# Handbook for Waste Rock Sampling Techniques

# MEND Project 4.5.1-2

This work was done on behalf of MEND and sponsored by
Atomic Energy Control Board,
INCO Limited,
Homestake Canada,
Environment Canada, and
the Canada Centre for Mineral and Energy Technology (CANMET)

**June 1994**

# HANDBOOK FOR WASTE ROCK SAMPLING TECHNIQUES

Prepared for:

Energy Mines and Resources
CANMET - MSL Division
(MEND Project 4.5.1)

Prepared by:

SENES Consultants Limited
121 Granton Drive
Unit No. 12
Richmond Hill, Ontario
L4B 3N4

June 1994

## TABLE OF CONTENTS

Page #

## LIST OF TABLES

# 1.0 INTRODUCTION

## 1.1 BACKGROUND

Acid rock drainage (ARD) is a major environmental issue at mining properties across Canada. ARD has been observed at virtually all types of mining operations including base metal, precious metal, uranium, coal and selected industrial mineral operations. Over the past 20 years, a series of monitoring techniques have been developed to predict the potential for ARD at mining sites and to monitor the acid generating characteristics of mine rock piles. There are a myriad of techniques available but little published data as to which techniques are most commonly used, which techniques are most cost-effective and more importantly which techniques provide the best data.

In order to provide guidance to the industry, the MEND Secretariat issued a contract to SENES Consultants Limited in 1992 to conduct a literature Review of Waste Rock Sampling Techniques. The Review provided a comprehensive list and description of sampling techniques along with a suggested guide to addressing waste rock sampling requirements for the exploration, operation and closure phases of a mining project. The Review did not provide guidance as to what techniques were most commonly applied at Canadian mining properties nor did it recommend any specific procedures as being preferred or industry standards.

In an effort to provide a more interactive review with industry and government, a second phase of the project included a detailed survey of waste rock sampling practices currently being applied at sites across North America, Australia and Europe. These data were summarized and a draft position paper was prepared by SENES which highlighted industry practice and preferred monitoring techniques, where possible. This draft position paper was used as the basis for an experts workshop held in Toronto, 11 and 12 March 1994. This workshop included a panel of 12 experts from industry, research organizations and government and was attended by 18 observers. The detailed proceedings are available on request from MEND. A list of persons who completed the survey and the participants at the experts workshop is provided in Appendix A.

Following the experts workshop, the draft position paper was updated and expanded to form this Handbook for Waste Rock Sampling Techniques. The Review was also updated to include the results of the survey, the information presented at the experts workshop, and any other new information presented in the Handbook.

The Handbook is a concise summary of currently available sampling techniques. It is assumed that the reader of this Handbook is familiar with each of the waste rock sampling techniques described and discussed in the Review. Both the Review and the Handbook are available through CANMET. We recommend that the interested reader read both documents. The Review should be consulted when a detailed description and comparison of waste rock sampling techniques is required. The Handbook should be consulted when a concise summary of sampling techniques available and recommended is required.

In Chapter 2, this Handbook briefly addresses: representative sampling, sampling program design, data management and quality assurance and control.

In Chapter 3, each category of waste rock sampling (chemical characterization, water monitoring, gas sampling, etc.) is discussed in a common format under the following headings:

- Possible Methods;
- Objectives;
- Background;
- Rating;
- Limitations and Advantages;
- Recommended Procedures;
- Requirements;
- Cost; and
- References.

Chapter 4 contains a summary of recommended techniques for obtaining information for: (a) rough cost estimates to be used for decision making regarding management, maintenance, monitoring and closure of ARD sites; (b) prediction (modelling) of potential ARD; and (c) identifying additional sample locations/sample types and associated analyses that should be considered for providing valuable supplementary information for decision making.

# 1.0 INTRODUCTION

## 1.1 HISTORIQUE

Le drainage rocheux acide (DRA) est une question environnementale importante qui se pose pour de nombreuses propriétés minières au Canada. Le DRA a été observe a pratiquement tous les types d'exploitations minières, notamment aux mines de métaux communs, de métaux précieux, d'uranium et de charbon et a certaines exploitations minérales industrielles choisies. Au cours des 20 dernières années, une série de techniques de suivi ont été élaborées pour prévoir le potentiel de DRA aux sites miniers et pour surveiller les caractéristiques acidogènes des haldes de stériles. Il existe une multitude de techniques mais peu de données ont été publiées pour indiquer les techniques les plus utilisées, les plus rentables et, ce qui est encore plus important, les plus exactes.

Afin d'orienter l'industrie, le Secrétariat du NEDEM a conclu, en 1992, un contrat avec SENES Consultants Limited pour qu'elle effectue une étude de la documention scientifique sur les techniques d'échantillonnage des stériles. L'étude de la documention a permis d'établir une liste complète et une description des techniques d'échantillonnage ainsi que de produire un guide pour répondre aux besoins en matière 'd'échantillonnage des stériles aux fins de la prospection, de l'exploitation et de la fermeture d'un projet minier. L'étude de la documention n'indique pas les techniques les plus utilisées sur les propriétés minières canadiennes et ne contient pas non plus de recommandations pour l'emploi de méthodes spécifiques ou de normes pour l'industrie.

Dans le but de fournir une analyse plus interactive avec l'industrie et les gouvernements, la deuxième phase du projet a comporte un sondage détaille sur les méthodes d'échantillonnage des stériles actuellement appliquées a plusieurs sites situes en Amérique du Nord, en Australie et en Europe. Ces données sont résumées, et un document de principes provisoire a été prépare par SENES qui a mis en évidence les méthodes de l'industrie et, si possible, les techniques de surveillance utilisées de préférence. Ce document provisoire a servi de base a un atelier de spécialistes tenu a Toronto, les 11 et 12 mars 1994. Cet atelier a réuni 12 specialistes de l'industrie, d'organismes de recherche et du gouvernement, auxquels se sont ajoutes 18 observateurs. Le compte rendu détaille peut être obtenu en s'adressant au NEDEM. Une liste des personnes qui ont répondu au sondage et des participants a l'atelier des specialistes est présentée a l'annexe A.

Apres la tenue de l'atelier, le document de principes provisoire a été mis a jour pour former le présent Manuel sur les techniques d'échantillonnage des stériles. L'étude de la documention (Rapport NEDEM 4.5.1-1) a également été mise a jour de façon a inclure les résultats du sondage, les informations présentées a l'atelier des spécialistes et tout autre nouvelle information présentée dans le manuel.

Le manuel est un résume concis des techniques d'échantillonnage actuellement utilisées.
On suppose que le lecteur du présent manuel connait chaque technique d'échantillonnage décrite et

traitée dans l'étude. On peut se procurer l'étude de la documention scientifique (Rapport NEDEM 4.5.1-1) et le manuel (Rapport NEDEM 4.5.1-2) en question en s'adressant a CANMET. Nous recommandons au lecteur intéresse de lire les deux documents. L'étude de la documention scientifique devrait être consultée lorsqu'une description détaillée et une comparaison des techniques d'échantillonnage des stériles est nécessaire. Le manuel devrait être consulte lorsqu'un résume concis des techniques d'échantillonnage disponibles et recommandées est nécessaire.

Au chapitre 2, les sujets traités brièvement sont les suivants : échantillonnage représentatif, conception d'un programme d'échantillonnage, gestion des données et assurance et contrôle de la qualité.

Au chapitre 3, chaque catégorie d'échantillonnage des stériles (caractérisation chimique, surveillance de la qualité de l'eau, échantillonnage des gaz, etc.) est abordée dans un format commun sous les entêtes suivantes :

- Méthodes possibles;
- Objectifs;
- Données de base;
- Classement;
- Limites et avantages;
- Procèdes recommandes;
- Exigences;
- Couts; et
- Références

Le chapitre 4 contient un résume des techniques recommandées afin d'obtenir des informations permettant : a) d'établir des estimations provisoires des couts aux fins des prises de décisions en matière de gestion, d'entretien, de surveillance et de fermeture des sites de DRA; b) de prévoir (par modélisation) le DRA potentiel; et c) de déterminer quels emplacements et types d'échantillonnage additionnels et quelles analyses associées permettraient d'obtenir des informations supplémentaires utiles pour fins de prise de décisions.

# 2.0 PREPARATION FOR SAMPLING

## 2.1 REPRESENTATIVE SAMPLE

It is generally accepted that the determination of what constitutes a "representative sample" of a waste rock pile is a challenging task. It must be decided which characteristics of waste rock (e.g. contaminant level, NNP-net neutralization potential, NP/AP ratio, etc.) and which statistical parameter(s) (e.g. mean, variance, etc.) will be used to assess "representativeness" and which strategy(ies) should be used to determine how many samples are required, and at which locations these samples should be taken.

A wide variety of sampling strategies and sampling are discussed in the Review. The major conclusions drawn from the experts workshop and the surveys are as follows:

- Sampling strategies should be site-specific. The number of samples required to characterize the waste rock at a site will depend on numerous factors including geology, uniformity of the mine rock, size of the geological units.

- There are mathematical formulations which can be applied to determine the number of samples. One technique presented in the B.C. AMD Draft Manual suggests the number of samples could be based upon the size of the geological unit. As a general comment, the experts felt this technique should be used with caution. Some practitioners have developed their own unique approach to using a statistical analysis to determine how many samples are required (e.g. Li, 1994).

- Virtually all participants believed a staged program is warranted. Analyses of the initial sampling provides guidance as to how many more samples may be required and which geological units/strata should be re-sampled. The input of the field geologist and mine engineer is essential in determining sample locations and compositing of samples.

- Compositing of samples should be avoided where possible, as each distinct zone should be assessed separately. If composite samples are used, each composite must be made from a single distinct lithology or alteration zone (in the case of *in situ* rock sampling), or from a distinct layer or zone within a waste rock dump. Compositing may be useful when a large number of samples are available for ARD characterization, such as drill core samples from exploration/development, and the cost of analyzing all samples individually would be prohibitive. Compositing may also be necessary in order to provide a sample of adequate size for testing.

## 2.2 SAMPLING PROGRAM DESIGN

- The objectives of the sampling program must be defined first.
- A properly designed sampling program is essential for estimating costs and for modelling.
- The ultimate waste rock disposal method will determine the scope for the sampling program. For example, if all reactive waste is to be placed in surface piles, or below water.
- Existing mine block models are useful in defining zones of waste rock and their mining sequence.

## 2.3 DATA MANAGEMENT

Sampling programs will generate a considerable amount of data that will need to be properly managed to facilitate periodic review and revision of the sampling strategy. A database format is recommended:

- spreadsheet programs are useful for carrying out numerous repetitive calculations; and
- database management software and geographic information systems (GIS) are also of great assistance for managing and interpreting data.

There are two B.C. AMD Task Force databases at the University of B.C.: DBARD (DataBase for Acid Rock Drainage) which may be made available to individual mines to store and organize their data; and a database of data from selected sites that can be used by researchers developing waste rock models.

## 2.4 QUALITY ASSURANCE AND CONTROL

The importance of QA/QC should always be given appropriate consideration as this is an essential component of sampling programs and analyses of waste rock samples. Procedures for QA/QC should be part of the sampling program and QA/QC protocols should be obtained from the laboratory conducting the various analyses. Field tests and laboratory tests should be standardized to allow comparison of results obtained from various sites. Unfortunately, the added costs associated with QA/QC (e.g. duplicates, triplicates) are often mistakenly viewed as being unjustified, particularly when these QA/QC programs demonstrate the quality is acceptable, and QA/QC is usually the first component dropped when the budgets for sampling are reduced. There are two approaches to ensuring QA/QC is part of your program:

(i) set the budget and try to obtain the best precision and accuracy possible for that budget; or
(ii) set the precision and try to minimize the costs.

# 3.0 SAMPLING TECHNIQUES

## 3.1 BACKGROUND

This chapter summarizes the sampling techniques for each category of waste rock characterization (chemical characterization, water monitoring, gas sampling, etc.). The following headings are used for each category:

***Possible Methods:*** list of methods described in the Review and methods suggested in survey responses or at the experts workshop;

***Objectives:*** explanation of the information obtained from each sampling category and what it will be used for;

***Background:*** where the information is used, and what other sampling work may be carried out in conjunction with this category, etc.;

***Rating:*** Level of use of the various techniques is discussed, and the techniques are categorized as to whether they are commonly used, or experimental. Also noted is whether the technique is essential for decision-making regarding management, maintenance, monitoring and closure, or merely of interest, and whether it is required for modelling/prediction. Ratings were derived from the survey, workshop and our experience;

***Limitations and Advantages:*** of the various methods are compared. Similar methods in a category may be either discussed as a group or summarized in tabular format, depending on the type and amount of information available;

***Recommended Procedures:*** determined from the Review, survey, workshop and experience;

***Requirements:*** materials, equipment, personnel;

***Cost:*** per sample, per hole, personnel, etc. Personnel costs are site-specific and will vary widely depending on: waste rock location and ease of access, size of waste rock piles, number of sampling locations, required training, availability of staff on-site, etc. It has been assumed that a geologist/mine engineer will be responsible for the sampling program and interpretation of the analyses results; their time has not been included in the cost estimates, but it has been noted where their expertise would be specifically required. A field technician would typically do most of the data collection/field tests recommended in this handbook. Often tasks for different categories can be combined to increase efficiency. The preferred method of estimating personnel costs is to decide on the combination of sampling categories required, and then estimate overall time requirements for field technician (i.e. 2 days/month, half time, etc.) and for supervision by geologist/mine engineer; and

***References:*** specific to each category. The Review of Waste Rock Sampling Techniques should also be consulted when a detailed description is required.

