tailings
- physical weathering characteristics such as slaking under field conditions, including freeze/thaw behaviour

Mineralogical analyses:

Methods used for mineralogical analysis range from simple visual examination of core or hand specimens, through standard thin section and reflected light microscopy, to more sophisticated methods of analysis such as XRD. Various computer programs also exist to provide an inferred analysis based on elemental or whole rock analysis.

Mineralogical features which are relevant to ARD studies and should therefore be noted include:

- *Sulphide Mineralogy* - mineral types and percent occurrence; frequency and nature of any direct contact between grains of different sulphides; crystal deformation and other signs of stress; presence of inclusions; and the presence of coatings and secondary minerals; morphological features such as fabric and habit; grain size
- *Carbonate Mineralogy* - mineral types and percent occurrence; presence of coatings; grain occurrence (random, structural controls); morphological features such as grain size, fabric and habit.
- *Silicate Mineralogy* - mineral types; percent occurrence of minerals, classified according to relative reactivity; morphological features.
- *Particle characteristics (for different size fractions)* - shape and angularity; presence of micro-fractures; competence/slaking potential; indications of porosity and permeability.
- *Realtionship and variability of Sulphides, Carbonates and Silicates* - presence of sulphides, carbonates and silicates on outer surfaces; spatial relationship of minerals (direct contact or separate within particles).

Short Term Leach Tests

Evaluation of the readily-soluble constituents of wastes is important to determine the water quality that might arise when wastes are first placed in the environment. A number of tests are can be used for this purpose. Tests are typically 24 hours in duration and involve contacting a finely ground sample with a leach solution in an agitated system. Test differ mainly in the type

of solution used which might simply be distilled water or an inorganic (e.g. sulphuric, nitric) or organic (e.g. acetic, citric) acid.

A list of some procedures used is as follows:

- Shake flask extraction using distilled or deionised water at 3:1 liquid:solid ratio
- Special Waste Extraction Procedure (SWEP) used in B.C. (acetic acid at 20:1 liquid:solid ratio)
- TCLP procedure (U.S. EPA Method 1311) (NaOH and acetic acid)
- WET procedure (California) (citric acid)
- ASTM 1320 (carbonic acid extraction)
- EPA Method 1312 (sulphuric/nitric extraction at pH 4.5 or 5.5)
- ASTM procedure D3987 (carbonic acid extraction)
- Nevada Meteoric Water Mobility Test (nitric acid)

Static Tests

Static tests are typically simple and inexpensive procedures to provide a preliminary assessment of the potential of a waste or other mine component to generate ARD. They are primarily intended to examine the balance between the acid-producing and acid-consuming components of a sample. Static tests do not provide definitive answers to all questions regarding the future behaviour of wastes and should not be used as such. They do, however, provide a means to classify wastes according to their potential to produce ARD and indicate the extent and type of further testing and evaluations that should be carried out.

Many types of static tests have been proposed. Only the most widely used tests will be described. In addition, some current developments in testing protocols and their interpretation will be presented. The following procedures will be discussed:

- The Sobek method of acid-base accounting
- Modified acid-base accounting procedures
- Carbonate NP determination
- B.C. Research Initial Test
- Peroxide Methods
- Lapakko Methods of NP determination
- Calculated NP

Acid-Base Accounting Method of Sobek et al.

Ref: Sobek, A.A, Schuller, W.A., Freeman, J.R. and Smith, R.M. 1978. Field and laboratory methods applicable to overburdens and minesoils. EPA-600/2-78-054 (U.S. Environmental Protection Agency Cincinnati, Ohio).

This method, also referred to as the EPA-600 method, has been the most widely used of all static test methods. It first involves the determination of NP by digesting a small (2.0 g) sample (minus 60 mesh) in excess hydrochloric acid at near-boiling temperatures. A fizz test is used to determine the volume and normality of acid added. The unreacted acid remaining at the end of the digestion is then titrated with NaOH to an end point of 7.0 so that the acid consumed can be calculated. The NP value can then be calculated as follows:

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

where:
$$
\begin{aligned}
NP &= \text{neutralization potential kg } CaCO_3 \text{ equivalent per tonne} \\
a &= \text{normality of HCl added in digestion} \\
b &= \text{normality of NaOH used in titration} \\
c &= \text{mass of sample in grams} \\
x &= \text{volume of HCl added in mL} \\
y &= \text{volume of NaOH added in titration}
\end{aligned}
$$

The acid potential, AP is calculated from a total sulphur analysis as follows

$$AP = S\% \times 31.25 \text{ kg } CaCO_3 \text{ equivalent per tonne}$$

One of the advantages of this test is that it is widely used and is accepted by many regulatory authorities. It is a quick and easy, low cost test and is ideal for the screening of a large number of samples. Like all static tests, however, the test provides no information on the rate and extent of both sulphide oxidation and neutralization that will occur in the field. In addition, the Sobek procedure has been shown in many studies to have a tendency to overestimate NP. This is due to the rigorous digestion conditions in which some minerals, which will not be effective neutralizers in the field, react and are accounted for in the NP value. Overestimation is exacerbated by application of the fizz test which is a subjective procedure and can lead to differences in the results obtained by different technicians for the same samples. Some laboratories do not use a fizz test either in an attempt to remove the subjectivity or else to simplify procedures. This practice leads to further problems in test interpretation. The potential for overestimation of NP in the Sobek test is discussed in Section 3.5.4.

Modified Acid-Base Accounting

Ref: Lawrence, R.W. and Wang. 1997. Determination of the neutralization potential in the prediction of acid rock drainage. Proc. 4th International Conference on Acid Rock Drainage, Vancouver, B.C., May 30 - June 6.

Modified ABA procedures have been developed primarily to reduce the potential for overestimation of NP values obtained in the Sobek procedure. In addition, AP is calculated from the sulphide-sulphur content so that the contribution from non-acid producing sulphur forms, primarily sulphate-sulphur, are not accounted for.

In the procedure of Lawrence and Wang, a small (2.0 g) finely ground sample (80% minus 200 mesh) is digested for 24 hours in excess hydrochloric acid at ambient temperature. The acid addition is based on the same fizz test as used in the Sobek procedure but is significant lower in strength and is added in increments to ensure that the excess is kept to a minimum. The pH at the end of the test must be in the range 2.0 to 2.5 or the test has to be repeated. The back titration is to a pH of 8.3, this being the usual endpoint for acidity titrations, corresponding to the stoichiometric equivalence point for carbonate/bicarbonate in natural waters in which carbonic acid is the most dominant weak acid. NP is calculated using the same formula presented for the Sobek method.

The acid potential , AP, is calculated from the sulphide-sulphur content as follows:

AP = Sulphide-sulphur % x 31.25 kg $CaCO_3$ equivalent per tonne

Carbonate NP

Determination of carbonate NP is a very useful stand-alone measurement or a measurement to be used in conjunction with the NP value obtained in another static test (e.g. acid-base accounting tests). Carbonate minerals are a rapidly available source of Analysis of a sample for its inorganic-carbon content allows calculation of carbonate NP, assuming that all inorganic carbon is present as carbonate minerals capable of neutralizing acid. Corrections should be made if mineralogical examination reveals the presence of carbonate minerals such as siderite, $FeCO_3$, which do not provide net neutralization due to the acid released when the iron hydrolyses as discussed in Section 2.

Analysis of inorganic carbon can be performed by several methods including:

1   Analysis of total carbon using a Leco apparatus. This method is straightforward and can be carried out by many commercial laboratories as a standard procedure. If non-carbonate carbon forms are known to be present, a correction must be made to determine the

carbonate-carbon content if the Leco method is to be used. This can be done by performing a carbon analysis by Leco on the residue from an NP method in which an acid digestion is used (e.g. Sobek), assuming that all carbonate-carbon has been dissolved by that method. Inorganic carbon can then be determined by difference. Alternatively, a different analytical procedure can be used as follows.

2 Dissolution of carbonate in acid in a sealed chamber, with analysis of the evolved gas (CO_2) by gas chromatography or other method such as a Coulometer.

3 Dissolution of carbonate in acid in a sealed chamber, with measurement of the increase in gas pressure

In all cases, the carbonate NP can be calculated as follows:

$$\text{Carbonate NP (kg } CaCO_3/\text{t)} = \frac{\text{mg C in sample x } 8.34}{\text{weight of sample (g)}}$$

Comparison of Sobek, Modified and Carbonate NP

Several studies have been carried out in the past 10 years to compare static test procedures. One of the most recent (Lawrence, R.W. and Wang, Y. 1996. Determination of neutralization potential for acid rock drainage prediction. MEND/NEDEM Report 1.16.3, Canadian Centre for Mineral and Energy Technology, Ottawa) compared NP values obtained by the Sobek, Modified and Carbonate NP procedures for 120 samples from 12 different mines. The study confirmed the tendency for overestimation of NP by the Sobek test. Modified NP and Carbonate NP values were more closely correlated, with Modified values marginally higher in many cases due to the accounting of the more reactive silicate minerals which react under the conditions of the test. Figure 3.5-1 provides a simple, non-quantitative, schematic which illustrates differences in NP values by showing some typical rock forming minerals in order of reactivity and an indication of the approximate extent of reaction achieved in each of the three test methods.
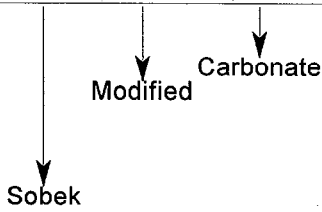
RELATIVE MINERAL REACTIVITY	NEUTRALIZING MINERAL	POSSIBLE EXTENT OF REACTION BY NP METHOD
More Reactive ↑ ↓ Less Reactive	Carbonates Ca-feldspar, Olivine Pyroxenes, Amphiboles Sorosilicates, Phyllosilicates Plagioclase feldspar K-feldspar Quartz	Modified ↓ Carbonate ↓ Sobek ↓

Figure 3.5-1. Relationship between mineral reactivity and method of NP determination

B.C. Research Initial Test

Ref: Bruynesteyn, A. and Hackl, R.P. 1984. Evaluation of acid production potential of mining waste materials. Minerals and the Environment, 4 (1), 5-8.

This test has been widely used for the determination of ARD potential although has largely been superseded in many studies by the use of the Sobek and Modified ABA procedures. This has largely been due to the greater inconvenience of carrying out the test in many commercial laboratories, especially when large numbers of samples are submitted for analysis.

The neutralization potential of a sample is determined by titrating a slurry of finely ground sample with 1.0 N sulphuric acid to a stable end-point of 3.5 using an automatic pH controller/titrator. This choice of end point is based on the assumption that it represents the limit above which iron and sulphide-oxidizing bacteria are not active. Therefore, if the theoretical acid production is not sufficient to lower the pH to below pH 3.5, then bacterial oxidation of the material will not occur and ARD formation is unlikely. The acid consumption, in units of kg H_2SO_4 per tonne of material is calculated as follows:

$$\text{Acid Consumption} = \frac{\text{mL } 1.0 \text{ N } H_2SO_4 \times 0.049 \times 1000}{\text{sample mass in grams}}$$

This value can be converted to units of kg $CaCO_3$/t for comparison with the results of acid-base accounting tests, although results are almost equivalent since the molecular weights of sulphuric acid and calcium carbonate are very similar.

The acid potential can be determined from the total sulphur analysis using the same calculation as for acid-base accounting. In the published method, AP is actually calculated in units of kg H_2SO_4 per tonne of material.

Typically, the test takes at least 24 hours to complete. Although the test is more time consuming than acid base accounting, the test is considered to provide a good estimation of the practical NP since excess acid is not employed as in the acid-base accounting methods. In addition, the use of sulphuric acid provides a better simulation of field conditions than hydrochloric acid. AP values based on sulphide-sulphur analysis is advisable.

Peroxide Methods (the NAP Test)

Refs: Lapakko, K. and Lawrence, R.W. Modification of the Net Acid Production (NAP) Test. Proc. BC Mine Reclamation Symposium, Port Hardy, B.C., 145-159, 1993.

Several different tests using hydrogen peroxide as an oxidant for sulphide minerals have been proposed. The Net Acid Production (NAP) test has been developed to provide an alternative procedure to acid-base accounting for acid rock drainage prediction. The NAP test has the advantage of not requiring a sulphur analysis and therefore has the potential of being used as a quick method for use in the field. The NAP test can also provide an accurate quantitative assessment of acid generation potential when run under controlled laboratory conditions. Work carried out to date indicates results of the NAP test correlate well with acid-base accounting results, particularly when net neutralization potential (NET NP) values are relatively low and negative (say -100 to 0), which is in the range where greater certainty is required. When Net NP values are more negative, NAP values tend to underestimate the acid generating potential, but this should not seriously affect waste management decisions.

The test relies upon the ability of hydrogen peroxide to oxidize sulphides such as pyrite present in a sample of mining waste to produce sulphuric acid. Acid that is produced is simultaneously neutralized by carbonates and/or other acid-consuming minerals present in the sample. At the end of the reaction, the final pH of slurry provides a qualitative indication of the acid generating potential. Titration of the slurry to determine the acid content allows calculation of the net acid produced by the peroxide digestion and a quantitative assessment of the acid generating potential.

The pH recorded at the end of the H_2O_2 digestion step, prior to titration, can provide a qualitative indication of the potential for acid generation for a sample. For example, an interpretation could be as follows:

Final pH in NAP Test	Acid Generating Potential
> 5.5	non-acid generating
3.5 to 5.5	low risk acid generating
< 3.5	high risk acid generating

Caution must be used in interpreting NAP data in this way, since the pH values obtained are dependent on the specific site lithology and mineralogy. Calibration with other tests and analyses is therefore recommended if the test is the be used in this way.

Lapakko Method

Ref: Lapakko, K. Evaluation of neutralization potential determinations for metal mine waste and a proposed alternative. Proceedings of the International Land Reclamation and Mine Drainage Conference, Pittsburgh, April 24-29, USBM SP 06A-94, Vol. 1, 129-137, 1994.

Kim Lapakko of the Minnesota Department of Natural Resources has considerable experience in the area of ARD prediction and has published several papers in which the subject of NP determination is discussed. He has coined the term "mineralogic NP" which is determined on the basis of mineralogical analysis and calcium and magnesium analyses to provide an estimate of NP based on the contribution of calcium and magnesium carbonates. He has further suggested that a laboratory procedure to determine an empirical value of mineralogic NP can be carried out in a manner analogous to the B.C Research Initial Test.

In the method, a slurry of finely ground sample is titrated with sulphuric acid to an end-pH of 6.0. This procedure is best carried out using an automatic pH controller/titrator. The amount of acid added can then be used to calculate the NP as follows:

$$\text{NP (kg CaCO}_3\text{/t)} = \frac{\text{Acid Volume (mL)} * \text{Acid Normality} * 50}{\text{Sample weight (g)}}$$

The test can be very time consuming, due to the slow rate of acid addition necessary to prevent over-addition. The acid strength should also be low (<0.05 N) for the same reason.

Calculated NP

Ref: Lawrence, R.W. and Scheske, M. 1997. A method to calculate the neutralization potential of mining wastes. Accepted for publication in Environmental Geology.

Different minerals can neutralize acid drainage at different rates and in different pH ranges. The test conditions of widely used laboratory procedures to determine NP do not distinguish between such differences and overestimation of NP can often result. A simple procedure has been proposed in which the effective NP is calculated based on mineralogical composition and the relative reactivities of component minerals. Mineralogical composition can be calculated from easily determined analytical values (whole rock chemistry and inorganic carbon) using a CIPW normative procedure. Comparison of calculated NP values for 92 samples with experimentally determined values from tests designed to prevent the overestimation of NP indicates that the method is successful in predicting an effective NP value in most cases. The procedure is considered to be a cost effective means of providing confident routine ARD prediction when used in combination with other tests and analyses.

For application at a particular mining project, customized modifications of the CIPW procedure to match actual rock chemistry with identified mineral components in defined lithological groups or waste management units, would provide mining operators with a rapid tool for classifying wastes to match disposal options. Further method development is required to modify normative calculations to predict the mineralogy of metasomatic rocks and assemblages of other altered rocks. In addition, further refinement of the values used for the relative reactivities of minerals is also required to improve calculation of a NP value from the predicted mineralogical composition.

Static Test Data Reporting and Presentation

The style and rigour of reporting of the results of static tests can vary significantly. It can often be observed that the reporting of the results of NP determinations in many reports and mine permit submissions often do not include a full description of methods used or a complete set of the data measured. Consequently, data cannot be properly assessed and confident interpretations cannot be carried out if variations in procedure are inadvertently used or if the test laboratory carries out undocumented variations in a particular procedure. Whatever static test is used therefore, it is very important that the actual test procedures used are properly documented. For acid base accounting, for example, reporting should include fizz-ratings and pH values at the end of the digestion stage.

To allow proper data interpretation and for comparison between one data set and another, the following raw data should be included as a minimum in the reporting of acid-base accounting results. Most of the following also apply for the reporting of all other test methods:

- Sample identification (e.g. date, location, drill hole #, depth in drill hole, composite details as required)
- Sample description (e.g. rock type, alteration, sulphide mineralization, carbonate mineralization)
- Elemental analysis
- Paste pH
- Fizz rating
- Method of NP determination, including any deviations or modifications to the accepted published methods
- Method of sulphur and sulphur-species analysis
- Sulphur species analyses
- pH after digestion, before the back titration of excess acid
- NP and sulphur species values

In addition, reporting of the following data is desirable:
- inorganic carbon analysis
- mineralogical description, either of individual sample or sample set
- whole rock analysis
- back titration data to allow plotting of the back titration curve if required (see later Sections)

Calculated data should include:

- NP and AP
- NPR (NP:AP ratio)
- Net NP

Statistical data for samples from the same lithological units or other groupings should be provided. Descriptive statistics should include:

- number of samples
- mean and median
- maximum and minimum values.
- percentiles

Usually, some graphical presentation of the data aids the interpretation. Typical examples include:

- NP vs AP
- paste pH vs NP and/or NPR
- NPR-S plot (NPR vs S or S$^=$)
- Surrogate elements (e.g. Ca, Mg...) vs NP
- Back-titration curves (see later sections)
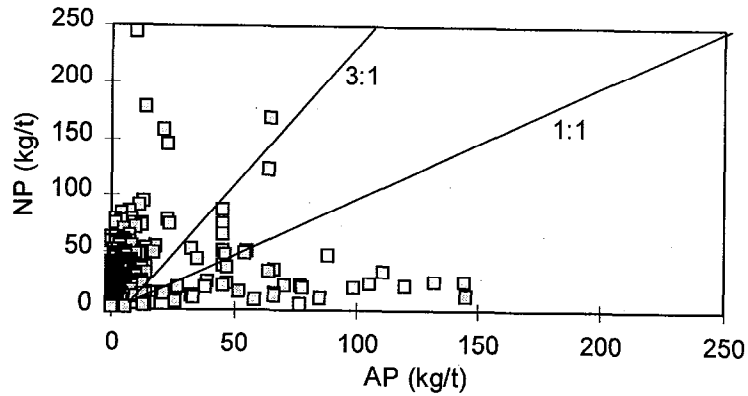
Some examples of plots for the same data set follow:
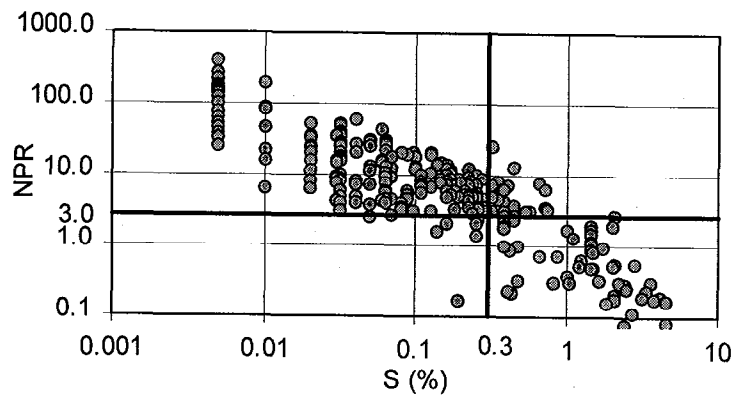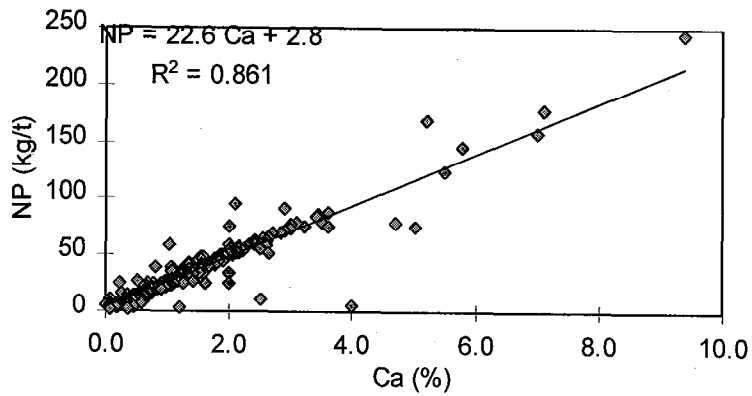
Figure 3.5-1 NP *vs* AP

Figure 3.5-2 NPR-S plot

Figure 3.5-3 Ca *vs* NP

Interpretation of Static Tests

Methods of interpretation of static test results vary. Regulators and experts in the field often hold different opinions as to how waste materials evaluated by static tests should be classified according to the results. Perhaps one of the keys to static testing is not so much which test is used but the manner in which the data are interpreted. It can be reiterated that it is highly unlikely that any one test can produce all the information necessary to evaluate all mine wastes.

As discussed previously, different static test methods do provide different values for the same parameter, particularly NP. The significance of the dependence of a NP value on the test method used, or on procedural variations within one test method, is particularly important when considering how the data are used to classify wastes for disposal and in the development of control methods to prevent acidic drainage for potentially acid generating materials. Regulatory agencies who are responsible for issuing permits for mining projects with respect to waste management typically use criteria such as the ratio of NP to AP to assist them in determining which wastes can be disposed of safely with little or no ARD control measures implemented, and which wastes will require special provision for their disposal. The wide variations in NP values that can be obtained for the same sample, as shown in this study, can significantly affect the value of the NP:AP ratio to the extent that the sample could be classified as either "safe" or "potentially acid generating" depending on the NP value used. The implication of this can be very significant. If a sample is classified as "safe" but might not be, the environment is at risk. Conversely, if a sample is classified as "potentially acid generating" but is not, then project viability might be at risk due to the additional, and often very costly, ARD control provisions that a company will have to employ.

Regulators in British Columbia are in the process of establishing ARD Guidelines for Mine Sites in British Columbia. Based on the criteria set out in the Guidelines, samples containing less than 0.3% sulphide-sulphur are regarded as having insufficient oxidizable sulphide-sulphur content to sustain acid generation. It is known, however, that some materials containing less sulphide-sulphur do generate ARD. Some caution in this guideline would, therefore be prudent. The Guidelines also suggest that sample results with a NPR (NP/AP ratio) values of above 4:1 can be regarded as containing sufficient buffering capacity to neutralize any oxidation products from the contained sulphide-sulphur. Samples with a NPR of between 1:1 and 4:1 are not conclusive with respect to acid generating potential. Samples with an NP/AP ratio below 1:1 and sulphide-sulphur above 0.3% are regarded as being potentially acid generating. Samples falling within either of these two latter groups may require further analyses and (kinetic) testing.

The cutoff NPR suggested in the guidelines (4:1) is provided as a general reference where little information is available regarding the potential acid generating and neutralizing minerals within a sample. However, where sulphide mineralization is not massive, the host rock is not highly

fractured and the neutralizing potential can be attributed to available carbonate minerals, the cutoff ratio may be reduced to as low as 2:1. Interpretations and classifications of materials must therefore be done with due regard for the conditions specific to a particular site or lithological group at the site. The results of acid base accounting tests or other static procedure must be considered with all other available information, particularly mineralogical data, when making predictions.

With respect to the importance of mineralogy in data interpretation, a method of interpreting acid-base accounting test data, particularly from the Sobek test, with respect to the possibility of overestimation of NP has been proposed in a recent study (Lawrence, R.W. and Wang, Y. 1996. Determination of neutralization potential for acid rock drainage prediction. MEND/NEDEM Report 1.16.3, Canadian Centre for Mineral and Energy Technology, Ottawa). A simply determined indicator of the degree of overestimation of NP in the Sobek test can be obtained by considering the profiles of the back-titration curves obtained following the digestion stage. Since a lesser or greater quantity of the minerals in a sample will be dissolved under the digestion conditions of the NP procedure depending on the amount of acid added, the constituent elements in those minerals will be in solution in lesser or greater amounts at the end of digestion. During the back-titration, these metal ions will precipitate within a characteristic pH range for the individual ions present. As precipitation occurs, the solution is temporarily buffered within that pH range and this will be evident from the shape of the titration curve. In the pH range of interest in the Sobek test (from the digestion pH up to pH 7), aluminum is the major silicate cation that will precipitate (pH range 4.0 to 5.0). If an inflection point in the curve in this pH range is obtained, the dissolution of alumino-silicate minerals would be indicated and a potential overestimation of NP suggested. Examples of back titration curves are shown in Figure 3.5-4 (a-c). Differences in the shape of the curves, indicating an increasing dissolution of aluminosilicate minerals as the acid quantity is increased, is evident.
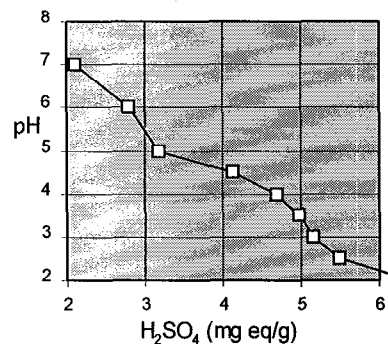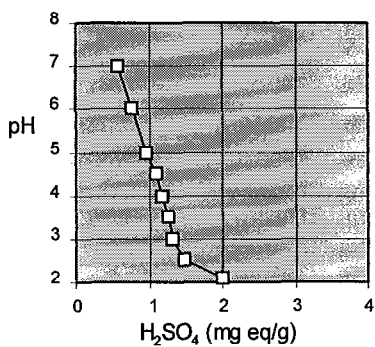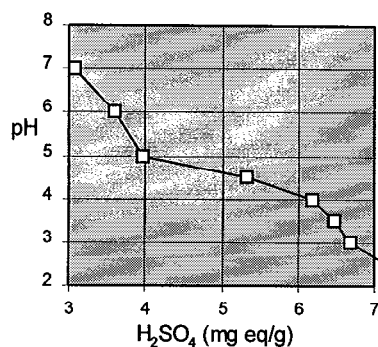
Slight Fizz rating: NP = 29   Moderate Fizz rating: NP = 105   Strong Fizz rating: NP = 153

Figure 3.5-4. Back titration curves for Sobek tests conducted on a waste rock sample with different acid additions (fizz ratings)

Problems and sources of uncertainty associated with all static test can be summarized as follows:

• representativeness of samples is uncertain
• field availability and reactivity of sulphides
• field availability and reactivity of carbonates
• stoichiometry of reactions
• no drainage quality data is obtained
• the time lag to acid generation is not determined

Reference and Standard Materials

Refs: Leaver, M.E., Bowman, W.S., Beaudoin, R.P. and McCorkell, R.H., 1994. AMD Standard Rock, Mineral Sciences Laboratories, Division Report MSL 94-12 (CR), CANMET, Ottawa.
Leaver, M.E. and Bowman, W.S., Inter-laboratory Measurement Program For The Standard ARD Material NBM-1, Mineral Sciences Laboratories, Division Report MSL 94-28 (CR), CANMET, July 1994.
Lawrence, R.W. and Wang, Y. 1996. Determination of neutralization potential for acid rock drainage prediction. MEND/NEDEM Report 1.16.3 (Canadian Centre for Mineral and Energy Technology, Ottawa), 149 p

Many workers in the field of ARD prediction testing have discussed for some time the desirability of having reference standards for acid base accounting. In 1994, CANMET, working under the Canadian Certified Reference Materials Project, produced such as standard, designated NBM-1 (Leaver et al., 1994). As part of the standardization of the NBM-1 material, samples were sent to 14 independent laboratories for analysis of both sulphur content and neutralization potential by the Sobek method.   Values obtained by the laboratories has resulted in the

assignment of provisional values of 0.298 % S and a NP of 52 kg $CaCO_3$ /t (Leaver and Bowman, 1994)

In addition, It should be noted that initial assessment of a fizz rating for the material was a matter of some dispute. In fact, in the original 14-laboratory assessment, unanimity on the assignment of a fizz rating was not achieved and exact instructions on how to carry out the Sobek procedure to determine NP were provided to the 14 laboratories supplied with the material for analysis. The possibility of procedural variations in procedure by which the laboratories would carry out the analysis, including interpretation of the fizz rating, was therefore theoretically removed. Even so, variations in the NP results reported by the laboratories were evident (45-60 kg/t). Independent studies (Lawrence and Wang, 1996) have shown that the determination of NP was very sensitive to the method used for its determination with values ranging from 16 (Lapakko method) to 95 (Sobek [strong fizz] method). The implications of differences in NP are apparent when NPR values are calculated. These values range from 1.7 to 10.1. The sample could, therefore be classified as "safe" or "unsafe" depending on the test method used.