## 3.2 CHEMICAL CHARACTERIZATION OF WASTE ROCK

### 3.2.1 Elemental Content (sulphide, buffering and trace minerals, radionuclides)

***Possible Methods:***

a) Acid Digestion followed by multi - element determination by ICP/mass spectrometry or an equivalent method.
b) X-ray fluorescence spectrometry.
c) Other:
   - energy dispersive ex-ray (EDX)
   - atomic absorption (AA), gas chromatography (GC), spectrophotometry
   - Simultaneous carbon sulphur instrument
   - ICP optical emission spectrometer
   - total sulphur - sulphide
   - strong (total) and partial extracts
   - petrographic (thin section) analysis
   - carbon - carbonate
   - major metal, whole rock, sulphur speciation
   - LECO furnace
   - wet chemistry.

***Objectives:*** To chemically characterize waste rock.

***Background:*** Waste rock samples for chemical characterization are usually obtained through boreholes drilled in waste rock piles or *in situ* before rock is excavated. The boreholes are logged by a geologist and samples are selected for chemical characterization, ARD assessment, and other tests such as pore water composition. Waste rock dumps may also be sampled without drilling. Some samples can be subjected to a particle size analysis, and the different size fractions should then be tested for elemental content and ARD potential.

***Rating:*** By far the most common technique used to determine elemental content is a). Item b) is used occasionally. Elemental content is essential for ARD assessment.

***Limitations and Advantages:*** Item a) is limited in that ICP sulphur analysis may not be reliable unless a quality assurance program is included (i.e. correlation with LECO sulphur). Also, other elements such as arsenic and mercury have to be assessed by alternate methods such as wet chemistry or atomic absorption. The limits of detection for Item b) are not as low as those for Item a), and Item b) is best suited for analysis of major elements.

***Recommended Procedures:*** Item a) - This is a simple, cost-effective method to obtain a large amount of useful data. The digestion method should be specified. Normally a total acid digestion is used. Low cost, low quality labs should be avoided. For arsenic, mercury etc. alternative analysis methods should be selected. A quality assurance program is required and limits of detection should be specified.

***Requirements:*** Samples are usually taken when boreholes are logged. Sample preparation (e.g. crushing) and analysis is usually done by a commercial lab.

***Cost:*** Sample preparation and analysis is about $200/sample on average. ICP laboratory analysis costs $5-$75/sample, depending on number of elements requested, lab, etc. X-ray diffraction laboratory analysis costs ~$25/sample. Sulphur speciation is $25/sample.

### 3.2.2 Mineralogy (distribution of minerals in waste rock particle)

***Possible Methods:***

a) X-ray diffraction.
b) X-ray scan with clay speciation.
c) SIMS (Secondary Ion Mass Spectrometry).
d) QEM*SEM or automated scanning electron microscopy.
e) Other:
   - Petrographic microscopic analysis
   - Energy dispersive x-ray
   - Whole rock assays
   - Sequential leaching to extract particular mineral phases.

***Objectives:*** To characterize the mineralogy of waste rock.

***Background:*** Selected representative samples are taken in conjunction with the elemental sampling program described above.

***Rating:*** Item a) is most common, and Item d) and petrographic microscopic analysis are also fairly common. Both are established techniques. Item c) has been used experimentally. Knowledge of mineralogy is essential for ARD prediction and modelling.

***Limitations and Advantages:*** Advantage of petrographic microscopic analysis is that it also can provide information on mineral forms. Advantage of x-ray diffraction is that it is generally less costly and can be used for powdered/crushed samples and for identification of secondary minerals.

***Recommended Procedures:*** All of the above.

***Requirements:*** Analysis is normally done commercially. Petrographic analysis, if done in house, would require geologist, microscope and preparation of thin sections from rock sample.

***Cost:*** Petrographic microscope examination costs approximately $100-$200/sample. X-ray diffraction costs $10-$150/sample, depending on parameters analyzed.

### 3.2.3 Mineral Forms (e.g. massive, nodular, disseminated, etc.)

***Possible Methods:***

a) Observation by geologist in the field.
b) Determined during mineralogical analysis.
c) Other: - Petrographic microscopic analysis.

***Objectives:*** To determine mineral forms, for both sulphides and non-sulphides. Mineral form can have a major impact on ARD.

***Background:*** Usually performed in conjunction with mineralogical analysis.

***Rating:*** All techniques are used, and all are common. Knowledge of mineral forms is essential for ARD prediction and modelling.

***Limitations and Advantages:*** Microscope work may be required, depending on grain size and nature of mineralization.

***Recommended Procedures:*** All of the above.

***Requirements:*** Geologist, microscope, thin sections.

***Cost:*** Costs for this item is the geologist's time and expenses. This would vary widely, depending on the size of the mine, geological complexity and nature of mineralization, etc. Geological descriptions, however, would normally be prepared as part of the exploration and development programs, and therefore may be available for the purpose of ARD assessment at little or no additional cost. Petrographic microscope examination costs approximately $100-$200/sample.

***References for Section 3.2:***

Fletcher, W.K. 1981. *Analytical methods in geochemical prospecting.* In: Govett, G.J.S., Editor, Handbook of Exploration Geochemistry, Elsevier, 254 pp.

Levinson, A.A. 1980. *Introduction to exploration geochemistry, second edition.* Applied Publishing Ltd. Wilmette, Illinois, U.S.A.

Thompson, M. 1986. *The future role of inductively-coupled plasma atomic emission spectroscopy in applied geochemistry.* In: Thornton, I. and Howarth, R.J. Editors, Applied Geochemistry in the 1980s, John Wiley and Sons, pp. 191-211.

## 3.3 ARD ASSESSMENT TEST PROCEDURES FOR WASTE ROCK

### 3.3.1 Static Tests (net neutralization potential in terms of kg $CaCO_3$ equivalents per ton of rock)

***Possible Methods:***

a) Protocol developed by B.C. Research (Duncan and Bruynesteyn 1979) for determination of oxidizable sulphur and carbonate.
b) Modified version of Duncan and Bruynesteyn 1979 test presented in B.C. AMD Task Force, Draft Acid Rock Drainage Technical Guide (SRK, Norecol and Gormely 1990) which involves differentiation between oxidized (i.e. sulphate), leachate and non-leachable sulphur.
c) Method developed by Finkelman and Giffin (1986) which uses hydrogen peroxide to determine the reactive sulphur content.
d) Method developed by Sobek et al. (1978) involving addition of excess hydrochloric acid followed by titration with sodium hydroxide to pH 7.
e) Modification of the conventional U.S. EPA method of excess hydrochloric acid treatment and titration of untreated acid to include removal of siderite (iron carbonate) before titration.
g) Modification of the conventional U.S. EPA method to include direct determination of dissolved alkali earth metals (calcium, magnesium) and iron by atomic adsorption spectrometry and calculation of the equivalent calcium carbonate content, rather than by titration.
h) Method for determination of pyritic sulphur by dissolution of the pyrrhotite fraction in hot hydrochloric acid followed by an assay for sulphur on the basis of iron in both the dissolved (pyrrhotite) and solid (pyrite) fractions (iron from pyrite released oxidatively with nitric acid) (Norecol 1991).
i) Same as above except hydrogen peroxide is used as oxidative agent for release of iron from pyrite (Norecol 1991).
j) Other:
   - NAG/NAP - hydrogen peroxide test.
   - Expanded acid base accounting including direct measurement for sulphur species and total carbonate content.
   - Alternative modifications of U.S. EPA method and/or Sobek method.
   - Modified version of Finkelman & Giffen (1986).
   - Net acid generation method developed by respondent (15% $H_2O_2$, pH - time profile, temperature - time profile, end pH and acidity, 24 hour, 7 day duration).

***Objectives:*** To determine the net potential acidity that could result from oxidation of the sulphides to acid (AP-acid potential) versus the neutralization potential (NP) provided by buffering minerals contained in the waste rock (e.g. acid-base accounting).

***Background:*** Static tests are performed on waste rock samples which are usually obtained through drilling of *in situ rock* or waste rock piles, or surface or trench sampling of waste rock piles. Static samples are usually taken as part of a program which would also involve selection of samples for chemical and mineralogical testing.

***Rating:*** Items a), b) and d) are all in common use, are recommended by industry and government, and are an essential step in ARD prediction. Many practitioners are investigating other modifications to these standard procedures.

***Limitations and Advantages:*** No static test is a true indicator of whether samples would produce acidity. Furthermore contaminated leachates can be produced without the production of acid. Depending on the waste rock, there is some concern that NP estimates may vary with test procedure. Therefore, some quality assurance using an alternative procedure for determination of NP could be warranted. Please refer to Table 3.1.

***Recommended Procedures:*** All of the above. For simplicity and speed, Item d) is preferred.

***Requirements:*** Tests normally performed by commercial laboratory. Samples normally obtained during drilling and logging of boreholes.

***Cost:*** Average cost is $75/sample.

### 3.3.2 Dynamic Tests (time dependent study of acid generation)

***Possible Methods:***

a) Soxhlet extraction tests.
b) Stirred Reactor Configurations.
c) Stationary Bed Reactor Configurations - e.g. column, lysimeter or humidity cells.
d) Other:
   - On-site monitoring, on-site rock pads, heap leach tests.
   - Full scale leach pads.
   - B.C. Research - biological.
   - Humidity columns.
   - Field test pads.
   - Simulation under water with controlled precipitation, evaporation and temperature.

***Objectives:*** To determine the rate and extent of acid generation from waste rock.

***Background:*** Dynamic tests are not performed routinely or in large numbers. A limited number of samples may be selected for dynamic testing based on the results of static and chemical tests.

***Rating:*** Item c), stationary bed reactor configurations, are most common and of these column and humidity cell tests are most frequently used. These tests are essential for ARD modelling/ prediction.

***Limitations and Advantages:*** No dynamic laboratory tests can represent field conditions; therefore the tests should be interpreted with caution. Lysimeter tests are very expensive to build and monitor and should not be used routinely. Please refer to Table 3.2.

***Recommended Procedures:*** For new sites, Item c), with preference to columns. For existing sites, on-site monitoring takes the place of dynamic tests. Samples that are not crushed and that include larger, more representative particle sizes are preferred. For samples with large particle sizes, column tests are preferred. Quality control (duplicates, triplicates) are important to assess the variability and reproducibility of the dynamic test program. The major issue with most dynamic tests is that the test duration is too short. Nominal test programs are conducted for 10 weeks while practice has shown it can take much longer periods (e.g. 1 year) for sample to become acidic and/or produce contaminated leachates.

***Requirements:*** Laboratory with necessary (columns, reactors) and instruments for analyses of solids and water samples. Construction materials for lysimeter installations.

***Cost:*** Costs for stationary bed reactor tests commonly range from $1,000-$5,000/test, including sample analysis. Costs for lysimeter tests are: $50,000 plus for design and set-up; and $30,000 to $50,000/year for operating.

***References for Section 3.3:***

British Columbia Acid Mine Drainage (B.C. AMD) Task Force 1989.

Duncan, D.W. and A. Bruynesteyn 1979. *Determination of the acid production potential of waste materials.* AIME Annual Meeting, New Orleans, Louisiana, U.S.A. Paper A-79-29.

Finkelman, R. and D. Giffin 1986. *Hydrogen peroxide oxidation: an improved method for rapidly assessing acid-generating potential of sediments and sedimentary rocks.* Reclamation and Revegetation Research, 5:521-534.

Halbert, B.E., J.M. Scharer, R.A. Knapp, R.A. and D.M. Gorber 1983. *Determination of acid generation rates in pyritic mine tailings.* 56th Annual Conf. of the WPCF, Atlanta, Georgia, U.S.A.

Norecol Environmental Consultants Ltd. (Norecol) 1991. *New methods for determination of key mineral species in acid generating prediction by acid-base accounting.* Prepared for CANMET, MEND Project 1.16.1(c), April.

Scharer J.M. and R.V. Nicholson 1991. *Coupled processes to extrapolate the kinetics of pyrrhotite and pyrite oxidation from the laboratory to mine tailings in the field.* Proceedings of the 1991 Geological Society of America Meeting, San Diego, California, U.S.A., August.