Use of standard or reference materials to calibrate or check on NP determination procedures should, therefore, be done with great caution and highlights the need for proper documentation and interpretation of the results of NP determinations. The considerable variation in the NP values obtained for the NBM-1 sample does not, however, necessarily preclude the use of reference materials. Although the use of a definitive value of NP for reference materials is not recommended, the value of NP for a reference material obtained by a laboratory using a specific procedure to determine the NP values of a sample set could provide a very useful tool to assist in the interpretation of the values, even if the exact procedure used is not clearly specified.

3.7 Laboratory Kinetic Tests

Kinetic tests are carried out to determine the weathering characteristics of a sample as a function of time. For a proposed new mine, specific objectives for both the short and long term can include:

- validation of static test results and classification
- determination of the rate of sulphide oxidation/acid generation
- determination of the rate of neutralization depletion
- determination of the availability of NP
- time to the onset of ARD
- evaluation and selection of ARD control methods
- prediction of water quality

For an existing mine where ARD might already be a problem, some or all the above objectives also apply. In addition, it might be necessary to add the following objectives to facilitate the selection of mitigation methods and for the development of a closure plan:

- evaluation of the extent of oxidation
- evaluation of the extent of neutralization
- evaluation of stored reaction products within wastes

Kinetic tests typically involve subjecting a sample of the waste material to periodic leaching and analysis of the drainage. The most reliable test would be one which replicates exactly the actual field conditions. In practice this is not possible, not only because of the time factor, but also because it is impossible to simulate the physical, chemical, biological, meteorological and other factors associated with an actual dump, tailings impoundment or other mine component. With respect to the time factor, the difficult choice in designing, performing and interpreting a kinetic test is either to have a test which attempts to approximate actual field conditions, in which case the test will usually be of too short a duration, or to provide accelerated conditions, in which case the test might be unrealistic. In the former case, kinetic tests can often fail to demonstrate the onset of ARD or reach any steady state with respect to oxidation rates, neutralization rates or water quality.

Many types of kinetic test have been documented and these can vary in complexity, duration, cost and the kinds of data that can be obtained. The most popular kinetic test is now the humidity cell test. The trend in humidity cell testing is to much longer test times. Column tests are also popular which are generally of a larger scale than humidity cells. These popular tests and two types of accelerated kinetic test will be described.

Humidity Cells

Humidity cells have become the most popular device for conducting kinetic tests. Cell designs can vary in the materials of construction, geometry and size. A typical cell, shown in Figure 3.6-1, is constructed of Plexiglas of dimensions 10cm diameter by 20 cm in length and has a nominal capacity for 1 kg of rock. The rock sample is typically crushed to minus 6 mm and is placed on a perforated plate to permit the flow of air up through the bed of rock. The cell can be provided with a bubbler tube containing water, attached to a tight fitting lid, through which the exiting air is passed. The bubbler provides a visual check that air is flowing through the cell and allows the operator to achieve a semi-quantitative balancing of air flows through a bank of humidity cells. Dry or humidified is added on the underside of the perforated plate. The temperature of the water in the humidifier should preferably be maintained slightly above ambient to ensure a good supply of humidified air. Leachate, usually distilled water, is added periodically through the lid

of the cell. The mode of addition can vary. In some test programs, the water, typically 250 to 500 mL, is added slowly over several hours (percolation leaching). In this method, the valve at the bottom of the cell is open to allow free draining. In other programs, sufficient water can be added to completely submerge the sample for a period of time, before the bottom valve is opened to allow draining. In the latter method, the rock sample is sometimes gently stirred during submergence to promote dissolution of reaction products. Variable infiltration (water addition) rates can be used to investigate the runoff quality and metals loadings that can be expected seasonally.
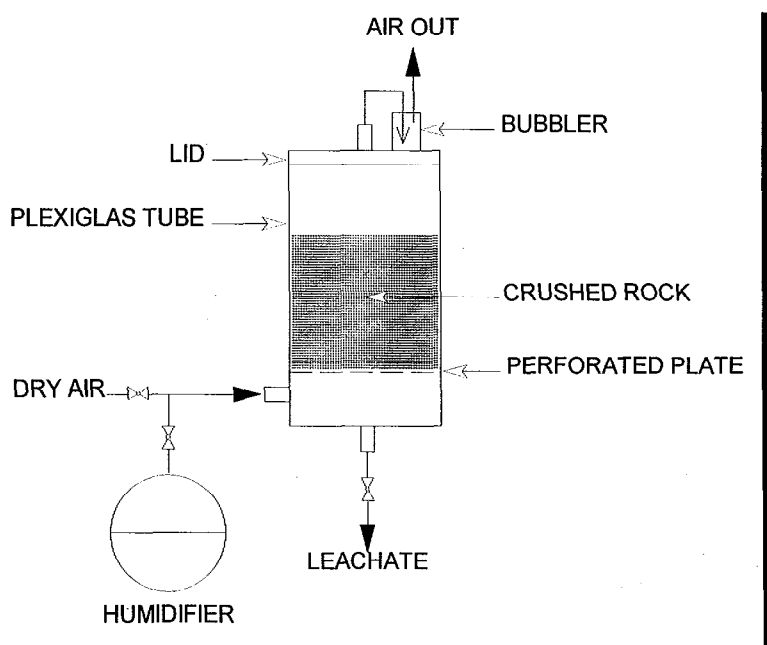
Figure 3.6-1 Schematic of a typical upflow humidity cell

In a typical test, a 7-day cycle is employed: 3 days of dry air, 3 days of humid air, followed by leaching on the 7th day. On the next day, the next cycle is started. Humidity cell tests should be carried out for as long as time as possible. It is normal for data to be quite erratic over the first few cycle before consistent results are obtained. This is due to the removal of readily soluble components from prior oxidation and weathering. It is not unusual for humidity cell tests to continue for several months or even more than 1 or 2 years.

For tailings and other low-permeability materials, the above design is not usually suitable, (a) because water might not drain adequately, (b) loss of fines in the drainage, and (c) the mechanism of oxidation is not the same as for more permeable waste rock. A larger diameter

and shallower cell is preferred because it exposes a greater surface area for reaction. Recent developments in cell design for tailings are taking into the relationship between sulphide oxidation rate and moisture content. Laboratory cells which rely only on gravity drainage of leachate might actually produce lower oxidation rates than in the field due to a higher retained moisture which reduces air diffusion into the material. Assisted drainage by using a partial vacuum to the underside of the tailings following leaching can assist in reducing moisture contents to field values. The use of dry and humid air through, which is not always possible, or over the surface of the tailings is not necessarily required.

For each cycle, the following parameters should be measured to facilitate calculations and interpretation:

- volume of leachate added and collected
- pH
- specific conductivity
- alkalinity and/or acidity
- sulphate
- dissolved metals of interest (must include Ca and Mg)

Other parameters which can be measured include:

- redox potential
- weight of cell and contents after each stage of each cycle to determine moisture content of the test sample

Column Tests

Column leach tests usually carried out on a larger scale than humidity cell test and can be used to observe the effect of control strategies such as water flooding and blending more effectively than the latter method. Columns are typically constructed from Plexiglas, PVC, glass, or other suitable inert material and can range in size from, for example, 5 cm diameter by 60 cm high up to 60 cm diameter by 600 cm high or larger for laboratory investigations. Intermediate sizes are probably more typical.

In a typical test protocol, columns are filled with the test material and leached with a periodic, single pass of distilled water or other leachate. The crush size of the material can vary but, as a rule-of-thumb, the top particle size should not be less than one sixth of the column diameter. Leachate draining from the column is collected and analyzed for parameters of interest in the same manner as for humidity cells.

Numerous test protocols are possible, depending on the test objectives , and can include the following:

- Continuous single pass leaching with distilled water
- Intermittent or periodic single pass leaching with distilled water
- Continuous or intermittent or periodic single pass leaching with an extractant other than distilled water (e.g. simulated acid rain, simulated or actual ARD)
- Recirculation of drainage
- Maintenance of a water table
- Assessment of flooded disposal, with upward or downward leachate addition
- Assessment of bacterial effects
- Assessment of rock blending or alkali addition
- Assessment of covers (e.g. rock, soil, vegetation)

Accelerated Kinetic Tests

Test methods can sometimes be used in which the conditions of the test are selected to accelerate the rate of weathering of a sample. Examples are increasing temperature to increase oxidation rates; decreasing pH to remove neutralizing minerals so that the sulphide oxidation reactions can be studied without delay; and the addition of bacterial cultures, usually in combination with decreasing pH, to enhance sulphide oxidation. However, the popularity of such tests have declined in recent years since such tests are further removed from reality and results are correspondingly more difficult to interpret. Two of the more popular accelerated kinetic tests are briefly described.

Bacterial oxidation tests

Ref: Bruynesteyn, A. and Hackl, R.P. 1984. Evaluation of acid production potential of mining waste materials. Minerals and the Environment, 4 (1), 5-8.

Sulphide-oxidizing bacteria can exert a major influence on the generation of ARD, particularly when pH values fall below around 3.5 due to higher reaction kinetics and increased solubility of ferric iron. In principal, therefore, kinetic tests in which bacterial activity is significant can provide additional reality to the simulated conditions. It must be noted, however, that the use of bacteria in kinetic testing requires special knowledge and experience lacking in most commercial laboratories involved in ARD testing. Several studies reported in the literature give conflicting evidence of the role and extent of bacterial action. This is likely due in many cases to poor culture adaptation, and to inexperience in growing bacteria and maintaining cultures in a suitable metabolic state for testing purposes.

The most widely used bacterial oxidation test has been the Confirmation Test developed by B.C. Research. In this procedure, sulphide-oxidizing bacterial cultures are used to oxidize pyrite and other sulphides present in a finely ground sample, previously shown to be a potential acid producer in the B.C. Research Initial Test, under agitated and acidified (pH 2.5) conditions and at an optimum temperature for bacterial activity. Once the reaction is complete (usually after 2 to 4 weeks), additional sample, equal in weight to the original sample is added in two increments. If sufficient neutralizing minerals are present in the sample to raise the pH to over 3.5, then the sample is classified as a non-acid producer. If the bacteria were able to oxidize sufficient acid so that the pH remains below 3.5, then the sample is confirmed as an acid producer.

A disadvantage of this and other tests in which acidified conditions are employed is that the effect of the ability of neutralizing minerals to prevent the onset of acid generation at circum-neutral pH is never assessed. Such tests are not, therefore widely used today.

Soxhlet Extraction

Ref: Lawrence, R.W. and Marchant, P.M. 1990. "Acid Rock Drainage Prediction Manual. A Manual of Chemical Evaluation Procedures for the Prediction of Acid Generation from Mine Wastes". MEND/NEDEM Report 1.16.1b (Canadian Centre for Mineral and Energy Technology, Ottawa).

The Soxhlet extraction apparatus, used widely by soil scientists to assess weathering of soils, has been adapted for ARD studies. A soxhlet extraction apparatus provides a chamber (the thimble) in which a sample is placed and subjected to leaching with condensate produced by the boiling of the leachate in a reservoir. Although the condensate is normally at high temperature, the apparatus can be modified so that the condensate is cooled before contact with the sample. Tests are typically completed in 1 to 2 weeks.

Tests data is not easy to interpret since the relationship to natural weathering is uncertain. The refluxing action of the procedure changes leachate chemistry significantly, especially with respect to iron which will precipitate extensively in the high temperature reservoir. The test is not widely used.

Kinetic Test Data Reporting and Presentation

The reporting and presentation of data for humidity cell and column tests will be presented since they are the most widely used of all kinetic test procedures.

The requirements for rigorous reporting of kinetic test results are the same as previously discussed in Section 3.6 for static tests. Full descriptions of methods used and a complete set of

the data measured are required if interpretations and predictions are to be done confidently. Data cannot be properly assessed if variations in procedure are inadvertently used or if the test laboratory carries out undocumented variations in a particular procedure.

Due to the significant quantity of raw and calculated data obtained in kinetic testing, well organized and clear presentation of the data is essential. It is suggested that tables of data that could be constructed to contain the following groupings of data:

Table	Raw and Calculated Data
1: Sample characterization and test conditions	• sample identification • summary of the test conditions • metals analysis • static/acid base accounting results • descriptive acid base accounting statistics of sample population
2. Parameters measured weekly	for each cycle... • Date, cycle and elapsed time (days) • Volume of leachate added and collected • pH • specific conductivity • alkalinity and acidity • sulfate
3. Water analysis	for each cycle... • cycle and/or elapsed time (days) • analyses of metals in leachates
4. Cumulative mass flux	for each cycle... • cycle and/or elapsed time (days) • cumulative values of the mass flux of each metal (mg/kg)
5. Cumulative metal extraction	for each cycle... • cycle and/or elapsed time (days) • cumulative percentage of each metal leached
6. Metal extraction rates	for each cycle... • cycle and/or elapsed time (days) • the rate of metal extraction (mg/kg/week or mg/kg/m^2): rates are often calculated rates as moving averages (e.g. for the last 5 cycles)

7. Sulfur data, mole data, neutralization data and times to depletion	for each cycle... • cycle and/or elapsed time (days) • cumulative sulfate flux (mg/kg/week) • total sulfur depletion (%) • sulphate-sulphur depletion (%) (if required) • sulfate leach rate (mg/kg/week or mg/kg/m^2) (moving averages ?) • the moles of SO_4, Ca and Mg extracted and the $[Ca + Mg]/[SO_4]$ molar ratio. Other molar ratios might be useful in some test programs • cumulative NP depletion (mg/kg) • NP depletion (%) • NP depletion rate (mg/kg/week or mg/kg/m^2) (moving averages ?) • time to 100% (or other percentage) sulfur and NP depletion (years)

In many longer term test programs, weekly analyses are not carried out in later stages of the test in order to save on analytical costs. For example, analyses might be done every 4, or even every 8, cycles. Weekly values for concentrations, fluxes and rates can be calculated by interpolation of the preceding and subsequent values.

Graphical presentation of data an include plots of the relationship between many of the raw and calculated data sets, usually as a function of time, and significantly enhances the interpretive process. A suggested list of graphs plotted against time (days) or cycle is a follows:

• volume collected (if variable infiltration rates are evaluated)
• pH
• conductivity
• alkalinity
• sulfate
• Ca
• $[Ca + Mg]/[SO_4]$ and other molar ratios
• sulphate depletion
• Ca depletion
• sulphate depletion rate
• NP depletion rate
• times to NP and sulphur/sulphide depletion
• metals of interest

Kinetic Test Data Interpretation

Due to the complexity of kinetic test data interpretation, a detailed description is beyond the scope of these notes. The reader is referred to the upcoming Guidelines and Recommended Methods for the Prediction of Metal Leaching and Acid Rock Drainage at Minesites in British

Columbia (Price 1997). Although these guidelines are intended as a draft report to allow ongoing modification, and significant debate is ongoing regarding methods of interpretation, much of the information on kinetic testing, and ARD prediction in general, is considered to be a good guide.

One of the major weaknesses of kinetic test interpretation is the lack of long-term data. Although tests are now generally run for significantly longer periods of time than in the recent past, the usual test duration of months or even 1 or 2 years, does not simulate the behaviour of a waste component in time frames often measured in years or tens of years. Assumptions have to be made, therefore that the stability of concentrations and rates observed after a reasonable length of time of testing can be extrapolated into the future. At this point in time, verification of the basis for this assumption is lacking since predictions made in the past were either too simplistic to be valid by today's criteria and understanding, or actual waste dumps or other mine component for which very recent predictions have been made, are still too early in their "life".

It should be noted that the operational conditions humidity cell and column tests have been selected arbitrarily. A typical humidity test might employ 500 mL water per week for a 1 kg sample. This liquid to solid ratio is much higher than will be experienced for most waste facilities, even in areas of high rainfall. Recent studies on humidity cell protocols have shown that frequency, intensity and duration of simulated rainfall events can have a marked effect on both sulfide oxidation rates and NP depletion rates. In addition, the value of some parameters, such as certain metals, are dependent on these variations in infiltration events, while others are not. This will depend on whether the reactions giving rise to the appearance of a parameter in solution are surface reaction controlled or solubility controlled. In the case of sulfide oxidation rates and NP depletion rates, significant differences in their values and the ratio of the values have been observed depending on the infiltration conditions used. In general, NP depletion rates increase with increasing infiltration volume and frequency.

It must be noted that the weathering characteristics of the test samples and the resulting leachate chemistry can not be necessarily be directly used to predict on-site performance of a commercial waste dump. Final assessment of the data and predictions for the performance of the material, including appropriate scaling of the parameters to full-size, should include some modeling to take into account factors which are not controllable or reproduced in laboratory conditions. These include physical factors such as temperature, particle size distribution, height of dump, infiltration rates, and the degree of wetting to take into account channeling and the umbrella effect. In addition, some geochemical modelling will be appropriate to be able to predict actual drainage quality from the test data.

3.7   Field Kinetic Methods

Background

Field tests can include:

- 🔥   Test waste rock piles.
- 🔥   Small tailings deposits.
- 🔥   Wall rock leaching.

The emphasis in the following sections is on test waste rock piles. Test tailings deposits are uncommon. A wall rock leaching method has been developed by MEND.

Test waste rock piles are usually set-up to determine weathering behaviour under field conditions for comparison with laboratory tests. The test material is usually obtained from mining (either at full or small-scale) and can therefore provide an indication of actual behaviour that might be expected in a full scale rock pile.

Processes occurring in a rock pile can include:

- 🔥   build-up of soluble weathering products due to oxidation of sulphide minerals;

- 🔥   release of oxidation products by rainfall or snow melt;

- 🔥   partial or complete neutralization of acid products due to contact with silicate and carbonate minerals;

- 🔥   freezing of the pile during sub-zero conditions; and

- 🔥   restriction of oxidation by application of covers;

Application and Limitations

Waste rock test piles are recommended for any prediction project to establish the relationship between weathering rates under laboratory and field conditions. They may be used simply to assess uncontrolled oxidation rates or may be designed to assess control alternatives. The following limitations should be considered:

- 🔥   **Initial Characterization.** For larger tests, characterization of the material prior to testing

becomes difficult.

      🖎   **Monitoring.** Leachate samples need to be collected on a regular basis. If the site is remote, sampling costs may be high;

      🖎   **Seasonal Effects.** Seasonal effects, particularly in small piles, can be severe thereby obscuring the other features of interest such as long term decay in release of oxidation products;

      🖎   **Duration of Tests.** Since the test is conducted under site conditions, the test may take much longer than the same test under laboratory conditions if the site experiences very cool conditions in part of the year;

      🖎   **Robustness.** As with any field test, the site needs to be carefully protected from damage by extreme climatic conditions and vandalism.

            Similarity to Full-Scale Rock Piles. It cannot be assumed that the test piles will behave the same as full-scale piles. Table 3.7-1 provides a comparison of differences between small and large rock piles.

      🖎   **Testing of ARD Control Alternatives.** Small-scale tests cannot reliably evaluate ARD control alternatives since duplication of operational conditions is difficult.

TABLE 3.7-1
COMPARISON OF PROCESSES IN TEST AND FULL-SCALE ROCK PILES

FEATURE/ PROCESS	TEST PILES	FULL-SCALE PILES
Physical Distribution of Particles	Relatively homogeneous, lack of layering unless planned. Probably low fines content due to removal of rock from exploration adit.	Extremely heterogeneous due to dumping techniques, variation in rock type and mining techniques. Layering and compacted layers probable. Relatively more fines than test piles due to mine blasting techniques.
Chemical Composition of Particles	Relatively homogeneous if planned. Readily defined by sampling.	Probably complex due to changes in rock type during mining. Difficult to characterize due to physical heterogeneity.
Water Movement	In small piles, relatively high proportion of rock particles contacted due to short distance from surface to base. Higher water:solid ratio. Retention time relatively low. Probable lack of water table(s).	Flow is complex due to internal variations in permeability. Flow is probably concentrated in a number of small channels resulting in relatively low proportion of particle contacted by water. Water table(s) are possible both perched and at the dump base.
Effect of Climactic Processes	Snow melt and major rainfall events result in more rapid flow and expansion of flow paths into seasonally dry areas. Flushing of weathering products occurs. During dry periods, weathering products accumulate.	Snow melt and major rainfall events result in more rapid flow and expansion of flow paths into seasonally dry areas. Flushing of weathering products occurs. During dry periods, weathering products accumulate.
Migration of Solids	Large scale failure unlikely. Small scale transport of solids probable due to downward movement of water.	Large scale failure possible. Small scale transport of solids probable due to downward movement of water.
Gas Transport	Wind advection is possibly dominant process of gas transport into and out of the pile. Significant oxygen depletion within pile unlikely.	Thermal advection accepted as dominant process due to formation of temperature gradients within pile. Oxygen concentration gradients likely.
Internal Reactions	Reactions comparable but less variable within pile due to lesser temperature and oxygen variation. Greater water flow and flushing of weathering products possibly important.	Extremely complex within various parts of the dump due to varying oxygen, temperature and water flow conditions.
Overall Water Chemistry	Less likely to be limited by saturation due to higher water flow. Metal concentrations potentially lower due to dilution and development of less acidic conditions, or higher due to lesser saturation control.	Expect water chemistry to be controlled by saturation.

NOTES:
1. Features of full-scale waste rock dumps from review by Morin (1991).
2. Relative terms compare test and full-scale piles.

Method

The test material may be obtained from any source. Usually run-of-mine material from an exploration adit or trench, or an active mine may be used. Several samples of the test material should be submitted for ABA, TIC, metal, size fractions and petrographic determinations. Size fractions analyses can be useful to estimate the relative exposed surface areas of different tests conducted at the same time. Analysis of individual size fractions using ABA may be useful if partitioning of sulphur and NP between the size fractions is suspected.

No standard method for test piles has been described. Figure 3.7-1 shows a design resembling a leach pad. The test pile is constructed on a liner with a drain layer and a slotted leachate collection pipe wrapped in geo-sock. Leachate is collected in a covered pail equipped with a siphon to prevent the bucket from overfilling. The advantage of this design it has been observed to last for many years without maintenance. The disadvantage is that the conical shape does not allow even distribution of flow through the entire rock mass.

Wooden crib type designs are also used. Again, the crib is lined to allow leachate collection (Figure 3.7-2). The main advantages of this design are that all rock in the pile receives the same incident precipitation and the slats in the crib sides allow free movement of air into the rock. The disadvantages are that it requires greater construction effort, the design is not as robust as a leach pile and there is probably a limit to the size of sample which can be contained by the rock.

Neither design is particularly recommended. If there are expected to be benefits from operating the tests over an extended period, or a larger test (>50 t) is planned, then the design in Figure 3.5-1 is recommended. If the test pad is to be used to evaluate a cover material it should probably be constructed using a design similar to Figure 3.5-1 but the sample would be placed as a thin flat layer rather than a tall cone. The cover will need to extend over the edges of the material to avoid "edge effects".

Precipitation and temperature monitoring is recommended. As a minimum, precipitation should be determined to allow leachate volumes to be estimated. A direct measure of leachate volume is preferred since this allows chemical loads to be calculated. If it is not practical to measure flows directly, they can be estimated from the area of the pad and evaporation. For longer term

Figure 3.7-1. Leach Pad Type Design for Waste Rock Pile. MEND Report 1.19.1

WASTE ROCK "PILE-TYPE"
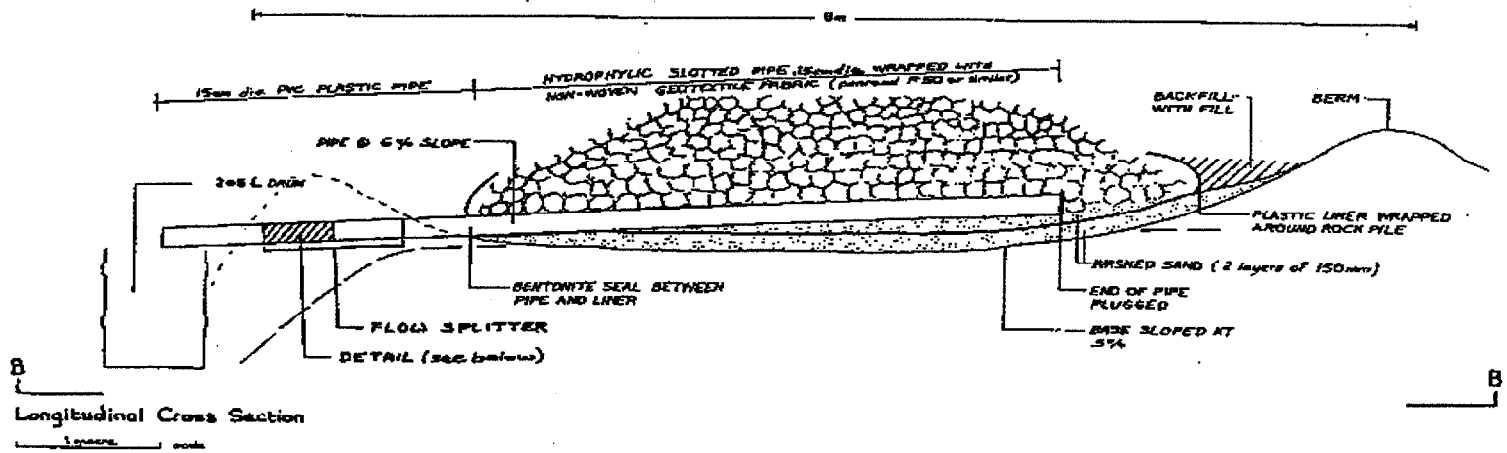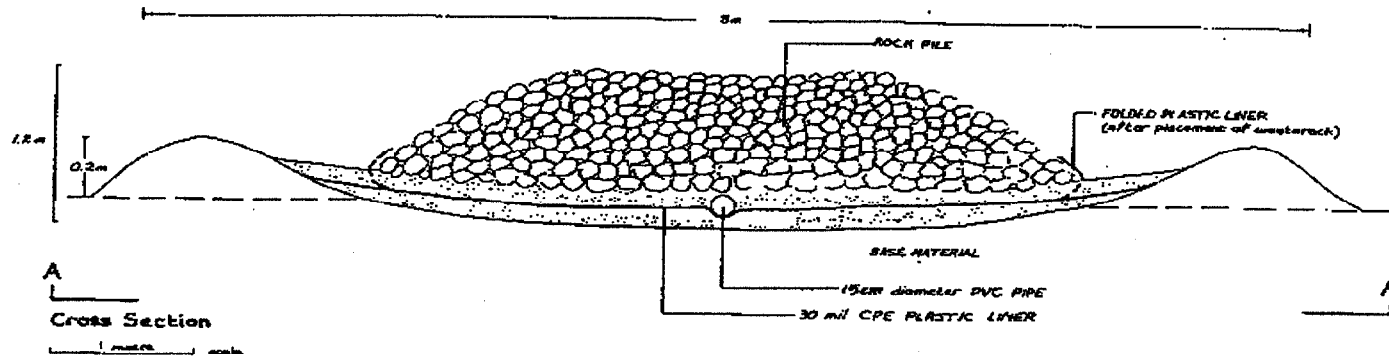
WASTE ROCK "CRIB-TYPE"
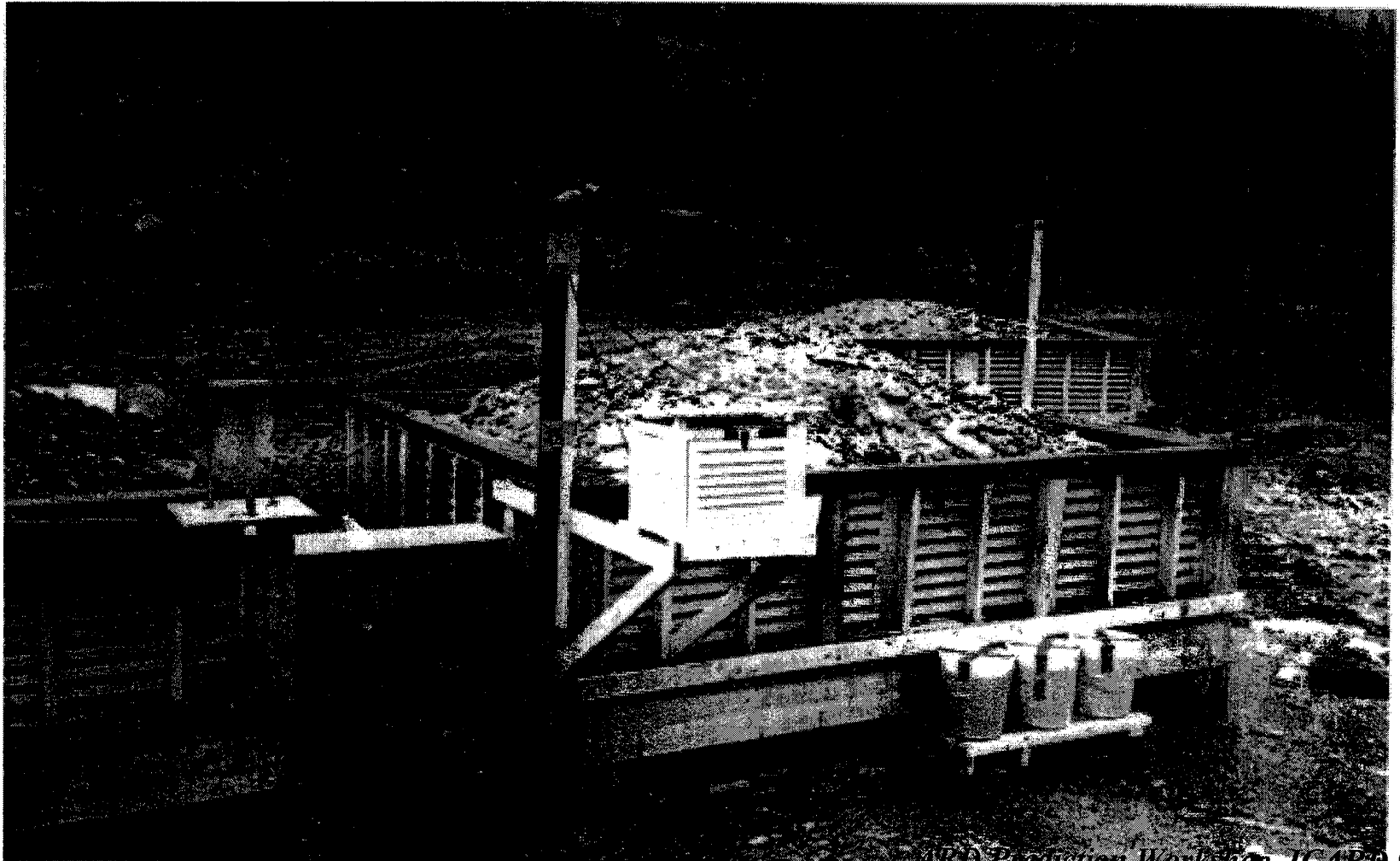
projects, a relationship between site precipitation and precipitation at a nearby permanent monitoring station can be developed.