Sobek, A.A., W.A. Schuller, J.R. Freeman and R.M. Smith 1978. *Field and laboratory methods applicable to overburdens and mine soils.* EPA-600/2-78-54, National Technical Information Service, Springfield, Virginia, U.S.A.

Steffen Robertson and Kirsten (B.C.) Inc. (SRK), Norecol Environmental Consultants and Gormely Process Engineering, 1990. *Draft acid rock drainage technical guide Volume II.* British Columbia Acid Mine Drainage Task Force Report, May.

Table 3.1

**CHARACTERISTICS OF THE STATIC ARD TESTS**

| Test Type | Advantages | Disadvantages |
|---|---|---|
| *Fizz Test*<br>Coastech 1991<br>Horberger 1989 | - easy to apply<br>- can be used in the field<br>- indicator of carbonate buffering | - qualitative only<br>- cannot be applied for prediction |
| *Paste pH*<br>Renton et al. 1989 | - easy to apply<br>- can be used in the field<br>- indicates net free acidity/alkalinity | - does not measure total acidity<br>- false positive/negative response<br>- cannot be applied for prediction |
| *Neutralization Potential (NP)*<br>Sobek 1978<br>Coastech 1991<br>*U.S. EPA and Modified U.S. EPA Methods*<br>Norecol 1991<br>*B.C. Research Initial and Modified (NP) Tests*<br>Coastech 1991<br>SRK, Norecol and Gormely 1990<br>Duncan and Bruynesteyn 1979 | - well known, popular laboratory procedure<br>- quantitative measure of total buffering capacity<br>- low cost<br>- reproducible if performed properly<br>- recommended by government agencies | - gives little indication of ARD potential<br>- no mineralogy (source of neutralization potential) |
| *Alkaline Production Potential Sulphur Ratio (APP/S)*<br>Coastech 1989 | - simple calculations<br>- rapid indicator of potential ARD<br>- useful preliminary analysis | - theoretical analysis<br>- results need to be confirmed by experimentation |
| *Net Acid Production (NAP)*<br>Coastech 1989<br>*Standard and Modified Acid Base Accounting (ABA)*<br>Coastech 1991 | - combination of acid production and acid neutralization test procedures<br>- can differentiate between sulphide minerals (pyrrhotite/pyrite)<br>- allows determination of carbonate and non-carbonate buffering capacity | - long, often complex procedures<br>- interpretation may be difficult<br>- no indication of reaction rate |
| *Net Acid Generation (NAG)*<br>Miller et al. 1990<br>*Hydrogen Peroxide*<br>Finkelman and Giffen 1990 | - simple, straight forward test procedure<br>- good reproducibility | - overestimates net acid production<br>- requires pulverized (unrepresentative) samples<br>- seldom used in Canada |
| *B.C. Research Confirmation Test* | - used to confirm results of static prediction tests | - usually grouped with dynamic test methods |

Table 3.2

## CHARACTERISTICS OF THE DYNAMIC ARD TEST

| Test Type | Advantages | Disadvantages |
|---|---|---|
| *Soxhlet Extraction*<br>Extraction with reactive, hot liquid<br><br>Renton et al. 1988<br>Sobek et al. 1978 | - simple to operate<br>- rapid test procedure<br>- options may be tested<br>- easy to interpret (model) results | - geochemistry may be altered<br>- oxidations tend to be aggressive<br>- unnatural conditions<br>- bacterial, temperature, pH effects cannot be determined |
| *Stirred Reactor Studies*<br>Reactions in fluidized solid suspensions<br><br>B.C. AMD Task Force 1989<br>Duncan and Bruynesteyn 1979<br>Filipek et al. 1991<br>Halbert et al. 1983<br>Lawrence et al. 1989<br>Scharer et al. 1991<br>Scharer & Nicholson 1991 | - amenable to fundamental studies (surficial reaction rate)<br>- environmental factors are easily assessed:<br>i) oxygen concentration<br>ii) temperature<br>iii) pH<br>iv) specific surface area<br>v) bacterial activity<br>- allows multilevel factorial statistical design<br>- control actions (submersion, oxygen exclusion, bacterial inhibition) may be evaluated | - tend to overestimate reaction rates (ideal rate)<br>- cannot be used to evaluate effect of moisture content on oxidation<br>- may be oxygen limited<br>- secondary mineralization may be affected<br>- complex data interpretation and modelling |
| *Stationary Bed Test Studies*<br>Reactions in stationary solid columns<br><br>Bradham and Caruccio 1991<br>B.C. AMD Task Force 1989<br>Caruccio 1968<br>Caruccio et al. 1981<br>Hood and Oerter 1984<br>Ritcey 1989<br>Ritcey and Silver 1982<br>Sobek et al. 1978 | - simulates natural conditions (including submerged conditions)<br>- simple to operate<br>- environmental factors can be assessed<br>- gives overall acid generation per unit mass of waste rock<br>- easy to monitor<br>- widely used in US and Canada<br>- control actions may be evaluated | - confounds kinetics with transport phenomena<br>- may be diffusion limited<br>- bacterial acclimatization may be difficult<br>- surfaces are undefined<br>- complex data interpretation and modelling<br>- may not represent field conditions |

## 3.4 PHYSICAL STABILITY OF WASTE ROCK

***Objectives:*** To assist in evaluation of physical stability of waste rock, which may have a significant impact on the rate and extent of acid generation.

***Background:*** Representative samples of each rock type would typically be selected for physical testing in conjunction with drilling/sampling program.

### 3.4.1 Hardness

***Possible Methods:***

a) ASTM C131-89 Los Angeles Abrasion test for small-size coarse aggregate.
b) ASTM C535-89 Los Angeles Abrasion test for large-size coarse aggregate.
c) Other:
   - RQD (Rock Quality Designation).
   - Slake durability.
   - 1 to 5 rock hardness scale.

***Rating:*** Items a) and b) are used most frequently, although hardness testing is not commonly performed, and is experimental when applied to ARD assessment.

***Limitations and Advantages:*** The tests provide an indication of rock stability rather than a quantitative estimate regarding rock weathering rates.

***Recommended Procedures:*** No preferred method.

***Requirements:*** Outside laboratory

***Cost:*** Costs for abrasion, hardness and slake testing are usually about $200 or $300/sample.

### 3.4.2 Weathering

***Possible Methods:***

a) Visual observation.
b) Humidity cell tests.
c) Scanning electron microscope and microprobe analyses.
d) Determined as part of acid generation tests.
f) Weathering potential indicator (WPI) based on chemical composition of rock sample.
e) Magnesium sulphate test (ASTM C88-90).
g) Other:
   - slake testing: wet/dry and freeze/thaw.

***Rating:*** Item a) is most common, and b) and d) are also fairly common. An understanding of potential effects of weathering on sulphide oxidation and buffering availability is important for ARD prediction. Weathering of rocks creates fines which increases the surface area of available sulphide minerals. In contrast weathering could also cause high fines contents which increases moisture retention and reduces oxygen flux to the pile.

***Limitations and Advantages:*** Tests are qualitative, not quantitative, and results are difficult to relate to field conditions for all methods. Advantage of humidity cell tests is that information on weathering can be obtained whenever humidity cells are used for dynamic test work. Advantage of other tests is low cost and faster turnaround time.

***Recommended Procedures:*** No recommendation. This is a major area of deficiency in current state-of-the-art waste rock sampling programs which seem to focus on static and dynamic test work.

***Requirements:*** Outside lab, or done as part of dynamic (humidity cell) tests.

***Cost:*** Weathering tests cost $200/sample, excluding sample collection. Costs for humidity cells range from $1,000-$5,000/test, including sample analysis.

***References for Section 3.4:***

American Society for Testing and Materials (ASTM) C88-90. *Test method for soundness of aggregates by use of sodium sulfate or magnesium sulfate.*

American Society for Testing and Materials (ASTM) C131-89. *Test method for resistance to degradation of small size coarse aggregate by abrasion and impact in the Los Angeles machine.*

American Society for Testing and Materials (ASTM) C535-89. *Test method for resistance to degradation of large-size coarse aggregate by abrasion and impact in the Los Angeles machine.*

## 3.5 WATER MONITORING ASSOCIATED WITH WASTE ROCK

### 3.5.1 Locations Monitored

***Possible Locations:***

a) Surface run-off from the waste rock.
b) Pore water.
c) Seepage.
d) Groundwater.
e) Surface water bodies.

***Objectives:*** To assess water quality and to calculate contaminant loadings, water samples at various locations around and within waste rock piles are required.

***Background:*** Water quality sampling and flow monitoring are usually done in conjunction.

***Rating:*** All above locations are commonly monitored. Site-dependent.

***Limitations and Advantages:*** Obtaining sufficient water for analyses and flow measurement may be difficult at some sites and for some climates. See subsequent sections for limitations and advantages of possible methods that can be used at each location.

***Recommended Procedures:*** All of the above.

***Requirements:*** Personnel to set-up and review program (monitoring locations, frequency, etc.) and to collect samples.

***Cost:*** Depends on collection method and location, see below.

### 3.5.2 Water Sampling Methods

#### *3.5.2.1 Run-Off*

***Possible Methods:***

a) Grab sample.
b) Other: - Automatic sampler composite

***Rating:*** Item a), grab sample is standard. Occasionally automatic samplers are used.

***Limitations and Advantages:*** Item a) is more labour intensive, and Item b) can fail. Also with Item b), field tests cannot be conducted immediately.

***Recommended Procedures:*** Items a) or b) - site-specific.

***Requirements:*** Personnel, sample containers.

***Cost:*** Cost for a) is labour, which is site-specific. An automatic programmable sampling system could cost \$5,000 - \$10,000/station.

### *3.5.2.2 Pore Water*

***Possible Methods:***

a) Sampling of wetted waste rock, and washing into measured volume of distilled water.
b) Suction lysimeter.
c) Core Squeezing.
d) Other:
   - Piezometers.
   - Buried gravity lysimeters and suction lift pump.
   - Internal bottom-lined water collection trench.
   - In stationary bed reactor.
   - Paste pH.
   - Centrifuge.

***Rating:*** Item a) is most common technique. Items b) and c) provide better results. All methods for collecting pore water samples in unsaturated waste rock are technically difficult. Collection of pore water below water table is commonly carried out using piezometers. Characterization of pore water is essential for ARD prediction and modelling.

***Limitations and Advantages:*** The disadvantage of Item a) is that washing can remobilize secondary precipitates. Disadvantage of Items a) and c) is that sampling is destructive and cannot be repeated in same location. Item b) is limited to coarse materials, which includes most waste rock dumps.

***Recommended Procedures:*** Site-specific, with preference to methods which collect pore water in-situ, such as b).

***Requirements:*** Item b) requires suction lysimeter, while Items a) and c) require drilling to collect a sample for testing.

***Cost:*** Site and option specific.

### *3.5.2.3 Seepage*

***Possible Methods:***

a) Drainage trench/collection ditch.
b) Surface piping.
c) Other:
- Grab samples.
- Collection pipe.
- Local seepages.
- Automatic sampler

***Rating:*** Item a) is commonly used.

***Limitations and Advantages:*** Seepage collection locations are important. Wherever sampled, seepage may be diluted by surface run-off or wash-through flow associated with precipitation events. Therefore, the location, time of sampling and a record of rainfall is important. Seepage flow and quality data provides a useful indication of state of acid generation within the waste rock pile.

***Recommended Procedures:*** No preferred method - site-specific.

***Requirements:*** Personnel, sampling containers,

***Cost:*** Cost for a) is labour, which is site-specific. An automatic programmable sampling system could also be used at a cost $5,000 - $10,000/station.

### *3.5.2.4 Groundwater (piezometer/standpipe wells)*

***Possible Methods:***

a) Bailer.
b) Suction - lift pumping.
c) Syringe sampler.
d) Submersible pump.
e) Air-lift.
f) Other:
- Inertia pumping system (Waterra).
- Nitrogen lift.
- BK pumps - positive displacement.
- Airborne EM-31 survey.
- Peristaltic pump.
- Dedicated sampling device.

***Rating:*** Most commonly used are Items a) and b). Items d) and e) are also fairly common. Groundwater sampling is important for monitoring the flow paths of contaminated seepage from waste rock piles.

***Limitations and Advantages:*** Please refer to Table 3.3.

***Recommended Procedures:*** No preferred method. Depends partially on sampling depth (i.e. suction methods only work to 8 metres). EM surveys are excellent screening tools for defining high conductivity plumes and provide guidance for designing borehole installation program. Please refer to Section 3.18.

***Requirements:*** Borehole with monitoring well installed, personnel, sampling device such as a pump.

***Cost:*** To drill hole and install piezometer, the cost is typically $100/metre for 20 metre well. Monitoring costs are mainly personnel. EM surveys will typically range from $5,000 to $10,000/site.

### *3.5.2.5 Surface Water*

***Possible Methods:***

a) Grab.
b) Composite.
c) Other: - Automatic/programmable sampler.
- Weir during run-off.