Generally, the leachate should be sampled and analyzed at least once a month. The sampling frequency may be increased during periods of high precipitation or the freshet to evaluate short term changes. If personnel are on-site continually, leachate pH and TDS (or EC) can be monitored weekly and derived relationships between TDS or EC and other parameters used to obtain data for other parameters.

Interpretation of pad leachate may include the following:

  Trend in pH to determine whether acidic leachate was produced and evaluate buffering reactions;

  Recalculation of parameter (sulphate, metals) concentrations as loads (mg/s), on a mass (mg/kg/s) or surface area (mg/m^2/s) basis to evaluate trends and determine sulphide and carbonate consumption rates, and metal release rates;

  Determination of trends in mole ratios (eg. $SO_4/(Ca+Mg+2K+2Na)$) to evaluate relative rates of oxidation and buffering;

  Testing of mineral saturation using aqueous equilibrium models (eg. MINTEQ);

  Determination of trends in mole ratios to evaluate changes in buffering mineral reactions (eg. Ca/Mg).

Early indications of acid release (other than a transition to low pH) can be indicated by $SO_4/(Ca+Mg+2K+2Na)$ ratios increasing from less than 1 to greater than 1.

Examples of data presentation are shown in Figures 3.7-3 and 3.7-4.
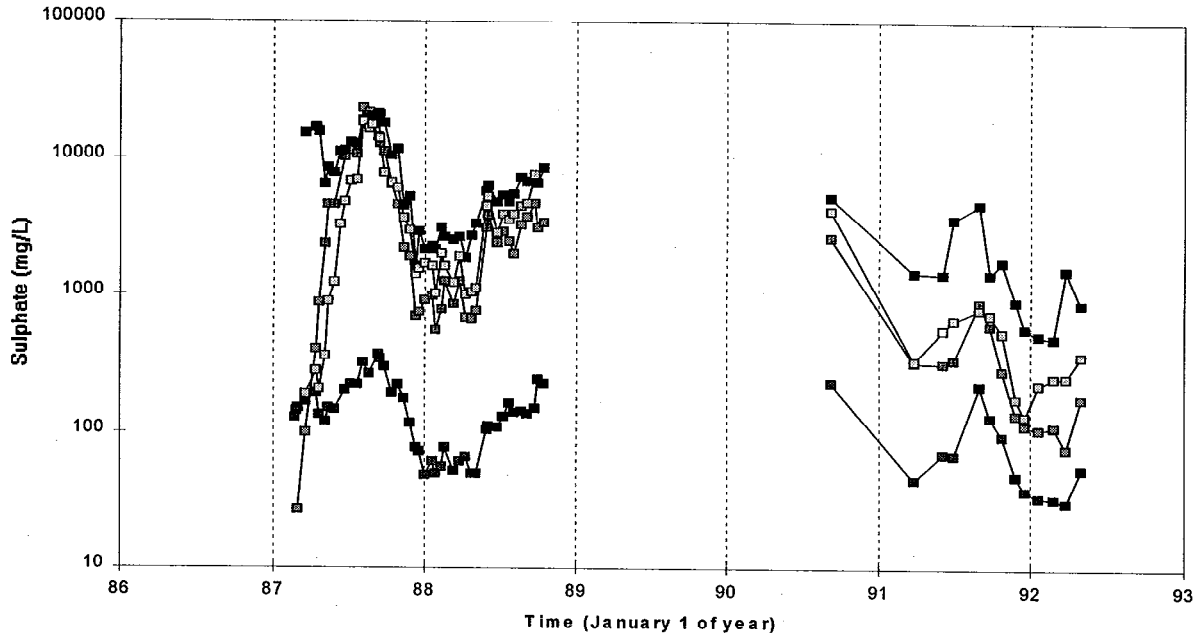
Figures 3.7-4 and 3.7-5. Examples of waste rock pad leachate sulphate concentration and load.
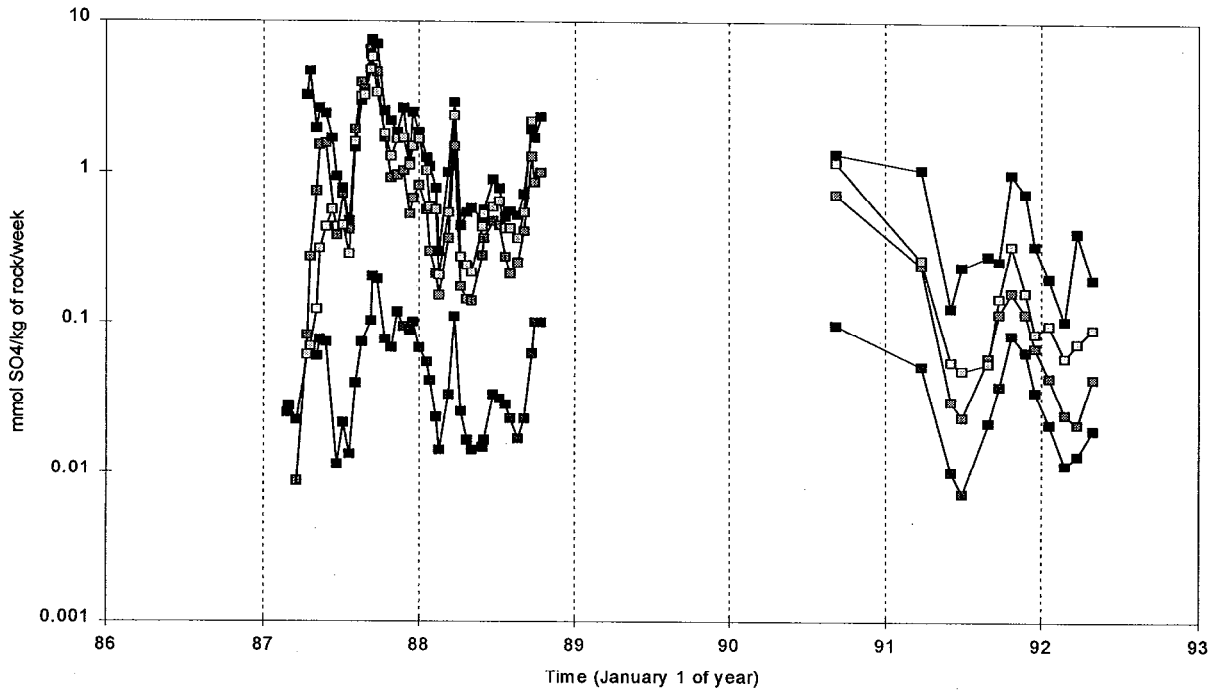
(MEND Project 1.19.1)

3.8   Putting the Methods Together

Overall Prediction Approach for Proposed Mines

Proposed mines present the greatest challenge because supporting field evidence is lacking unless there are existing historical workings that are relevant to the proposed operation. Prediction studies leading to development of a waste management plan should proceed through the following stages:

Initial Evaluation

&   Geological information relevant to acid generation should be compiled and compared with existing knowledge of acid generation in similar geological environments.

&   The site should be inspected to examine any existing historical mine workings or natural features such as gossan, talus and seepage.

&   An initial suite of samples should be collected to evaluate potential for acid generation using acid-base accounting. Sampling can be limited to major rock types (classified according to lithology, alteration and weathering) and should be biassed towards potential acid producers (based on mineralogical features). Three to five samples per rock type should be adequate.

&   The results of the initial evaluation are used to determine the need to proceed to the next level of evaluation.

Follow-up Characterization

&   Initial concepts for waste management need to be developed at this stage to determine the types of testing required for follow-up.

&   The follow-up characterization generally consists of further testing to quantify the acid generation potential of individual rock types with particular emphasis on rock types of uncertain or variable acid generation potential.

&   Mineralogical and chemical studies should be initiated to ensure that the types of minerals contributing to acid generation and neutralization potential are understand in the context of static testing.

♭   A few typical samples should be selected for kinetic testing using humidity cells as soon as practical to begin building a long term kinetic database. While these may not be immediately relevant to waste management planning, data obtained supports predictions from static testing.

♭   If suitable test material is available from bulk sample collection (small-scale mining or large diameter drilling), on site test pads should be constructed.

♭   As a result of this stage of testing, waste management concepts should be refined and used to design the subsequent stage of testing.

Predictive Testwork in Support of Waste Management Planning and Environmental Impact Assessment

♭   Further static testing may involve block modelling of acid generation potential in the mine. The need for block modelling should be determined based on the proposed waste management plan and may be warranted if waste segregation is planned.

♭   Further kinetic testwork may be necessary to evaluate specific waste management concepts or obtain data for modelling studies. These may include humidity cells, leach columns and on-site test pads.

Overall Prediction Approach for Existing Mines

The difference between proposed and existing mines is that at existing mines waste deposits are present and provide a source of site specific information. In the case of operating mines, personnel may also be available to monitor site experiments. The following stages are recommended:

Initial Data Review and Program Design

♭   Existing data relevant to acid generation assessment should be reviewed and interpreted. These might include results of historical acid generation testwork, site water quality monitoring data, permit compliance monitoring data, pre-mining baseline water quality monitoring data and any existing geological information such as research papers, regional geological reviews.

♭   The site should be carefully inspected to determine actual or potential sources of poor quality water.

   ✤   The initial data review should result in design of a program to characterize solid mineral wastes and monitor leachate quality. The requirements for subsequent characterization will depend on the extent of existing information and the need for information to support long term water quality predictions.

Subsequent Characterization

   ✤   The characterization approach follows the same general guidelines described above for proposed mines

   ✤   Solid mineral waste sampling may include fresh drill hole cuttings and existing waste disposal facilities. The possible usefulness of data obtained from sampling of existing waste rock dumps needs to be carefully assessed before embarking on a drilling program since waste rock dumps can be very complex.

   ✤   On-site test leach pads should be constructed with corresponding laboratory test cells.

   ✤   Leachate monitoring (surface water and groundwater) should include parameters indicative of acid generation and neutralization (eg. SO_4, Ca, Mg, Al, K, Na, Fe etc) in addition to compliance parameters (heavy metals). Monitoring should include flows as well as chemistry and should be designed to determine load variations particularly during critical flow periods.

SECTION 4 - CASE STUDIES

Aspects of three case studies will be presented to illustrate some of the aspects of waste characterization, static testing and kinetic testing presented in the preceding sections.

4.1 Dublin Gulch Project, Yukon Territory

The Dublin Gulch Project is a proposed open-pit and cyanide heap leach operation, located in the centre of the Yukon Territory, approximately 85 km northeast of Mayo by road, and 20 km northwest of Elsa. A waste management plan for the project is being developed will include provision for safe storage of waste rock, leached ore, and water management control.

Approximately 37.5 million tonnes of waste rock will be generated by the mining operations and will comprise 69% metasediments, 7% unaltered granodiorite, 18% weathered granodiorite, and 6% sericite altered granodiorite. 214 samples of waste rock, representing the four types, have been analyzed for whole rock chemistry, metals by multi-element ICP scan, short-term leaching tests, petrographic and mineralogic composition, and acid base accounting. In the case of the acid base accounting testing, detailed analyses were carried out on composite of the four rock types, using various procedures, to provide an assessment of practical NP values.

Although the requirements for kinetic testing, usually performed to evaluate longer-term sulfide oxidation and neutralization rates, are, therefore, of lower priority than in projects where the potential for ARD generation is significant, there remains a question as to the mobility of specific elements, particularly As, Sb, Cd, Pb, Hg and Zn in the shorter term from the wastes. Kinetic tests are still in progress to evaluate ARD generation and short-term metal mobility.

The detailed static test work will be described and interpretations of the kinetic test data will be discussed. Of particular interest in this program is the use of non-standard humidity cells to investigate the runoff quality and metals loadings that can be expected seasonally.

4.2 Huckleberry Project, British Columbia

The Huckleberry Project is a porphyry-copper deposit located in west central British Columbia, approximately 85 km southwest of Houston. The project is at an advanced stage of development and will be a large open pit - mill complex to produce copper concentrate form 94 million tonnes of mineable reserves.. Waste characterization programs have been in progress for over 3 years to address issues concerning the disposal of waste rock from the Main Zone and East Zone pits. Extensive static testing has indicated that a significant proportion of the waste rock from the larger East Zone pit is potentially acid generating using the BC Guidelines criteria. Much of the

recent testwork has been carried out to attempt to establish the minimum NPR values for this waste that will enable the mine proponents to obtain final approvals for the waste management plan. Of particular current concern is the quantity of construction rock required for the tailings dam and whether the is sufficient non-acid generating waste available for this purpose. Of special interest in the ongoing kinetic test program is the difficulty in data interpretation due to the relatively high gypsum contents in the test samples. Sulphate and calcium leaching from gypsum dissolution make the task of determining both the extent and rate of sulfide oxidation and neutralization difficult. Despite the high potential for acid generation from some of test samples, ARD generation is not indicated even after nearly three years of testing.

4.3   Kudz Ze Kayah Project Yukon

Introduction

Permission from Cominco Ltd. to use this project as a case example is appreciated. Full details of the study can be found in the project=s Initial Environmental Evaluation (IEE).

This example illustrates:

1.   Design and execution of a prediciton study for a relatively complex proposed mine.

2.   Progression of a project from initial assessment to the environmental impact assessment.

3.   Adaptation of standard testing procedures to address site specific characterization issues.

4.   Design of chemical prediction studies to address specific waste management issues.

Background Information

The Kudz Kayah Project is located in east-central Yukon Territory. It is a gently dipping stratiform massive sulphide deposit hosted by weakly mineralized schist. The deposit is Ablind@ that is, it is completely buried beneath surficial deposits and was discovered by tracing the source of mineralized boulders and high metal concentrations in stream sediments. The deposit is in the bottom of a small valley.

Early assessment of the 11.3-million tonne deposit indicated it is amenable to open pit mining methods. The massive sulphide ore was suitable for conventional flotation milling to produce zinc, lead and copper sulphide concentrates.

ARD Studies

Initial Assessment

During exploration drilling, Cominco geologists noted several features of the deposit that were relevant to assessment of ARD potential:

    ♠   The ore zone is massive sulphide composed of pyrite, pyrrhotite, sphalerite, chalcopyite and galena.

    ♠   The ore zone is surrounded by a zone of lower grade but strongly mineralized rock.

    ♠   The rock above the ore zone (the hangingwall) contains a few percent pyrite and pyrrhotite disseminated as fine grains. At least two carbonate-type minerals were observed including one iron-bearing variety.

    ♠   Most of the hangingwall rock is classified as schist but some variations could be identified.

An initial suite of samples was collected for acid-base accounting by the project geologists (Table 3.2-2).

The results indicated that the ore and adjacent waste was potentially acid generating due to high sulphur concentrations. Classification of the wastes around the ore was unclear. Typical classification criteria applied in BC indicated that a considerable volume of waste rock would be conservatively classified as potentially acid generating. An important outcome from the perspective of project economics was that management of a large proportion of the rock as acid generating would be costly.

Subsequent Characterization

The next step was to identify potential concepts for management of potentially acid generating wastes (Table 3.1-1). These were used to define a test program (Table 3.2-1) which was presented for discussion to regulators. Given the complexity of the project, only a few details of selected aspects of the project are presented below.

The Carbonate Mineralogy Problem

The presence of several carbonate minerals (calcium, magnesium and iron) indicated that it was

important to determine which carbonate minerals were relevant to acid consumption. The calcium and magnesium carbonates (calcite and dolomite, respectively) are acid consuming. Iron can be contained in either of these minerals and also as ankerite and siderite. Iron carbonates are not acid neutralizers under oxgenated conditions because the iron liberated by neutralization then goes on to oxidize and hydrolyze released as much acid as is consumed:

$$FeCO_3 + H^+ \rightarrow HCO_3^- + Fe^{2+}$$

$$Fe^{2+} + 2O_2 + 2H^+ \rightarrow Fe^{3+} + H_2O$$

$$Fe^{3+} + H_2O \rightarrow Fe(OH)_3 + H^+$$
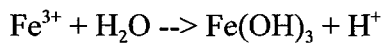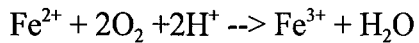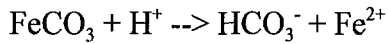
It is important when determining the acid neutralizing potential to ensure that iron carbonates are not contributing to a false high neutralization potential. Various comparisons of methods were used to evaluate this issue (see following Figures).

The outcome was selection of a single neutralization potential method.

Waste Rock Segregation Criteria

In concept, three different types of waste material were identified:

SPAG   **Strongly Potentially Acid Generating.** Waste rock requiring rapid subaqueous disposal (co-disposed with PAG tailings).

WPAG   **Weakly Potentially Acid Generating.** Waste rock suitable for life-of-mine stockpiling (final backfill to pit)

PAC   **Potentially Acid Consuming.** Waste rock suitable for perpetual on-land disposal (on-land dumps adjacent to pit).

Criteria were required for:

1.   Segregation of rock requiring immediate subaqueous disposal from rock which can be stockpiled on land during mining (SPAG from WPAG); and

2.   Segregation of rock which is not expected to generate acid during the life of the mine from rock which has a very low probability of ever generating acid (WPAG from PAC).

The former criteria was developed based on assessment of lag times. In practice, the segregation would be based almost entirely on the geological characteristics since there is a very sharp distinction between the well-mineralized rock adjacent to the ore zone and the weakly mineralized rock in the hangingwall and footwall.

The latter criteria was developed based on lag times and measured relative rates of acid generation and acid consumption in kinetic tests. Figure 8.2-2 summarizes the criteria as an overlay of on the ABA data.

Block Modelling of Waste Rock Geochemical Characteristics

The development of criteria led to the need to calculate waste volumes for material management planning. A block model for waste rock characteristics was developed with the additional objective of mapping ARD/metal leaching potential in the pit walls. In order to make use of the existing large ICP dataset for the rock, correlations between NP and calcium and magnesium were investigated and found to be very useful. Sulphur determinations were performed using XRF which has a higher detection level than the Leco method but was suitable for expected sulphur concentrations. The correlation between the Leco and XRF methods was investigated.

Geochemical Modelling for Environmental Impact Assessment

The final objective of the prediction study was to develop individual predictive water quality models using the static and kinetic test work results.

TABLE 3.1-1

ACID GENERATION AND METAL LEACHING POTENTIAL - GENERAL STUDIES
KUDZ-ZE-KAYAH PROJECT

COMPONENT	INITIAL DATA ON ACID GENERATION AND METAL LEACHING POTENTIAL	CONTROL ALTERNATIVES	ENVIRONMENTAL/ PROJECT ISSUES	STUDIES
WASTE ROCK	Potentially acid generating to potentially acid consuming	1.1 Segregation and special disposal of PAG (sub-aqueous or encapsulation)	1.1a. Segregation criterion. 1.1b. Volumes of PAG wastes. 1.1c. Weathering of PAG wastes prior to submergence. 1.1d. Metal leaching from segregated PAG & PAC rock.	1.1a. Kinetic studies, relative AG, AC under non-acid conditions. 1.1b. ABA Characterization of waste rock. 1.1c. See 1.1a. 1.1d. Kinetic studies - subaerial and subaqueous disposal.
STOCKPILES OF ORE OR WASTE ROCK	Potentially acid generating	2.1 Limit stockpiling time. 2.2 Collect drainage and treat.	2.1 Rate of NP consumption under non-acidic conditions. 2.2 Quality and quantity of drainage.	2.1 Kinetic studies, AC rate under non-acidic conditions. See 1.1a. 2.2 Kinetic studies on acid-generating rock.
TAILINGS	Potentially acid generating	3.1 Sub-aqueous disposal.	3.1 Leaching rate underwater.	3.1 Kinetic studies - Subaqueous disposal.
PIT WALLS (OPERATING)	Potentially acid generating to potentially acid consuming	4.1 Direct discharge of pit water to tailings pond. 4.2 Collect and treat pit water.	4. Quality of pit water.	4a ABA of pit wall. 4b. See 1.1a.
PIT WALLS (CLOSURE)	Potentially acid generating to potentially acid consuming	4.3 Direct discharge of pit water or passive treatment. 4.4 Perpetual collection and treatment of pit water.	4b Quality of pit water. 4c Stored acidity in pit walls.	4b. Flooding model. Water balance. 4c. Kinetic studies. Storage of acidity.

PAG = Potentitally acid generating
PAC = Potentially acid consuming.
AG = Acid generation
AC = Acid consumption
ABA = Acid-Base Accounting

TABLE 3.2-1
ACID GENERATION AND METAL LEACHING POTENTIAL - SPECIFIC STUDIES
KUDZ-ZE-KAYAH PROJECT

COMPONENT	STATIC TESTS			KINETIC TESTS		
	Type	Sample Source	Number	Type	Sample Source	Number
WASTE ROCK	Acid-Base Accounting	Four DDHs - every 2 m.	273	Humidity cells (NP:AP~1)	DDH Core	17
	ICP Metal Scan	All delineation drilling samples	2400	Humidity Cells (NP:AP<<1)	DDH Core	5
	Carbonate Speciation	Selected ABA samples	45	Humidity cells - trickle leach	DDH Core	2
	Petrography	DDH Core	101	Columns - mixed rock	DDH Core	5
				Subaqueous columns	DDH Core	3
STOCKPILES	See Waste rock	DDH Core		See waste rock.		
TAILINGS	Acid-Base Accounting	Pilot plant tails	5	Subaqueous Columns	Pilot plant tails	2
	Carbonate Speciation	Pilot plant tails	5	Humidity cells	Pilot plant tails	1
PIT WALLS	See waste rock			Humidity cells - Delayed Leach	DDH Core	5

TABLE 3.2-2
INITIAL ACID BASE ACCOUNTING
KUDZ-ZE-KAYAH PROJECT

DDH	INTERVAL feet	PASTE pH	S(T) %	S(SO4) %	NP kg CaCO3/t	AP	NP:AP	NNP kg/t	Preliminary ARD Class	Est. % (by weight)
MINERALIZATION									PAG	
94-46	82.4-85.9	8.6	6.44	0.09	69	201	0.3	-133		
94-46	93.4-94.0	8.4	5.28	0.08	159	165	1.0	-7		
HANGING WALL METASEDIMENTS									PAC	10
94-19	17.6-21.0	9.0	0.28	0.01	291	9	33.3	283		
94-17	34.8-71.0	8.8	0.83	0.02	129	26	5.0	103		
94-32	18.7-62.1	8.8	0.32	<0.01	113	10	11.3	103		
94-32	30.0-67.1	8.6	0.55	0.02	168	17	9.8	151		
HANGINGWALL FELSIC VOLCANICS - UPPER									PAC?	19
94-18	15.6-32.2	8.8	0.59	0.03	97	18	5.2	78		
94-22	15.6-32.2	9.4	0.63	0.02	59	20	3.0	39		
94-19	32.0-53.6	9.1	0.61	0.03	53	19	2.8	34		
HANGINGWALL FELSIC VOLCANICS - MIDDLE									PAU	24
94-9	41.1-53.1	8.5	1.35	0.03	88	42	2.1	45		
94-10	6.7-30.5	9.1	1.28	0.04	82	40	2.1	42		
94-22	87.2-102.4	9.2	0.51	0.01	61	16	3.8	45		
HANGINGWALL CHLORITE LAMINATED QUARTZ/SERICITE SCHIST									PAG ?	12
94-09	90.0-99.0	9.0	2.29	0.07	43	72	0.6	-29		
94-43	30.6-34.9	9.1	1.12	0.06	18	35	0.5	-17		
94-40	95.4-133.1	9.2	1.03	0.04	93	32	2.9	61		
HANGINGWALL QUARTZ-SERICITE SCHIST									PAU	35
94-9	69.0-87.0	9.2	0.45	0.01	23	14	1.6	8		
94-10	54.5-69.5	8.9	2.41	0.05	141	75	1.9	65		
94-22	146.2-163.4	9.3	1.3	0.03	93	41	2.3	52		
FOOTWALL									PAC?	0
94-22	221.2-239.5	9.5	1.7	0.07	156	53	2.9	103		
94-22	218.4-236.5	9.5	0.23	0.06	47	7	6.5	40		
94-19	251.0-260.0	9.0	0.07	0.02	140	2	64.2	138		

Notes:

1. Rock types indicated are initial classifications and are not used subsequently.

NP(Sobek)=1.0NP(Modified)+5.1

NP(Sobek) = NP(Modified)