***Rating:*** Item a) is most common. Item b) is also used fairly frequently. Surface water quality sampling is important for establishing normal background, and monitoring is important to detect changes associated with contaminated drainage.

***Limitations and Advantages:*** Advantage of grab and manually collected composite samples is that field analysis can be done immediately. For programmable samplers, there is a delay between collection of sample and field analysis, which can affect results.

***Recommended Procedures:*** Item a) - Grab samples are acceptable for most locations. It is very important to measure flow when sampling.

***Requirements:*** Personnel.

***Cost:*** Labour which is site-dependent.

Table 3.3

**GROUNDWATER SAMPLE COLLECTION METHODS (Golder and SENES, 1985)**

| Type | Application | Limitations |
|---|---|---|
| **Saturated Zone** | | |
| 1) Bailers | - Simple, inexpensive method for collection of samples. | - Samples are highly disturbed and must be extensively handled during filtration.<br>- Can be time consuming in small diameter wells. |
| 2) Depth-specific bailer | - Simple, inexpensive method less disruptive than bailer. | - Requires relatively large diameter wells. |
| 3) Syringe sampler | - Allows collection of samples without exposure to the atmosphere and allows filtration down-the-hole.<br>- Can collect samples from any depth. | - Only small volumes of pore water are collected in each syringe.<br>- Requires piezometers greater than 3 cm diameter. |
| 4) Suction-lift pumping | - For collection of relatively large volumes of water from shallow depth.<br>- Permits use of in-line filters to reduce sample handling. | - Sampling limited to water depths less than 8 m. |
| 5) Submersible pumps | - For collection of large volume samples from depths greater than 8 m. | - Requires relatively large diameter wells.<br>- Costly. |
| 6) Air-lift | - For collection of water samples from conventional wells or special air-lift samplers.<br>- No limitation on depth of water. | - Samples can be highly disturbed. |
| 7) Inertia pumping system (Waterra) | - Low cost, unlimited depth, no power requirements, dedicated instalment (no cross-contamination), direct filtering capabilities. | |
| **Unsaturated Zone** | | |
| 8) Suction lysimeters | - For collection of pore water samples from unsaturated tailings solids samples. | - Reliable only in relatively coarse sandy materials. |
| 9) Core squeezing | - For collection of pore water from tailings solids samples by squeezing or displacement | - Destructive sampling, monitoring at precisely the same location is not possible. |

## 3.5.3 Water Quality Parameters

### *3.5.3.1 Field Analysis*

***Possible Tests:***

a) pH.
b) Paste pH.
c) Electrical conductance.
d) Temperature.
e) Dissolved oxygen.
f) Other:
  - Alkalinity.
  - Acidity.
  - Redox potential.
  - Sulphate field kit.
  - Colour.
  - Turbidity.
  - Ferrous/ferric iron ratios.

***Objectives:*** Field analysis is conducted because some parameters can change prior to analysis in laboratory.

***Rating:*** Field parameters analyzed for commonly are Items: a), b), c), d) and e).

***Limitations and Advantages:*** Item b), paste pH, can vary widely depending on procedure used. Electrical conductance can be monitored continuously and is used to signal changes in quality. Redox potential measurements can be unstable.

***Recommended Procedures:*** Items a), b), d) and e) should be performed in the field. Standard test procedures should be documented and adhered to.

***Requirements:*** Field water quality sampling kit, instruments (e.g. pH meter, dissolved oxygen meter, conductivity meter, Redox meter), personnel.

***Cost:*** varies widely depending on the ease of access to sample locations, number of samples, parameters measured, etc.

### *3.5.3.2 Sample Preservation*

***Possible Methods:***

a) Unpreserved.
b) Nitric acid.

c) Hydrochloric acid.
d) Other:
   - Refrigeration.
   - Ship to lab within 24 hours.
   - Filtering.
   - NaOH for CN.

***Objectives:*** Preserve sample so that laboratory analysis results reflect original composition of sample.

***Rating:*** Please refer to Table 3.4. Preservation is important for establishing accurate quality, e.g. ferrous/ferric iron ratio can be altered by change in oxygen conditions associated with sample collection, storage and transport.

***Limitations and Advantages:*** Please refer to Table 3.4.

***Recommended Procedures:*** Follow appropriate provincial/federal standards.

***Requirements:*** Please refer to Table 3.4.

***Cost:*** Minimal, except for groundwater filtering at $50/sample (labour and filters).

#### *3.5.3.3 Sample Container Preference*

***Possible Containers:***

a) Glass.
b) Polyethylene.
c) Other:

***Rating:*** Item b) is preferred and most common. Please refer to Table 3.4.

***Limitations and Advantages:*** Please refer to Table 3.4. Note that attention should also be given to the materials used for the caps of these containers, as well as liners in the caps.

***Recommended Procedures:*** Items a) or b) but polyethylene preferred.

***Cost:*** Minimal.

Table 3.4

## SAMPLE CONTAINERS, PRESERVATION METHODS AND STORAGE TIMES

| Parameter | Field Analysis | Sample Container | | | Preservation With | Maximum Storage Time |
|---|---|---|---|---|---|---|
| | | Glass[1] | | Polyethylene | | |
| pH | X | | | | unpreserved | 6 hours |
| Electrical conductance | X | | | | unpreserved | 24 hours |
| Temperature | X | | | | - | - |
| Dissolved Oxygen | X | | | | - | - |
| TDS | | X | or | X | unpreserved | 7 days |
| TSS | | X | or | X | unpreserved | 7 days |
| Acidity | | X | or | X | unpreserved | 24 hours |
| Alkalinity | | X | or | X | unpreserved | 24 hours |
| Calcium | | | | X | $HNO_3$ | 6 months |
| Magnesium | | | | X | $HNO_3$ | 6 months |
| Sodium | | | | X | $HNO_3$ | 6 months |
| Potassium | | | | X | $HNO_3$ | 6 months |
| Chloride | | X | or | X | unpreserved | 7 days |
| Sulphate | | X | or | X | unpreserved | 7 days |
| Nitrate | | X | or | X | unpreserved | 24 hours |
| Total Iron | | | | X | $HNO_3$ | 6 months |
| Ferrous Iron | | | | X | $HNO_3$ | 24 hours |
| Aluminum | | | | X | $HNO_3$ | 6 months |
| Arsenic | | | | X | $HNO_3$ | 6 months |
| Cadmium | | | | X | $HNO_3$ | 6 months |
| Copper | | | | X | $HNO_3$ | 6 months |
| Lead | | | | X | $HNO_3$ | 6 months |
| Nickel | | | | X | $HNO_3$ | 6 months |
| Zinc | | | | X | $HNO_3$ | 6 months |
| Mercury | | X | | | $H_2SO_4$+$K_2Cr_2O_7$ | 1 month |
| Uranium | | X | | X | $HNO_3$ | 6 months |
| Radionuclides[2] | | X | | X | HCl or $HNO_3$ | 5 days |

Notes:
(1) Glass containers are not commonly employed except when analyzing for organic constituents.
(2) Radium-226, Polonium-210, Lead-210, Thorium-230.

### *3.5.3.4 Laboratory Analysis*

***Possible Tests:***

a) pH.
b) Major metals.
c) Sulphate.
d) Acidity.
e) Alkalinity.
f) Total dissolved solids.
g) Elemental scan.
h) Radionuclides.
i) Total suspended solids.
j) Other:
   - Nutrients (nitrates).
   - Conductivity.
   - Redox potential.
   - Density, $Fe^{2+}/Fe^{3+}$ Speciation, $Fe_{TOTAL}$.
   - Chloride.
   - Major anions.
   - Fluoride.
   - Inorganic carbon.
   - Trace metals.

***Rating:*** Laboratory analysis of water samples commonly involves all of the parameters listed above except for those in the Other category and Item h).

***Limitations and Advantages:*** Laboratory analysis for above constituents are fairly standard. Limits of detection are often not met by contract laboratories making data unsuitable for the purpose intended.

***Recommended Procedures:*** Requirements are site-specific. As a minimum Items a), c), d), e), f) and g) would normally be conducted. Other parameters should be added where warranted (e.g. sulphide solids, arsenic, radionuclides). Always specify limits of detection and request a copy of written procedures and quality assurance documents. Charge balances should be used as a simple check on the precision of the data.

***Requirements:*** Analysis usually done by commercial laboratory.

***Cost:*** Cost for a complete analysis ranges from $100-200/sample.

## 3.6 GAS SAMPLING IN WASTE ROCK

***Objectives:*** Gas sampling is used to evaluate oxygen availability as a function of depth within waste rock dumps and to monitor products of acid production (e.g. $CO_2$). Oxygen is critical in controlling oxidation rates. Gas sampling is also used for monitoring the effectiveness of covers.

***Background:*** Gas sampling ports are often installed in boreholes in conjunction with temperature thermistors. Gas sampling ports may also be used for air permeability tests.

### 3.6.1 Gas Constituents Sampled

***Possible Constituents:***

a) Oxygen
b) Carbon dioxide
c) Nitrogen
d) Water
e) Hydrogen sulphide
f) Sulphur dioxide
g) Methane
h) Other: - Rare gases

***Rating:*** Oxygen and carbon dioxide are the only two constituents commonly assessed. Oxygen concentrations are essential to monitor oxygen levels with depth for use in modelling and to confirm cover effectiveness. Others are assessed for site-specific reasons.

***Recommended Procedures:*** Project-specific - Item a) for most requirements, others as necessary.

### 3.6.2 Gas Sampling Techniques

***Possible Methods:***

a) Sampling from tubes installed at different depths in borehole. Sampling devices include portable peri-staltic pump or hand bulb.
b) Use of on-line gas meters.
c) Sampling into container for future analysis (e.g. Tedlar bags).
d) Installation of oxygen and/or carbon dioxide probes.

***Rating:*** The most common gas sampling technique is a). Item b) is also fairly common.

***Limitations and Advantages:*** Most carbon dioxide meters cannot measure values greater than 2-3% by volume. If these concentrations are encountered, gas must be collected for analysis by gas chromatography or infrared spectrometer. Below 0□C, sample lines may freeze on on-line gas meters.

***Recommended Procedures:*** Items a) and b) are cost-effective.

***Requirements:*** Boreholes with gas sampling ports installed, pump, on-line gas meter.

***Cost:*** Drilling and installation of gas ports costs approximately $1,000 to $2,000/hole (depending on depth and number of ports). Drilling costs approximately $70-$100/metre, and may also be used for temperature measurements, waste rock sampling, installation of piezometers, etc. Instrumentation costs $15-$20/metre. Costs for an on-line gas analyzer range from $1,000 to $3,500. Labour time estimates to sample a hole range from 10 to 30 minutes (depending on depth and number of ports). Re-usable syringes ($30 to $50 each) are used to collect samples for gas chromatography ($50 to $80/sample).

### 3.6.3 Associated Measurements

a) Temperature
b) Partial pressure
c) Humidity
d) Other:
- Pore water in vadose zone collected by suction lysimeter
- Wind direction, wind velocity, precipitation
- Water level (water table)

***Rating:*** Item a) temperature at gas sampling location, is the most common associated measurement conducted.

***Limitations and Advantages***: Temperatures and partial pressures are easily measured at same time as gas sampling.

***Recommended Procedures:*** Item a), temperature is generally required in any event and should be measured at same time gas is sampled.

***Requirements:*** Thermistors, precision manometer/pressure transducer, meteorological instrumentation - please refer to Section 3.15, personnel to install equipment, personnel to record readings or automatic data loggers.

***Cost:*** Please refer to Section 3.15.

***References for Section 3.6***

Nolan, Davis and Associates (N.B.) Limited 1993. Draft. *Field procedures manual gas transfer measurements waste rock piles Heath Steele Mines New Brunswick.* Prepared in association with Australian Nuclear Science and Technology Organisation for CANMET, File No. F92-081, May.

## 3.7 TEMPERATURE MEASUREMENTS IN WASTE ROCK

### 3.7.1 Location

***Possible Locations:***

a) Measurements at surface.
b) Thermistors in boreholes.
c) Seepage collection point.
d) Other: - Infrared thermometry (airborne and hand-held).

***Objectives:*** Temperature recordings inside waste rock dumps are important to evaluate several processes: reaction rates, diffusion and convection, control of bacterial growth, oxygen solubility in water, water movement in the vapour phase and general monitoring of dump evolution.

***Background:*** Borehole temperature measurements are often taken in conjunction with gas monitoring.

***Rating:*** Temperature measurements of waste rock pile are commonly performed and are essential for modelling. The most common location to measure temperature is within boreholes using a thermistor. Less common are temperature measurements at surface and at seepage collection points.

***Limitations and Advantages:*** Measurements at surface and at seepage collection points are not as useful as internal temperatures, because readings are affected by ambient conditions.

***Recommended Procedures:*** Item b) - very useful data.

***Requirements:*** Boreholes, instrumentation, personnel to record readings or automatic data loggers.

***Cost:*** Thermistors are usually installed in boreholes drilled for a combination of purposes such as rock sampling, installation of piezometers, gas ports, etc. The cost of installing instrumentation is typically $500-$2,000/hole. Thermistors are read at a rate of 7-15 per hour, and each hole may have 10-20 thermistors. Cost for measurements may be reduced by combining with gas monitoring costs. Automatic data logger capital cost is $2,000 to $3,000 plus per borehole and is more expensive than manual readings unless readings are required frequently (this is site-specific and also depends on sampling frequency).

### 3.7.2 Associated Measurements/Observations

***Possible Measurements:***

a) Air temperature
b) Wind velocity
c) Precipitation
d) Snow cover
e) Atmospheric pressure
f) Relative humidity
g) Other: - Predominant seasonal wind direction.

***Rating:*** The most common associated measurements are air temperature, precipitation and snow cover. Also common are wind velocity, atmospheric pressure and relative humidity measurements.

***Recommended Procedures:*** Item a) as a minimum.

***Requirements:*** Please refer to Section 3.15.

***Cost:*** Please refer to Section 3.15.

***References for Section 3.7:***

Lefebvre, R., P. Gélinas, and D. Isabel 1994. *Heat transfer during acid mine production in a waste rock dump, La Mine Doyon (Quebec).* Prepared for MEND, Report 1.14.2, March.

## 3.8 PERMEABILITY MEASUREMENTS IN WASTE ROCK

### 3.8.1 Water Permeability (Hydraulic Conductivity in Saturated Zone)

***Possible Methods:***

a) *In situ* - slug test
   i) Falling head
   ii) Rising head
b) *In situ* - pumping from test well in a network of observation wells.
   i) Constant head permeameter
   ii) Falling head permeameter
c) Laboratory testing of samples
d) Empirical methods based on grain size distribution.
e) Other:
   - Petrographic analysis
   - Lysimeter tracer test
   - Mass balance between rainfall and water level response with peak tracking during flow path
   - Double ring infiltrometer and pan lysimeters in test pile formulation

***Objectives:*** To evaluate permeability (hydraulic conductivity) of waste rock piles and/or surrounding soil or bedrock.

***Background:*** Hydraulic conductivity is measured in the field using piezometers installed in boreholes. The boreholes are often also used for other purposes such as waste rock sampling, gas monitoring, temperature monitoring and air permeability tests.

***Rating:*** Water permeability is rarely required when assessing waste dumps, as they are usually unsaturated. Water permeability measurements of underlying and surrounding soil/rock are often required. The most common techniques used for measuring permeability in waste rock or surrounding soil/rock are a)i) and d), which are both established techniques.

***Limitations and Advantages:*** Slug tests such as a)i) are relatively inexpensive and can be performed on materials ranging from high to low permeability. Pumping tests are more expensive but are good for estimating bulk or average hydraulic conditions. Packer tests may be required for bedrock testing. Empirical methods from grain size are only approximate and should be used only for materials with low silt or clay content.

***Recommended Procedures:*** Use whatever works. Infiltration estimates are perhaps more important than permeability measurements.

***Requirements:*** For Item a)i): bucket, funnel, water level finder, stop-watch and installed monitoring well.

***Cost:*** Cost for slug test is approximately $100/hour, or on average $200/borehole, although this will vary widely with the permeability of the material being tested. Drilling and installation of monitoring well costs approximately $100/metre.

### 3.8.2 Permeability to Air

***Possible Methods:***

- a) Air pumping tests.
- b) Air injection tests.
- c) Estimated from measuring natural barometric gradients
- d) Other:
  - Modelling heat flow
  - Density-void ratio
  - Estimated from grain size

***Objectives:*** To evaluate air permeability of waste rock pile, which is required for any prediction or quantitative modelling.

***Background:*** Gas sampling ports may also be used to evaluate air permeability.

***Rating:*** Items a), b) and c) are all used but all are fairly experimental. Air permeability is required for modelling oxygen transport.

***Limitations and Advantages:*** For Item a), risk of test failure is high, especially for coarse dump materials. Item b) is not recommended as it modifies gas composition and temperature in pile and introduces oxygen. Item c) has the limitation that natural barometric changes are required, which are unpredictable, and if permeability is large, method may not work. Unpredictable weather changes can be compensated for by using pressure transducer and automatic recorder.

***Recommended Procedures:*** Item c), or a good estimate of air permeability.

***Requirements:*** Multi-level gas sampling ports as described in Section 6, and manometer. Pressure transducers and recording device if air pressure to be sampled continuously.

***Cost:*** Can be less than $1,000 per test if suitable boreholes with gas sampling ports are already installed. See Section 3.6.2 for cost of ports.

### 3.8.3 Associated Measurements

***Possible Measurements:***

a) Temperature
b) Porosity
c) Other: - Thermal Conductivity
  - Neutron Probe

***Rating:*** Temperature (at surface and/or within pile) and porosity are needed to calculate permeabilities.

***Recommended Procedures:*** Temperature data and porosity data.

***Requirements:*** See Section 3.10 for porosity and Sections 3.7 and 3.15 for temperature.

***Cost:*** See Section 3.10 for porosity and Section 3.7 and 3.15 for temperature.

### 3.8.4 Oxygen Diffusion

***Possible Methods:***

a) Use of non-reactive gas (nitrogen, carbon dioxide, argon, etc.) in gas permeation (column diffusion) studies.
b) Use of highly volatile organic liquid (ether, chloroform) vapour in column diffusion tests.
c) Dynamic measurements of oxygen diffusion in a column test.
d) Other: - Oxygen convection from field tests.
  - Non-reactive gas injection and measure concentration over time in nearby gas ports.
  - Estimated by calculation.

***Objectives:*** To assess diffusion of oxygen into waste rock piles, which is an important often rate-limiting step for acid generation, when diffusion controls oxygen transport, as is often the case for a covered dump.

***Background:*** Oxygen diffusion is measured in the lab, or estimated empirically using known physical parameters. Oxygen concentration with depth profiles are measured in boreholes into the waste rock pile.

***Rating:*** Items a) and c) are most commonly used to assess oxygen diffusion. If diffusion controls oxygen transport, this assessment is essential for modelling. Oxygen diffusion through cover materials is also important for long-term predictions and modelling.

***Limitations and Advantages:*** Items a), b) and c) are laboratory methods as controlled conditions are required for accurate measurements, in order to estimate values for the parameters describing oxygen diffusion. The largest problem is the heterogeneity of the waste rock dump and obtaining representative samples. Samples of different areas of the dump should be analyzed in column studies. For Item c) to give reasonable estimates, the waste rock dump should be less than 50% water saturated.

***Recommended Procedures:*** No preferred method. Laboratory estimates should be compared to oxygen profiles measured in the field.

***Requirements:*** Sample collection, laboratory test equipment. Gas meter for *in-situ* measurements in pile.

***Cost:*** Laboratory program to assess diffusion into waste rock or cover materials is approximately $5,000/sample.

***References for Section 3.8:***

Domenico, P.A. and F.W. Schwartz 1990. *Physical and chemical hydrogeology.* John Wiley and Sons.

Freeze, A.R. and J.A. Cherry 1979. Groundwater. Prentice-Hall Inc., Englewood Cliffs, New Jersey, U.S.A.

Hvorslev, J. 1951. *Time log and soil permeability in groundwater observations.* Waterways Experiment Station, Corps of Engineers, U.S. Army, Bulletin No. 36, Vicksburg, Mississippi, U.S.A.

Weeks, E.P. 1978. *Field determination of vertical permeability to air in the unsaturated zone.* U.S. Geol. Surv. Prof. Paper, 1051:1-41.

## 3.9 WASTE ROCK PARTICLE SIZE CHARACTERIZATION

***Possible Methods:***

a) Visual estimate(s) for larger particles.
b) Large scale sieves or "Grizzlys" for larger particles (e.g. greater than 15 cm).
c) Standard soil sieves combined with hydrometer analysis (ASTM D422-63) to estimate surface area of finer particles (e.g. less than 15 cm for standard soil sieves, hydrometer analysis for samples with significant fraction less than 0.075 mm).
d) Other:
   - observations during drilling
   - Preliminary screen analysis

***Objectives:*** Waste rock particle size distribution and the concentration of sulphides in each particle size classification is required to estimate the surface area of sulphide minerals. This is important because the production of ARD is proportional to the specific surface area of sulphide minerals.

***Background:*** Particle size characterization of waste rock in dump should be performed as part of a waste rock sampling program.

***Rating:*** Particle sizes are commonly measured as they are important for predictive modelling. Item c) is good for finer particle sizes. Item b) is preferred for large particles, although Item a) is most commonly used for large particles.

***Limitations and Advantages:*** Standard soil sieves are only suitable between a particle diameter of 15 cm and 0.075 mm. If a significant portion of the sample is smaller than 0.075 mm, hydrometer analysis is required to adequately characterize the sample. If a significant portion of the sample is greater than 15 cm in diameter, large scale sieves will also be needed to adequately characterize the sample. Visual estimates of the distribution of particles larger than 15 cm are acceptable, as these larger particles are not as important for acid generation.

***Recommended Procedures:*** For modelling purposes, both the proportion of fine particles (i.e. percentage <2 mm) and the particle size distribution are important. Representative sampling is very difficult. Large scale sieves and soil sieves should be used. Elemental, mineral, and static ARD tests should be conducted on each sieve fraction to determine the distribution of AP and NP with grain size. A large number of characterizations are not required, however characterizations are required for each rock type or distinct unit within the dump.

***Requirements:*** Grizzlies, sieves, hydrometer. A hydraulic shovel may be required to take samples if large particle sizes are present.

***Cost:*** Costs range from between $60 to $100/test for simple sieve analyses. Costs can be much higher for coarse waste as machine time, labour for hand picking, etc., will be required. This raises costs to $500 to $1,000/sample.

***References for Section 3.9:***

American Society for Testing and Materials (ASTM) D422-63 (reaff. 1990). *Method for analysis of soils.*

## 3.10 POROSITY OF WASTE ROCK

***Possible Methods:***

a) Standard procedure (ASTM C29-91, C127-88) from bulk mass density and particle mass density.
b) Based on rock relative density established by water displacement test.
c) Other:
   - Structural analysis
   - Total volume and total mass from mine records
   - Gravimetric survey of dump combined with water content measurement
   - Nuclear back scatter
   - Water level changes during storms
   - Sand cone

***Objectives:*** Porosity is required for predictive modelling techniques.

***Background:*** During an integrated rock sampling program, estimates of field porosity can be made from other physical measurements.

***Rating:*** Porosity is commonly measured and is essential for modelling. Both a) and b) are commonly used. Calculation of overall bulk porosity can also be done when the volume and mass of the dump are known.

***Limitations and Advantages:*** The limitation of a) and b) is that the measurements are conducted on a disturbed sample, and estimates based on samples are assumed to apply to entire pile.

***Recommended Procedures:*** Item a) or b), unless volume and mass of dump are available. Estimates from both methods can be used as a check.

***Requirements:*** None except personnel to obtain sample.

***Cost:*** Costs are $200 for a) and $100 for b), plus sample collection.

***References for Section 3.10:***

American Society for Testing and Materials (ASTM) C29-91. *Test method for unit weight and voids in aggregate.*

American Society for Testing and Materials (ASTM) C127-88. *Test method for specific gravity and absorption of coarse aggregate.*

## 3.11 WATER CONTENT OF WASTE ROCK

***Possible Methods:***

a) From difference in weight between wet and oven-dried sample, water content is defined as the ratio of water to weight of the solids (ASTM D2216-90).
b) Based on porosity and rock density.
c) Other:
   - Gravity survey of dump
   - Compressive wave velocity measurements
   - Column testing to establish field moisture content

***Objectives:*** Water content is required for predictive modelling techniques.

***Background:*** Water content can be determined from drying samples prior to other test work, e.g., particle size classification, elemental analysis, etc.

***Rating:*** By far the most common method to determine water content of waste rock dump is Item a). Water content is essential for ARD prediction and modelling.

***Limitations and Advantages:*** Item a) can only be performed with good results on unsaturated waste rock samples. For saturated locations within a waste rock pile, which are rare, Item b) is required. If the waste rock dump contains a high proportion of coarse material, it may be difficult to obtain a representative sample for method a). The evaluation of water content is very challenging and no good methods for waste rock have been proven.