NP(Modified), kg/t

NP(Sobek), kg/t
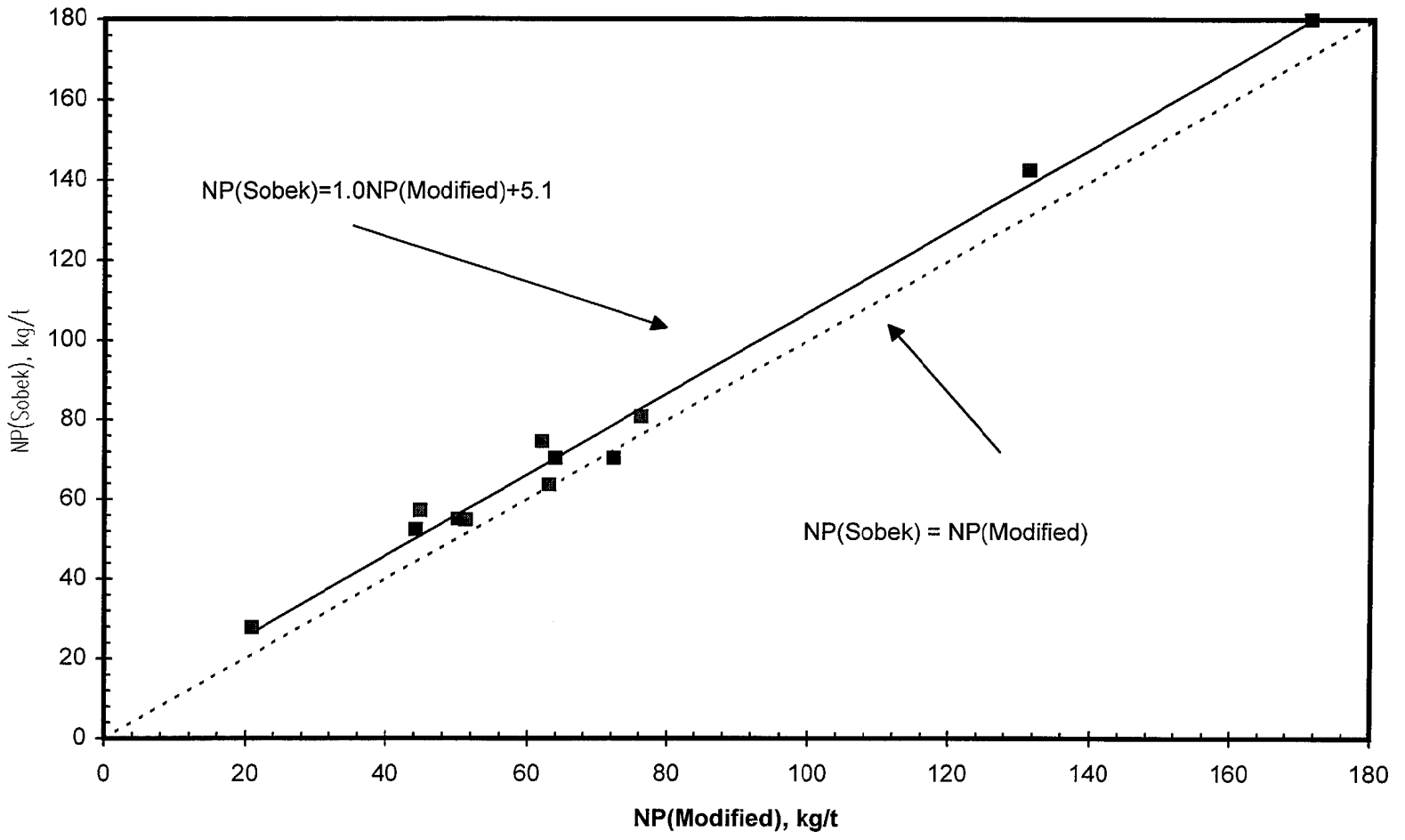
COMPARISON OF NP BY
SOBEK AND COASTECH
METHODS

COMINCO LTD.

JANUARY 1996 | FIGURE 5.1-1

NORECOL, DAMES & MOORE, Inc

TIC = 1.3NP - 1.3

- Data Points - TIC Method
- Regression - TIC Method
- - - - NP=NP(Est.)

NP (Est. other methods), kg/t

NP (Coastech Method), kg/t
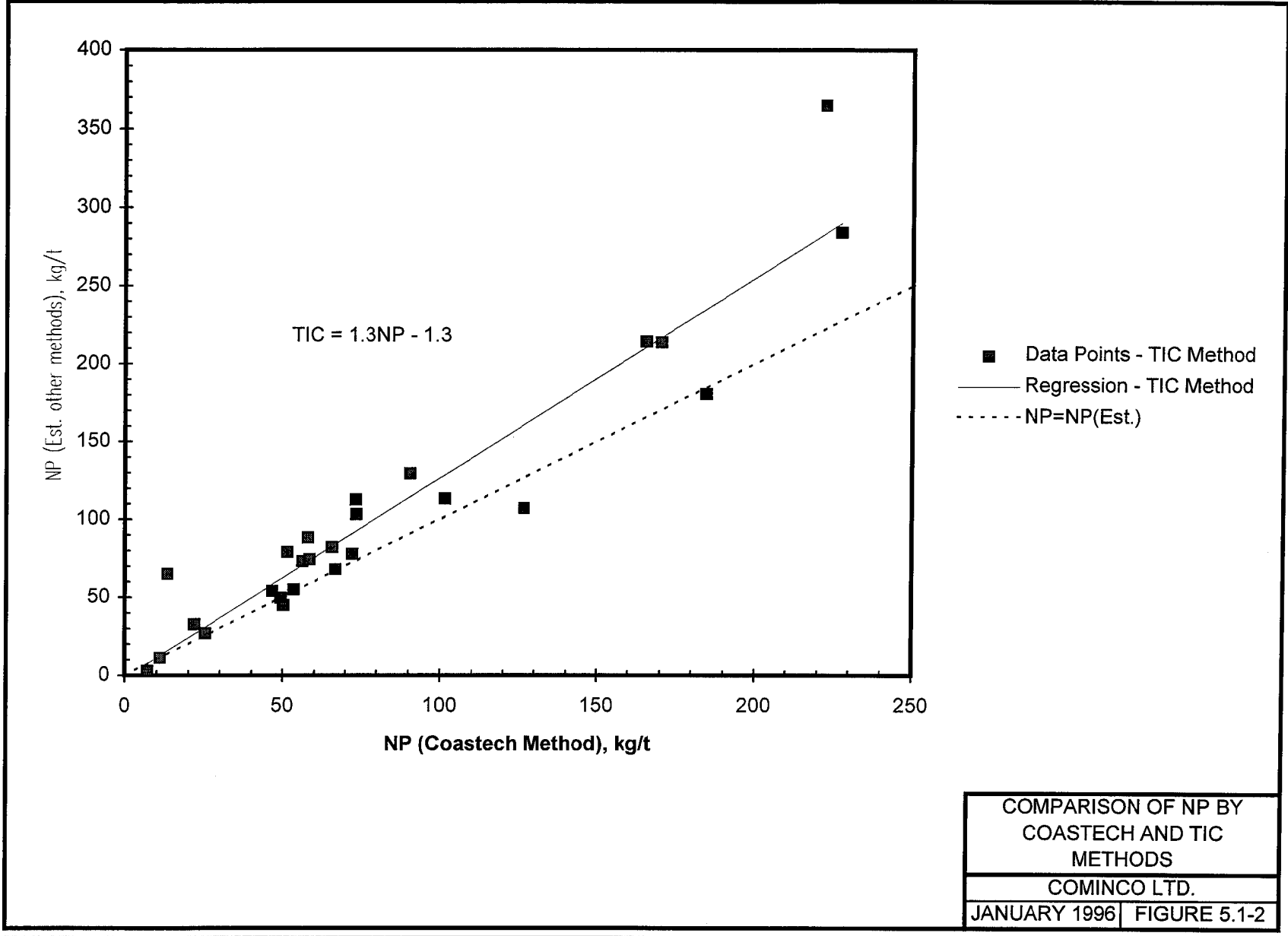
COMPARISON OF NP BY
COASTECH AND TIC
METHODS

COMINCO LTD.

| JANUARY 1996 | FIGURE 5.1-2 |

NORECOL, DAMES & MOORE, Inc

NP = (Ca + Mg)

Y-axis: HCl Leachable (Ca+Mg) (equiv kg/t)

X-axis: NP (kg/t)
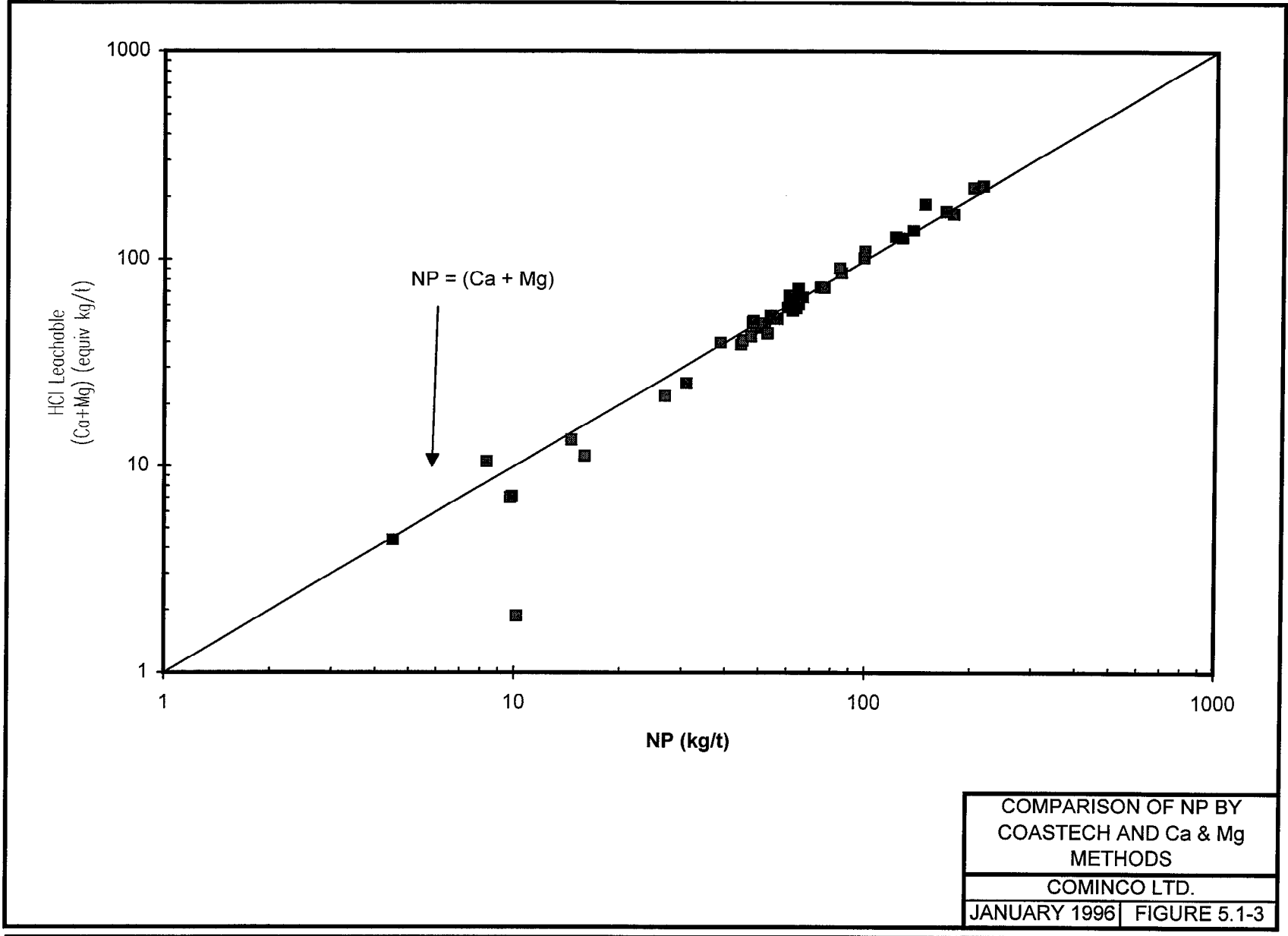
COMPARISON OF NP BY COASTECH AND Ca & Mg METHODS	
COMINCO LTD.	
JANUARY 1996	FIGURE 5.1-3

NORECOL, DAMES & MOORE, Inc

ln(NP)=0.99ln(Ca+Mg) + 3.23
r=0.97
n=67

NP (kg/t)

Ca+Mg (%)

COMPARISON OF NP AND AQUA REGIA DIGESTED Ca+Mg	
COMINCO LTD.	
JANUARY 1996	FIGURE 5.1-4
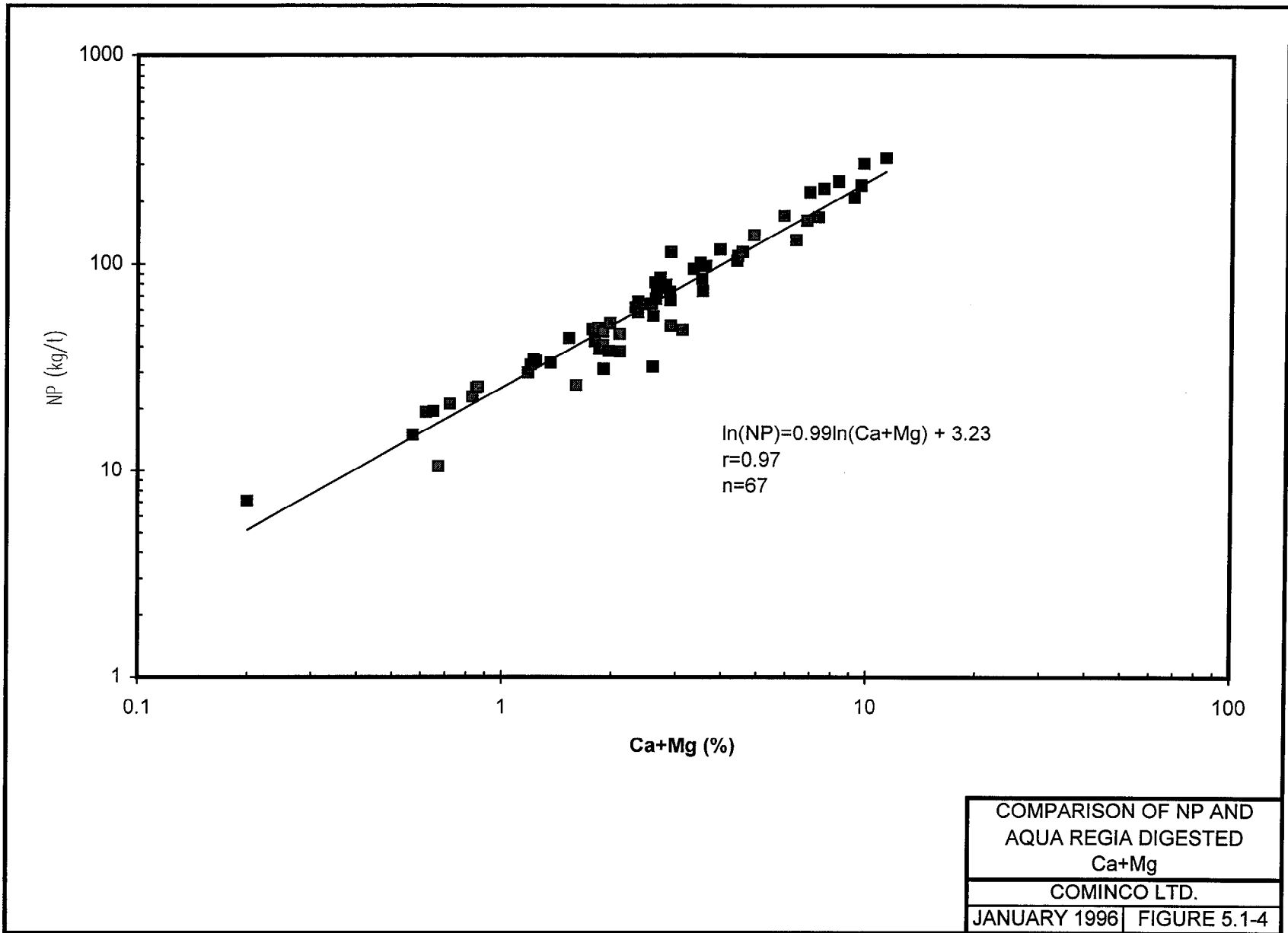
A. Total S vs. Fe corrected for silicates, carbonates and oxides.