***Recommended Procedures:*** Item a) is simple and cost-effective.

***Requirements:*** None if tests performed by commercial lab.

***Cost:*** Cost for analysis is approximately $20/sample. Sample collection would be extra.

***References for Section 3.11:***

American Society for Testing and Materials (ASTM) D2216-90. *Test method for laboratory determinations of water (moisture) content of soil and rock.*

## 3.12 FLOW MONITORING ASSOCIATED WITH WASTE ROCK

### 3.12.1 Locations Monitored

a) Sump.
b) Channel.
c) Collection ditch.
d) Stream.
e) Pond outflow.
f) Other:
- Wells, boreholes
- Toe of waste rock pile
- Internal bottom lined collection trench
- Piezometers near pile where groundwater impacted
- test pits

***Objectives:*** Flow monitoring is required to perform water balances and calculate contaminant loadings.

***Background:*** Flow monitoring should be performed in conjunction with water quality sampling.

***Rating:*** Locations commonly monitored for flow are: collection ditch, pond outflow, sump, channel and stream. The locations monitored are site-specific.

***Limitations and Advantages:*** Need to consider water flow balance for entire pile.

***Recommended Procedures:*** The locations to monitor are site-specific.

***Requirements:*** See below.

***Cost:*** See below.

### 3.12.2 Methods Used

***Possible Methods:***

a) Seepage meter (measure shallow groundwater discharge to surface water).
b) mini-piezometers installed manually to shallow depths below stream or groundwater discharges.
c) Rating curve correlating depth readings using staff gauge and flow rate (e.g. ASTM D3858-90).
d) Float, pressure or electronic depth measuring devices connected to automatic recorders.

e) Other: - Weirs used to prepare rating curve.
- Bucket and stopwatch.

***Rating:*** Flow monitoring is very important as it is essential in order to calculate loadings. Flow should be measured whenever water quality samples are taken. The most common method to monitor surface water flow is a rating curve correlating depth readings using staff gauge and flow rate. Also commonly used are float, pressure or electronic depth measuring devices connected to automatic recorders.

***Limitations and Advantages:*** Manual flow monitoring has the advantage that it is less likely to fail and the disadvantage that measurements cannot be obtained as frequently as they can using electronic monitoring devices. Automatic recorders can be useful for remote locations that cannot be accessed or measured frequently, and for locations where flow is intermittent and associated with precipitation events.

***Recommended Procedures:*** Site-specific.

***Requirements:*** Personnel to install manual and automatic stations and to monitor manual sampling locations regularly and maintain/repair automatic stations periodically. Depending on method: weir, staff gauge, continuous recording device, bucket.

***Cost:*** Installation costs are from $200 to $2,000 for V-notch weir or staff gauge. Electronic flow meters range from $1,500 to $2,000 and up.

***References for Section 3.12:***

American Society for Testing and Materials (ASTM) D3858-90. *Practices for open channel flow measurement of water by velocity-area method.*

## 3.13 INFILTRATION ESTIMATES ASSOCIATED WITH WASTE ROCK

***Possible Methods:***

a) Estimate based on meteorological data (monthly precipitation, temperature and evapotranspiration, etc.).
b) Infiltration rates measured directly using lysimeters and correlation developed with site precipitation data.
c) Use of predictive models (e.g. HELP).
d) Other:
   - Calibrated seepage models (FEM methods).
   - Measure surface flows in collection ditches and combine with measured precipitation to back-calculate infiltration.

***Objectives:*** Water infiltration estimates are used in modelling to predict ARD generated from a waste rock pile.

***Background:*** Infiltration estimates are normally associated with flow monitoring in order to perform a water balance.

***Rating:*** Infiltration estimates are in common use, and are required for modelling. All methods listed above are commonly used. Often more than one of these methods is used.

***Limitations and Advantages:*** Lysimeters have the advantage that direct measurements are being obtained. Problems with lysimeters are the high variability within waste rock piles, whether or not the lysimeters installed reflect the entire waste rock pile, and the seasonal variations in infiltration which require adequate year round monitoring. Predictive infiltration models have the advantages of speed and lower overall cost. The reader should be cautioned that waste rock is normally dry when placed into the pile (<3% volumetric water content) while at field capacity water content can exceed 10%. Therefore, seepage during early deposition does not reflect infiltration.

***Recommended Procedures:*** No preferred method. Use of more than one method will improve confidence in estimates. Uncertainty in infiltration estimates may translate to uncertainty in model predictions of contaminant loadings.

***Requirements:*** Meteorological station for a), HELP model for c) and excavation equipment and lysimeters for b).

***Cost:*** See Section 3.15 for cost of meteorological station. Lysimeters cost approximately $1,000 to install per lysimeter. Costs for HELP model are approximately $2,000.

***References for Section 3.13:***

Schroeder, P., R. Peyton, B. McEnroe, and J. Sjostrom 1989. *The Hydrologic Evaluation of Landfill Performance (HELP) Model, user's guide for Version 2.* U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, U.S.A., Interagency Agreement Number DW21931425-01-3.

## 3.14 BIOLOGICAL (BACTERIA) MONITORING ASSOCIATED WITH WASTE ROCK

***Possible Methods:***

a) Selection of moist rock samples from surface, or interior of heap (e.g. during drilling) and placement (submergence) in sterile nutrient solution for analyses by laboratory subculture.
b) Collection of liquid (i.e. seepage) samples for laboratory subculture.
c) Use of "bacteria traps" (e.g. sampling devices filled with sulphide substrate).
d) Other: - Bacterial identification and count using optic phase contrast.

***Objectives:*** To confirm presence and oxidative activity of bacteria within waste rock pile.

***Background:*** Bacteria sampling can be carried out in conjunction with drilling, trenching or seepage sampling.

***Rating:*** Biological monitoring is not common but is occasionally used as an experimental technique. When it is used the most common methods are a) and b). Biological monitoring is of academic interest and is not normally a useful parameter for monitoring acid production within a waste rock dump.

***Limitations and Advantages:*** Biological monitoring may confirm the presence of bacteria, but laboratory test work would be required to identify the specific strains and to assess growth rates and oxidative activity.

***Recommended Procedures:*** Biological monitoring is normally not required for ARD assessment. It can be assumed the dominant sulphide oxidizing bacterium is Thiobacillus Feroxidans, for which kinetic rates for growth and biological oxidation are well-established.

***Requirements:*** No special requirements, unless samples from interior of waste rock pile are required, in which case boreholes or trenches are required.

***Cost:*** Cost to collect samples is site specific but generally low as sampling is combined with other required sampling programs. Analysis costs depends on level of investigation, i.e., confirming presence of bacteria is inexpensive, costs quotes for isolating strains and conducting experiments can be obtained from individual laboratories.

***References for Section 3.14:***

Guay, R. 1993. *Development of a modified MPN procedure to enumerate iron oxidizing bacteria.* Prepared for MEND, Report 1.14.2, February.

Lafleur, R., E. D.-Roy, D. Couillard and R. Guay 1993. *Determination of iron oxidizing bacteria numbers by a modified MPN procedure.* In: Biohydrometallurgical Technologies. (A.E. Torma, J.E. Wey and V.L. Lakshmanan, eds.) The Minerals, Metals & Materials Society, pp. 433-442.

Ragusa, S.R. and J.C. Madgwick 1993. *The use of autoradiography to accurately enumerate viable iron oxidizing leaching bacteria.* In: Biohydrometallurgical Technologies. (A.E. Torma, J.E. Wey and V.L. Lakshmanan, eds.) The Minerals, Metals & Materials Society, pp. 681-694.

## 3.15 METEOROLOGY MEASUREMENTS ASSOCIATED WITH WASTE ROCK

### 3.15.1 Parameters That Can Be Measured On-Site

***Possible Parameters:***

a) Air temperature.
b) Rainfall.
c) Surface soil temperature.
d) Evaporation.
e) Wind direction.
f) Wind speed.
g) Snowfall.
h) Relative humidity.
i) Solar radiation.

***Objectives:*** Meteorological observations are necessary to carry out detailed research investigations and modelling.

***Background:*** On-site measurements are useful whenever modelling is being conducted, and if a nearby climate station or other sources of meteorological data are not available.

***Rating:*** Meteorological information is essential for ARD modelling and prediction. The following are all commonly measured on-site: rainfall, air temperature, snowfall, wind speed and direction, and relative humidity. Surface soil temperature, evaporation, and solar radiation are not as commonly measured.

***Limitations and Advantages:*** The selection of appropriate locations for meteorological measuring devices is important, should consult with climatologist.

***Recommended Procedures:*** Meteorological data are essential. Need for on-site measurements will be site-specific. Some parameters are simple to measure (e.g., air temperature, relative humidity, soil temperature) and can be compared with nearby stations.

***Requirements:*** Weather station, staff to install, monitoring staff, possibly phone line (depending on method of data collection).

***Cost:*** for an automated weather station ranges from $5,000 to $10,000, depending on measurements required, power source, etc. Cost for monitoring is variable, depending on how much of data collection and recording is automated.

### *3.15.1.1 Methods Used to Measure Air Temperature*

***Possible Methods:***

a) Aspirated temperature sensor.
b) Thermistor or platinum resistance thermometer.
c) Other: - Thermometer

***Rating:*** Air temperature is a commonly measured parameter. A thermistor or platinum resistance thermometer is most commonly used to measure temperature.

***Limitations and Advantages:*** Note location and time of day that air temperatures are measured.

***Recommended Procedures:*** No preferred method.

***Requirements:*** Part of weather station.

***Cost:*** Part of weather station.

### *3.15.1.2 Methods Used to Measure Rainfall/Precipitation*

***Possible Methods:***

a) Tipping bucket precipitation gauge.
b) Weighing precipitation gauge.
c) Snow gauge.

***Rating:*** To measure rainfall, a tipping bucket gauge is by far the most common method.

***Limitations and Advantages:*** Systems must take into account winter operation and monitoring of snow fall as snow fall is often a substantial component of the water balance.

***Recommended Procedures:*** Item a) is simple and commonly applied.

***Requirements:*** Part of weather station.

***Cost:*** Part of weather station.

### *3.15.1.3 Methods Used to Measure Soil Temperature*

***Possible Methods:***

a) Thermistor buried in soil.
b) Other: - Temperature from heat dissipation for suction measurements

***Rating:*** The measurement of soil temperature is not common, however a thermistor buried in soil is the technique used when soil temperatures are measured.

***Limitations and Advantages:*** Air temperature should be measured at same time as soil temperature.

***Recommended Procedures:*** Thermistor buried in soil.

***Requirements:*** Site and method specific.

***Cost:*** Normally a component of other monitoring systems.

### *3.15.1.4 Evaporation*

***Possible Methods:***

a) Recording evaporation balance.
b) Pich□ type evaporation gauge.
c) Atmometer.
d) Other: - Environment Canada evaporation pan with associated wind measurements.

***Rating:*** Evaporation is not commonly measured. Estimate of evaporation could be useful in estimating percentage infiltration of precipitation.

***Limitations and Advantages:*** Measurement of evaporation is difficult and estimates can be inaccurate.

***Recommended Procedures:*** No preferred method.

***Requirements:*** Part of weather station. Cost for standard evaporation pan installation is $1,000.

***Cost:*** Part of weather station.

***References for Section 3.15:***

United States Environmental Protection Agency 1989. *Quality assurance handbook for air pollution measurement systems. Volume IV - Meteorological measurements.* Office of Research and Development, Atmospheric Research and Exposure Assessment Laboratory, Research Triangle Park, North Carolina, 27111.

Manufacturers of meteorological instrumentation should also be contacted, as they often have detailed catalogues/brochures describing instrumentation available.

## 3.16 THERMAL ANALYSIS OF WASTE ROCK

***Possible Methods:***

a) Surface soil thermistor.
b) Surface measurements using hand-held "infrared guns".
c) Infrared imagery by aerial survey with infrared thermographic camera.

***Objectives:*** To assess air and heat convection in waste rock dumps.

***Background:*** Can be used in conjunction with modelling to confirm model predictions.

***Rating:*** Thermal analysis of waste rock is not common, or essential to ARD assessment. A few respondents conduct this analysis and use infrared imagery from aerial or ground surveys, and surface soil thermistors.

***Limitations and Advantages:*** Large areas can be surveyed quickly using aerial techniques; however, the disadvantage is high cost. For infrared photography, care must be taken to avoid any solar heating of waste rock pile surface, which would interfere with observation of internal temperatures (i.e. survey should be performed before sunrise).

***Recommended Procedures:*** Aerial infrared imagery is interesting but too expensive for most sites. Adequate information can be obtained from use of soil thermistors or hand-held "infrared guns".

***Requirements:*** Infrared camera, labour, and helicopter if aerial survey required.

***Cost:*** Cost estimates for infrared imagery range from $500 for rental of a unit (labour for ground survey would be extra) to $17,000 for a complete survey including helicopter, corrections to raw data, and rental of unit.

***References for Section 3.16:***

Lefebvre, R., P. G□linas, and D. Isabel 1994. *Heat transfer during acid mine production in a waste rock dump, La Mine Doyon (Quebec).* Prepared for MEND, Report 1.14.2, March.

## 3.17 DRILLING TECHNIQUES FOR WASTE ROCK

***Possible Methods:***

a) Drag bits (unconsolidated or semi-consolidated sediments).
b) Cone-type bits (soft to moderately hard rocks).
c) Down-the-hole hammer with button bits or roller bits which are either concentric or eccentric with the drill casing (hard, dense rocks and rock fill).
d) Other:
   - Auger drills, Becker Hammer, core penetration test.
   - Trenching, test pits
   - ODEX
   - Coring
   - Reverse circulation

***Objectives:*** Drilling is used to collect samples within waste rock piles, as well as to provide access for the installation of monitoring devices for air, temperature, water levels etc.

***Background:*** Many waste rock assessment techniques are dependent on boreholes to obtain samples or to allow the installation of instrumentation. Trenching or test pits may be used instead of drilling at some sites.

***Rating:*** Drilling into waste rock piles is common. If information on the waste rock pile is not available from other sources (i.e. records of waste rock characteristics before excavation combined with dump placement records) then drilling is essential for characterizing the waste rock pile. The most common method used is the down-the-hole hammer technique. For shallow requirements (up to 6 m deep), trenching or test pitting is suitable instead of drilling.

***Limitations and Advantages:*** Down-the-hole hammer provides the best sample recovery in waste rock piles and least likelihood of encountering problems with drill hole alignment, but may not work below 40 metres. Drag bits are only suitable for very soft sedimentary rocks. Cone-type bits are more suitable for bedrock drilling, as maintaining drill hole alignment can be a problem within coarse waste rock piles. Air filters can be expensive (for controlling dust emissions). Auger drills are not suitable for coarse material. For fine or soft material augers are suitable to a depth of 5 metres. For deep sampling requirements, coring or ODEX work, but are poor alternatives to down-the-hole hammer techniques in terms of sample recovery.

***Recommended Procedures:*** Down-the-hole hammer drilling is preferred because it provides good sample recovery, good production rates and is the least likely method to cause drilling problems.

***Requirements:*** Drill rig and operators, geologist to log hole and take samples, instrumentation and technician to install gas and temperature monitoring equipment, if required.

***Cost:*** Costs of drill and operators range from $50 - $100/metre for down-the-hole hammer. Geologist for drilling supervision also required. Typical drilling rate is 4 metres/hour. Test pits cost $300-$500/day for backhoe plus geologist (10-15 3 metre pits/day, or 2-6 6 metre pits/day).

## 3.18 GEOPHYSICAL TECHNIQUES FOR WASTE ROCK

***Possible Methods:***

a) Electromagnetic (EM) surveys:
   - airborne
   - ground
   - down-hole.

b) Induced Polarization (IP) surveys.

c) Self Potential (SP) surveys.

d) Gravity surveys.

***Objectives:*** To detect sulphide minerals in waste rock (*in situ* or in waste rock piles). To detect acidic drainage sources and migration paths. To obtain density of waste rock pile for calculation of water content.

***Background:*** The use of geophysical methods in exploration programs is a well established method that is used in conjunction with diamond drilling, etc. The area surveyed in an exploration program would typically encompass any potential waste rock.

***Rating:*** For characterizing *in situ* rock, geophysical methods are in common use, and form part of an integrated exploration assessment program which might include diamond drilling, sampling, surface geophysics, down-hole geophysics. The method of geophysics used is dependent on the nature of the sulphide mineralization. Disseminated sulphide deposits respond well to IP, while more massive sulphides respond well to EM. For characterization of waste rock, all methods are experimental, and there is currently no preferred method. MEND (1994) describes a review of geophysical methods for monitoring acid mine drainage from tailings. The application of these techniques to waste rock is by far more experimental than for tailings; however, these non-intrusive techniques are likely to be of more importance as they are developed. Gravity surveys are useful mainly as a research tool.

***Limitations and Advantages:*** The advantage of geophysical methods is that a large volume of rock can be characterized more economically through a combination of drilling and geophysics, than through a drilling only program.

***Recommended Procedures:*** None yet. Experimental.

***Requirements:*** Geophysical surveys are often contracted out to specialists.

***Cost:*** Dependent on area to be surveyed and method.

***References for Section 3.18:***

Mine Environment Neutral Drainage (MEND) Program 1993. Bulletin, November.

Mine Environment Neutral Drainage (MEND) Program 1994 (in preparation). *Applications of geophysical methods for monitoring acid mine drainage.*

# 4.0 SUMMARY OF RECOMMENDED TECHNIQUES

## 4.1 BACKGROUND

Table 4.1 summarizes which waste rock sampling categories are required to obtain information for decision making regarding management, maintenance, monitoring and closure, and which analyses are necessary for prediction/modelling, or are of additional interest. Cost estimates for the recommended techniques in each category are also summarized.

Below is a summary of recommended techniques for each category of waste rock sampling:

## 4.2 CHEMICAL CHARACTERIZATION OF WASTE ROCK

### 4.2.1 Elemental Content

Total acid digestion followed by ICP/mass spectrometry is the standard, accepted technique, except for a few elements which should be assessed by alternate methods due to interference problems, etc.

### 4.2.2 Mineralogy (distribution of minerals in waste rock particle)

X-ray diffraction and petrographic microscopic analysis are common, accepted methods. Petrographic work also gives information on mineral forms.

### 4.2.3 Mineral Forms (e.g. massive, nodular, disseminated, etc.)

Geologist's observations and petrographic microscope work are the standard, common methods. If grain size is small, microscope analysis may be required.

## 4.3 ARD ASSESSMENT TEST PROCEDURES FOR WASTE ROCK

### 4.3.1 Static Tests (net neutralization potential in terms of kg $CaCO_3$ equivalents per ton of rock)

Several different tests are in common use (see Section 3.3.1) and modifications to these tests are being investigated, however no static test is a true indicator of whether acid will be produced.

### 4.3.2 Dynamic Tests (time dependent study of acid generation)

Stationary bed reactor configurations, especially columns, are preferred. Inclusion of larger particles in tests, quality control, and length of test are all important considerations. Tests should be interpreted with caution.

## Table 4.1: APPLICATION OF SAMPLING CATEGORY

| Category | Required for Cost Estimates for Decision Making | Required for Modelling/Prediction/ Validation | Of Interest | Approximate Cost for Recommended Techniques3 |
|---|---|---|---|---|
| Statistical Sampling Program | Yes | Yes | | |
| Elemental Content | Yes | Yes | | $25 - $75/sample for ICP |
| Mineralogy | Yes | Yes | | $100 - $200/sample for petrographic analysis |
| Mineral Forms | Yes | Yes | | Part of above |
| Static Tests | Yes | Yes | | $75/sample |
| Dynamic Tests | Yes, depending on static | Yes | | $1,000 - $5,000/test |
| Hardness and Weathering | No | Yes | | $200-$300/sample |
| Water Monitoring | No | Yes | | Labour, site-specific |
| Pore Water | Yes | Yes | | Site- and option-specific |
| Seepage | Yes | Yes | | Site- and option-specific |
| Groundwater | Site-specific | Site-specific | | Site- and option-specific |
| Surface Water | Yes | Yes | | Site- and option-specific |
| Water Quality - Field Analysis | Yes | Yes | | Variable but inexpensive |
| Water Quality - Lab Analysis | Yes | Yes | | $100 - $200/sample |
| Gas Sampling | No | Yes | | ~ $100/m installation, ~ $1,000-$3,500 for gas meter, plus sampling labour |
| Temperature Profile in Waste Rock | No | Yes | | $500-$20,000/hole for instrumentation, plus measurement labour |
| Water Permeability | No | No | Yes | ~ $100/m for installation of piezometer, plus testing |
| Air Permeability | No | Yes, if convection controls | | Requires gas sampling ports, as above, plus measurement labour |
| Oxygen Diffusion | No | Yes, if diffusion controls | | Lab program ~ $5,000 |
| Particle Size | Yes | Yes | | $60 - $100/test for sieve analysis, up to $1,000/test incl. coarse fraction |
| Porosity | Yes | Yes | | $100 - $200/test |
| Water Content | Yes | Yes | | ~ $20/sample |
| Flow Monitoring | Yes | Yes | | $200-$2,000 per location plus measurement labour, >$1,500/electronic recording flow meter |
| Infiltration Monitoring | No | Yes | | ~ $1,000 per barrel lysimeter, ~ $2,000 HELP model. |
| Biological Monitoring | No | No | Yes | |
| Meteorology | No | Yes | | $5,000 - $10,000/station |
| Thermal Analysis | No | No | Yes | Relatively expensive |
| Drilling | Site-dependent | Site-dependent | Yes | Variable, $50 - $100/metre |
| EM Surveys | No | No | Possibly | Area dependent |

## 4.4 PHYSICAL STABILITY OF WASTE ROCK

### 4.4.1 Hardness

Hardness testing is experimental when applied to ARD assessment and is not commonly performed. It only provides an indication of weathering rates, rather than a quantitative estimate. ASTM C131-89 and C535-89 Los Angeles abrasion test are methods used most frequently.

### 4.4.2 Weathering

Weathering is determined most commonly by visual observation and as part of humidity cell and acid generation tests. At present there is no recommended method. The assessment of weathering is currently a major area of deficiency in waste sampling programs which focus on static and dynamic test work.

## 4.5 WATER MONITORING ASSOCIATED WITH WASTE ROCK

### 4.5.1 Locations Monitored

Surface run-off from waste rock, waste rock pore water, seepage, groundwater and nearby surface water bodies are all commonly monitored to assess water quality and to calculate contaminant loadings. Specific locations are site- and project-dependent. Whenever possible, flow measurements should be taken in conjunction with water quality samples so that contaminant loadings can be calculated.

### 4.5.2 Water Sampling Methods

Run-off is usually grab sampled. Occasionally automatic samplers are used. Pore water is most commonly sampled by washing wetted waste rock, however suction lysimeter or core squeezing provides better results. Recommended procedure is suction lysimeter. Seepage collection locations are site-specific with sampling from a collection ditch being the most common technique. For any seepage collection method used, seepage may be diluted by precipitation events, so a record of rainfall is important. For groundwater sampling there is no preferred method, however the method chosen is dependent on sampling depth (i.e. suction methods only work to 8 metres). Grab sampling of surface water bodies is usually acceptable.

### 4.5.3 Water Quality Parameters

Field tests that should be performed are: pH, paste pH, temperature, and dissolved oxygen. Electrical conductivity is also commonly measured in the field.

For sample preservation protocols, please refer to Table 3.4 and appropriate federal/provincial standards. For sample containers, polyethylene is preferred, except where mercury is of concern.

At a minimum, the following parameters should be determined during laboratory analysis: pH, sulphate, acidity, alkalinity, total dissolved solids and elemental scan. Requirements for other parameters are site-specific (i.e. sulphide solids, arsenic, radionuclides). Always specify limits of detection required and request a copy of written procedures and quality assurance documents.

## 4.6 GAS SAMPLING IN WASTE ROCK

Oxygen is usually the only gas that is required. Other gases are assessed for site-specific reasons. The most common and cost effective procedure for gas sampling is: sampling from tubes installed at different depths in each borehole using portable pump or hand bulb, and analysis through on-line gas meters. Temperature measurements at each gas sampling location are also required.

## 4.7 TEMPERATURE MEASUREMENTS IN WASTE ROCK

Waste rock temperature should be measured using thermistors installed in boreholes. As a minimum, air temperatures should be taken at the same time.

## 4.8 PERMEABILITY MEASUREMENTS IN WASTE ROCK

### 4.8.1 Water Permeability (Hydraulic Conductivity)

Use what ever method works. Infiltration estimates are perhaps more important than permeability measurements, as waste dumps are usually unsaturated.

### 4.8.2 Permeability to Air

Air permeability measurements are experimental. The recommended procedure is to estimate air permeability measuring natural weather induced barometric gradients through multi-level gas sampling ports.

### 4.8.3 Associated Measurements

Temperature data at surface and within the pile, and porosity are needed at calculate air permeabilities.

### 4.8.4 Oxygen Diffusion

There is no preferred method for assessing oxygen diffusion, which is measured in the lab or estimated by calculation.

## 4.9 WASTE ROCK PARTICLE SIZE CHARACTERIZATION

Large scale sieves and soil sieves should be used as a minimum, and hydrometer analysis may also be required. Chemical characterization and static ARD tests should be carried out on each sieve fraction to determine the distribution of AP and NP with grain size. Size characterizations are required for each rock type or distinct unit within the dump.

## 4.10 POROSITY OF WASTE ROCK

Porosity should be assessed from bulk mass density and particle mass density (ASTM C127-88 and C29-91) or from rock relative density established by water displacement test.

## 4.11 WATER CONTENT OF WASTE ROCK

Water content can be determined from difference in weight between wet and oven-dried samples, which is a simple and cost-effective technique.

## 4.12 FLOW MONITORING ASSOCIATED WITH WASTE ROCK

Flow measurements are required to perform water balances and calculate contaminant loadings. Locations to monitor are site-specific. The recommended procedure to measure flow is site-specific. Automatic recorders are useful for remote locations, or intermittent flow locations.