$\ln(S) = 0.087x + 1.4$
for $x > 3$

$\ln(S) = 0.40x - 0.17$
$x < 3$

Total S, %

Fe - (Ca+Mg+Al) = x, %
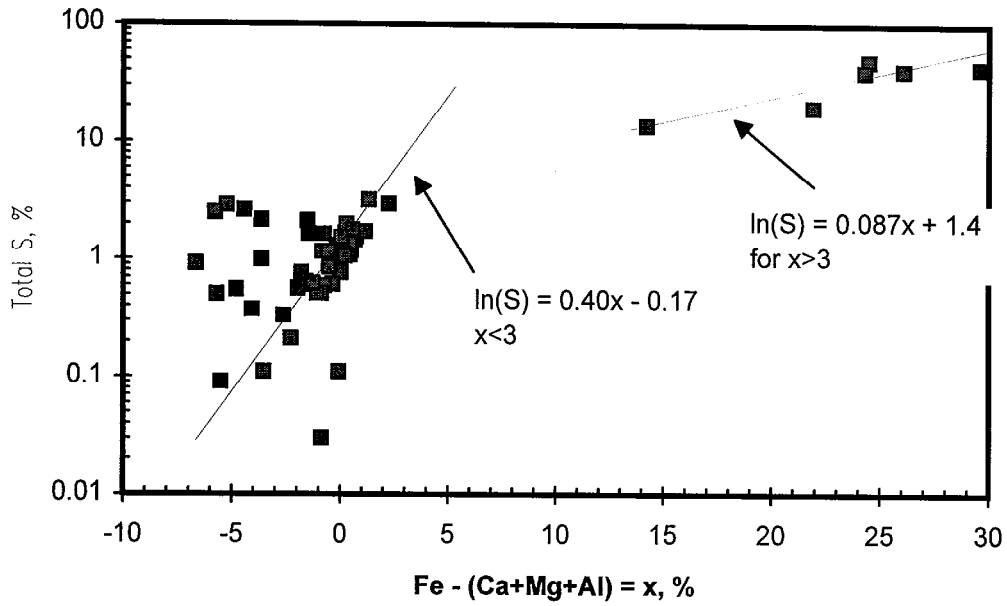
B. Total S by Leco vs. Total S by XRF.

Leco = $1.4XRF^{0.83}$
r=0.91
n=9

Leco, S %

XRF, S %
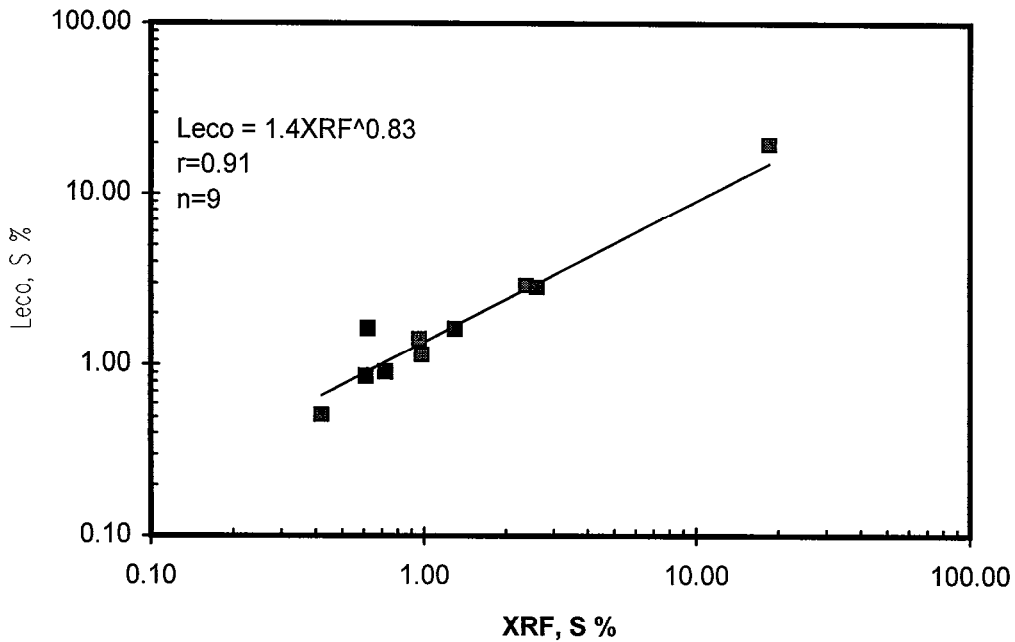
COMPARISON OF SURROGATE METHODS FOR TOTAL S	
COMINCO LTD.	
JANUARY 1996	FIGURE 5.1-5

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DDH 94-34

DDH 94-40

DDH 94-50

DDH 94-46

NP:AP FROM SELECTED
DIAMOND DRILL HOLES
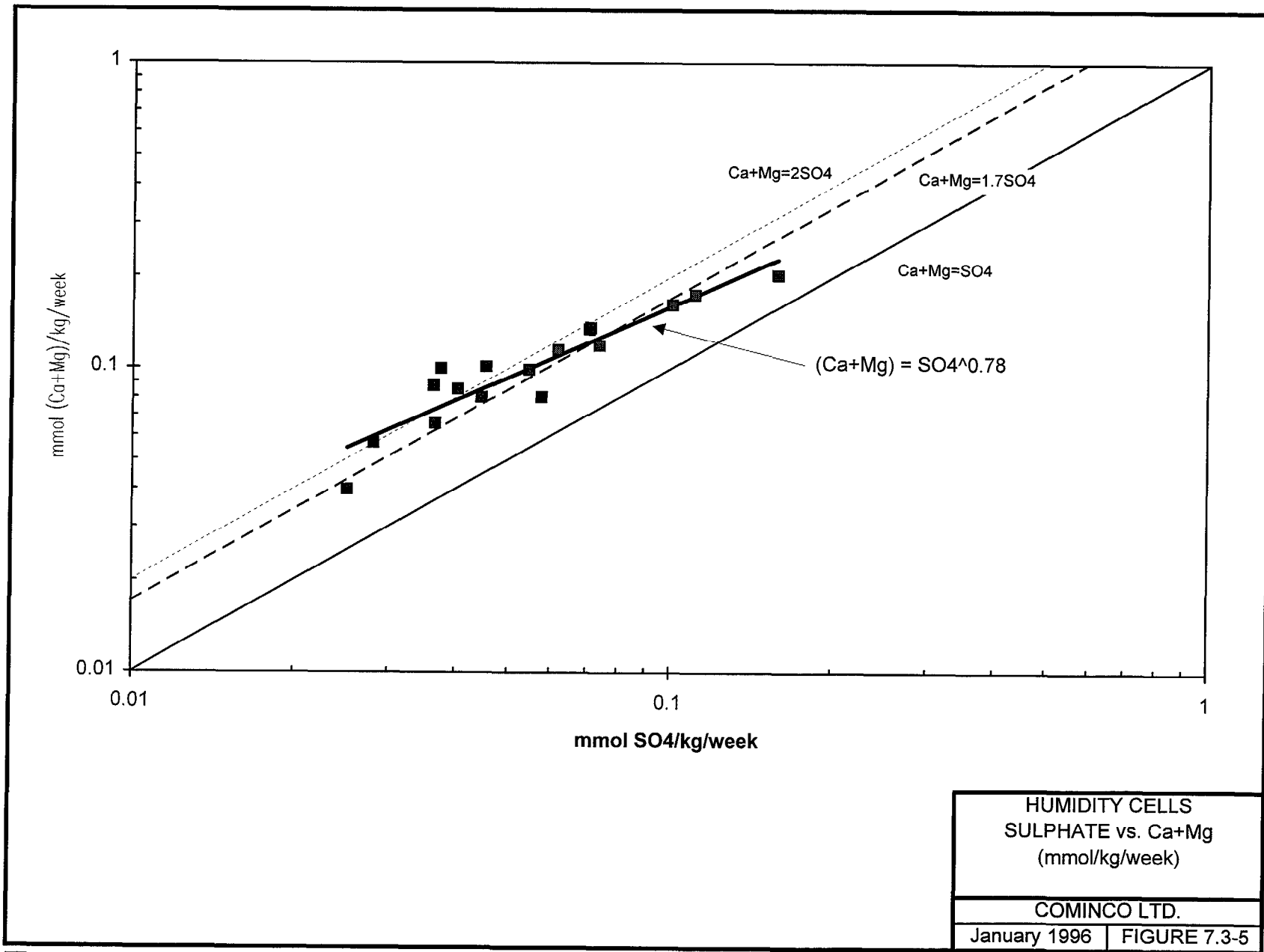KUDZ ZE KAYAH PROJECT
YUKON TERRITORY

COMINCO LTD.

January 1996 | FIGURE 6.3-5
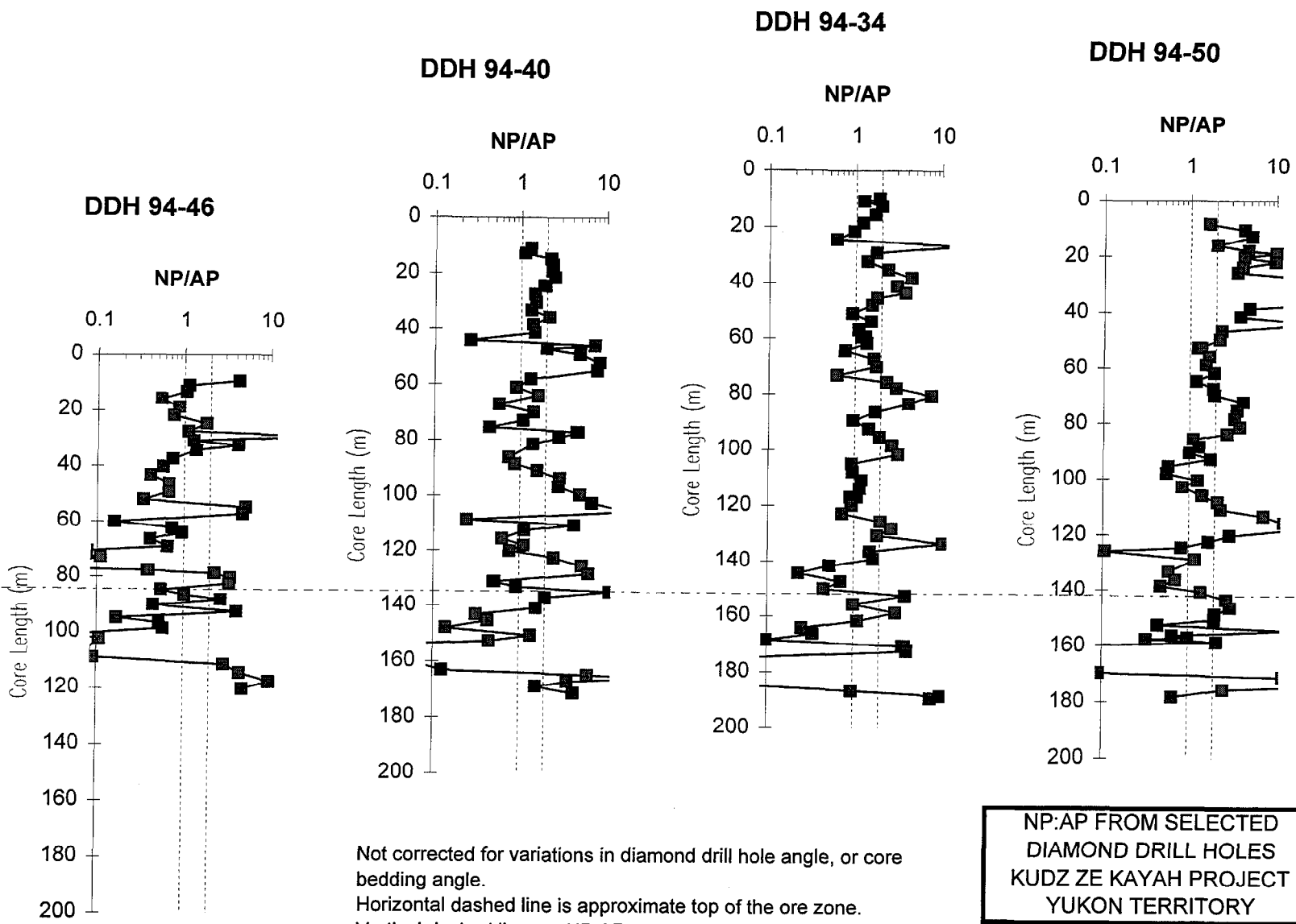
Not corrected for variations in diamond drill hole angle, or core bedding angle.
Horizontal dashed line is approximate top of the ore zone.
Vertical dashed lines at NP:AP=1 and 2.

Job No. 25141-023-310

NORECOL, DAMES & MOORE, Inc

Ca+Mg=2SO4

Ca+Mg=1.7SO4

Ca+Mg=SO4

(Ca+Mg) = SO4^0.78

mmol (Ca+Mg)/kg/week

mmol SO4/kg/week

HUMIDITY CELLS
SULPHATE vs. Ca+Mg
(mmol/kg/week)

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WASTE ROCK REGIONS
IN
NP vs. AP SPACE

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Job No.: 25141-023

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NP/AP
Mean = 4.9
Median = 4.1
P(12) = 1.7

Total S
Mean = 0.57%
Median = 0.49%
P(95) = 1.28%

Percentile (%)

NP/AP

DISTRIBUTION OF NP/AP
PAC DUMP

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DISTRIBUTION OF NP/AP
WPAG DUMP

COMINCO LTD.

January 1996 | FIGURE 8.3-1