## 4.13 INFILTRATION ESTIMATES ASSOCIATED WITH WASTE ROCK

There is no recommended method to estimate infiltration, however the use of more than one method improves confidence in estimates. Methods commonly used are: based on meteorological data, measured directly using lysimeters and correlated with precipitation data, and use of predictive models such as HELP.

## 4.14 BIOLOGICAL (BACTERIA) MONITORING ASSOCIATED WITH WASTE ROCK

Biological monitoring is not normally required for ARD assessment.

## 4.15 METEOROLOGY MEASUREMENTS ASSOCIATED WITH WASTE ROCK

Meteorological data is essential. Need for on-site measurements is site-specific, depending on distance from other sources of meteorological data. Rainfall, air temperature, snow fall wind speed/direction and relative humidity are all commonly measured.

## 4.16 THERMAL ANALYSIS OF WASTE ROCK

Thermal analysis is not common or essential. Aerial surveys are interesting but expensive. Adequate information can be obtained from soil thermistors or hand held "infrared guns".

## 4.17 DRILLING TECHNIQUES FOR WASTE ROCK

Down-the-hole hammer drilling is preferred because it provides good sample recovery, good production rates and is the least likely method to cause drilling problems.

## 4.18 GEOPHYSICAL TECHNIQUES FOR WASTE ROCK

No geophysical techniques are recommended yet, as they are experimental when applied to waste rock.

# APPENDIX A:

## LIST OF RESPONDENTS TO EXTERNAL SURVEY AND PARTICIPANTS AT WORKSHOP

| FULL NAME | COMPANY / ADDRESS | SURVEY COMPLETED | WORKSHOP | |
|---|---|---|---|---|
| | | | PANELIST | OBSERVER |
| **INDUSTRY** | | | | |
| Mr. L.W. Adrian | Cameco Corporation<br>2121 - 11th Street West<br>Saskatoon, Saskatchewan, S7M 1J3 | Y | | |
| Mr. Luc St. Arnaud<br><br>Mr. Mark Woyshner<br><br>Mr. Robert Prairie | Noranda Technology Centre<br>Environment & Mining Laboratory<br>240 Hymus Blvd.<br>Pointe-Claire, Québec, H9R 1G5 | Y | Y | |
| Mr. Mike Aziz | Equity Silver Mines Ltd.<br>P.O. Box 1450<br>Houston, British Columbia, V0J 1Z0 | Y | N | |
| Mr. Charles H. Bucknam | Newmont Exploration Limited Metallurgical Services<br>417 Wakara Way, Suite 210<br>Salt Lake City, Utah, 84108 U.S.A. | Y | Y | |
| Mr. Michael P. Davies | Klohn-Crippen Consultants Ltd.<br>10200 Shellbridge Way<br>Richmond, British Columbia V6X 2W7<br>or<br>Department of Civil Engineering<br>University of British Columbia<br>2324 Main Mall<br>Vancouver, British Columbia V6T 1Z4 | Y | | |
| Mr. Stephen Day<br>Mr. David Harpley | Norecol Dames & Moore Inc.<br>1212 West Broadway, Suite 500<br>Vancouver, British Columbia, V6H 3V1 | Y | Y | |
| Mr. Eric Denholm<br>Mr. John Froese | Metall Mining Corporation<br>Winston Lake Division<br>P.O. Bag #2<br>Schreiber, Ontario, P0T 2S0<br>Samatosum Division<br>477 Barriere Town Road<br>P.O. Box 739<br>Barriere, British Columbia, V0E 1E0 | Y | | Y |
| Mr. Bruce W. Downing<br>Mr. M. Filion | Teck Exploration Ltd.<br>600-200 Burrard Street<br>Vancouver, British Columbia, V6C 3L9 | Y | | |
| Mr. K.D. Ferguson | Placer Dome Inc.<br>P.O. Box 49330<br>Bentall Postal Station<br>1600-1055 Dunsmuir Street<br>Vancouver, British Columbia, V7X 1P1 | Y | | |

| FULL NAME | COMPANY / ADDRESS | SURVEY COMPLETED | WORKSHOP | |
|---|---|---|---|---|
| | | | PANELIST | OBSERVER |
| Mr. Wayne Fraser | Hudson Bay Mining & Smelting Co. Limited<br>P.O. Box 1500<br>Flin Flon, Manitoba, R8A 1N9 | Y | | |
| Mr. Terry Hodson<br>Mr. Andy N. Veltmeter | Cominco Metals<br>Snip Operations<br>Bag 9000<br>Smithers, British Columbia, V0J 2N0 | Y | | |
| Mr. Ian A. Horne | Island Copper Mine<br>(BHP Minerals Canada Ltd.)<br>Hardy Bay Road<br>P.O. Box 370<br>Port Hardy, British Columbia, V0N 2P0 | Y | | |
| Dr. Ed Kustan | INCO Limited<br>77 King Street West<br>Toronto Dominion Centre, 22nd Floor<br>Royal Trust Tower, P.O. Box 44<br>Toronto, Ontario, M5K 1N4 | | | Y |
| Mr. Michael Li<br>Ms. Serena Domvile | Klohn-Crippen Consultants Ltd.<br>10200 Shellbridge Way<br>Richmond, British Columbia, V6X 2W7 | Y | Y | |
| Mr. Manfred Lindvall<br>Mr. Hans Jousson | Boliden Mineral AB<br>S-936<br>81 Boliden<br>Sweden | Y | | |
| Mr. Brian B. MacQuarrie | INCO Limited<br>Manitoba Division<br>Environmental Control<br>Thompson, Manitoba, R8N 1P3 | Y | | |
| Mr. William Napier | Homestake Canada<br>1000 - 700 West Pender Street<br>Vancouver, British Columbia, V6C 1G8 | | | Y |
| Mr. Robert Patterson | Gibraltar Mines Limited<br>P.O. Box 130<br>McLeese Lake, British Columbia, V0L 1PO | Y | | |
| Mr. Marty J. Puro<br>Mr. Rodney Stuparyk | INCO Limited<br>Central Process Technology,<br>General Engineering Building<br>Highway #17 West<br>Copper Cliff, Ontario, P0M 1N0 | Y | | Y |
| Mrs. E. Quarshie<br>Mr. Curt Andrews | COGEMA Resources Inc.<br>P.O. Box 9204<br>817 - 825, 45th Street West<br>Saskatoon, Saskatchewan, S7K 3X5 | Y | | |

| FULL NAME | COMPANY / ADDRESS | SURVEY COMPLETED | WORKSHOP | |
|---|---|---|---|---|
| | | | PANELIST | OBSERVER |
| Dr. Andrew M. Robertson<br>Mr. John Chapman<br>Ms. Linda Broughton | Steffen Robertson and Kirsten (Canada) Inc.<br>800 - 580 Hornby Street<br>Vancouver, British Columbia, V6C 3B6 | Y | Y | |
| **RESEARCHER** | | | | |
| Dr. Frank T. Caruccio<br>Dr. Gwendolyn Geidel<br>Mr. Bill Bradham | Department of Geology<br>Environmental Hydrogeology Programs<br>University of South Carolina<br>Earth Water Science Center, Room 617<br>Columbia, South Carolina, 29208 U.S.A. | | Y | Y<br>Y |
| Dr. Pierre Gélinas | Laval University<br>Départment de Géologie,<br>Faculté des Sciences et de Génie<br>Pavillon Adrien-Pouliot<br>Ste-Foy, Québec, G1K 7P4 | Y | Y | |
| Dr. David Gibson<br>Dr. Ian M. Ritchie<br>Dr. John W. Bennett | Australian Nuclear Science & Technology Organisation<br>Environmental Science Program<br>ANSTO, PMB 1<br>Menai NSW, Australia 2234 | Y | Y | |
| Mr. Edmund Kwong | University of Waterloo<br>Waterloo, Ontario | | | Y |
| Dr. Richard W. Lawrence | Dept. Mining & Mineral Process Engineering<br>University of British Columbia<br>6350 Stores Road, Room 517<br>Vancouver, British Columbia, V6T 1Z4 | Y | Y | |
| Dr. Richard Lowson<br>Dr. Josick Comarmond | Australian Nuclear Science & Technology Organisation<br>New Illawarra Road<br>Lucas Heights<br>NSW 2334<br>PMB 1, Menai NSW 2234<br>Australia | Y | | |
| Dr. K. Morin<br>Ms. Nora Hutt | Morwijk Enterprises Ltd.<br>Suite 703<br>1155 Harwood Street<br>Vancouver, British Columbia, V6E 1S1 | Y | | |
| Dr. Ron Nicholson<br>Dr. David Blowes | Department of Earth Sciences<br>University of Waterloo<br>Waterloo, Ontario, N2L 3G1 | | Y | |
| Mr. Ulf Quarfort | Environmental Geology<br>University of Uppsala<br>75236 Uppsala<br>Sweden | Y | | |

| FULL NAME | COMPANY / ADDRESS | SURVEY COMPLETED | WORKSHOP | |
|---|---|---|---|---|
| | | | PANELIST | OBSERVER |
| **GOVERNMENT** | | | | |
| Mr. Rodger Albright<br>(Roy Parker) | Environment Canada<br>Environmental Protection Branch<br>15th Floor, Queen Square<br>45 Alderney Drive<br>Dartmouth, Nova Scotia, B2Y 2N6 | Y | | |
| Mr. William B. Blakeman<br>Dr. M. Stefanski<br>(Mr. R. Albright) | Industrial Programmes Branch<br>Environment Canada<br>Mining Division - ISB<br>Place Vincent Massey<br>Ottawa, Ontario, K1A 0H3 | Y | | |
| Ms. Marcia Blanchette<br>Mr. Grant Feasby<br>Dr. Henry Steger<br>Mr. Errol Van Huyssteen | MEND/CANMET<br>555 Booth Street<br>Ottawa, Ontario, K1A 0G1 | | | Y<br>Y |
| Mr. Bruce Clyburn<br>Mr. Ron Nicholson | Cape Breton Development Corporation<br>P.O. Box 2500<br>Sydney, Nova Scotia, B1P 6K9 | Y | | |
| Mr. Richard Doepker | U.S. Bureau of Mines<br>Spokane Research Center<br>East 315 Montgomery Avenue<br>Spokane, Washington, 99207 U.S.A. | | | Y |
| Mr. Peter Dugandzic | Atomic Energy Control Board<br>280 Slater Street<br>Ottawa, Ontario, K1P 5S9 | | | Y |
| Mr. Glenn Groskopf<br>Dr. D.W. Lawson | Environment Canada<br>Environmental Protection<br>2365 Albert Street<br>Room 300, Park Plaza<br>Regina, Saskatchewan, S4P 4K1 | | | Y |
| Mr. Richard Humphreys | State of California<br>State Water Resources Control Board<br>901 P Street<br>P.O. Box 100<br>Sacremento, California, 95801-0100 U.S.A. | Y | Y | |
| Mr. David M. Hyman<br>Dr. Robert Kleinman | U.S. Bureau of Mines<br>Pittsburgh Research Center<br>P.O. Box 18070<br>Pittsburgh, PA, 15236 U.S.A. | Y | | |

| FULL NAME | COMPANY / ADDRESS | SURVEY COMPLETED | WORKSHOP | |
|---|---|---|---|---|
| | | | PANELIST | OBSERVER |
| Mr. Steve Mlot<br>Mr. Rod Doran<br>Mr. John Robertson<br>Mr. Steve Reitzel<br>Mr. Dick Tallon<br>Hue. DeSousa<br>Toni Tessarollo | Ministry of Northern Development and Mines<br>933 Ramsey Lake Road, 5th Floor<br>Sudbury, Ontario, P3E 6B5 | | | Y<br>Y |
| Mr. Roy Parker | Environment Canada<br>Conservation and Protection<br>5th Floor, Queen Street<br>45 Alderney Drive<br>Dartmouth, Nova Scotia, B2Y 2N6 | Y | | |
| Dr. Bill Price | Ministry of Energy, Mines and Petroleum Resources<br>Mine Review & Permitting Branch<br>4th Floor<br>1810 Blanshard Street<br>Victoria, British Columbia, V8V 1X4 | Y | | Y |
| Mr. Dan Roumbanis | Commercial Chemicals & Nuclear Programs Section<br>Environmental Protection Branch - Ontario Region<br>Environment Canada<br>25 St. Clair Avenue East<br>7th Floor<br>Toronto, Ontario, M4T 1M2 | | | Y |
| Mr. Denis Schryer | Atomic Energy Control Board<br>307 - 101 22nd Street East<br>Saskatoon, Saskatchewan, S7K 0E1 | | | Y |
| Mr. Leonard S. Sinclair | Saskatchewan Environment and Resource Management<br>Mineral Industry Environmental Protection Branch<br>12th Floor, McIntosh Mall<br>800 Central Avenue<br>P.O. Box 3003<br>Prince Albert, Saskatchewan, S6V 6G1 | Y | Y | |