



MEND MANUAL
VOLUME 2 – SAMPLING
AND ANALYSIS
MEND 5.4.2b

Editors:

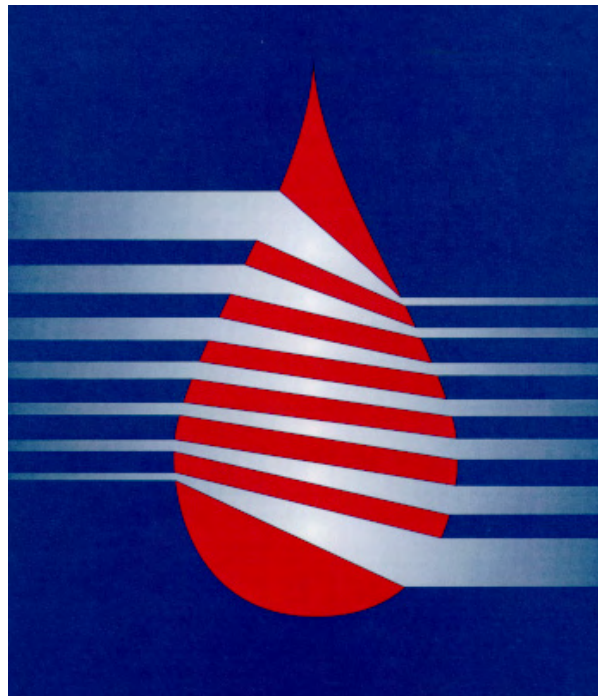
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MEND MANUAL



VOLUME 2

**SAMPLING AND
ANALYSIS**

AUTHORS OF THE MEND MANUAL

This Manual was compiled on behalf, and under the direction of MEND and MEND 2000, by URS Norecol Dames & Moore, in association with SENES Consultants Limited, SRK Consulting, BC Research Inc., EVS Environment Consultants and O’Kane Consultants Inc. The different volumes and sections of the Manual were authored as follows:

Volume 1:	SENES Consultants Limited
Volume 2:	
Section 2.1 to 2.3	SENES Consultants Limited
Section 2.4	URS Norecol Dames & Moore EVS Environment Consultants
Section 2.5	SENES Consultants Limited
Section 2.6	BC Research Inc.
Volume 3:	
Section 3.1 to 3.3	URS Norecol Dames & Moore SRK Consulting BC Research Inc.
Section 3.4	SENES Consultants Limited URS Norecol Dames & Moore SRK Consulting
Volume 4:	
Section 4.1	SENES Consultants Limited
Section 4.2	SENES Consultants Limited SRK Consulting
Section 4.3	SENES Consultants Limited
Section 4.4	O’Kane Consultants Inc.
Section 4.5	SENES Consultants Limited
Section 4.6	URS Norecol Dames & Moore SRK Consulting
Section 4.7	SENES Consultants Limited SRK Consulting
Section 4.8	SENES Consultants Limited URS Norecol Dames & Moore
Section 4.9	SENES Consultants Limited
Volume 5:	
Section 5.1	SENES Consultants Limited URS Norecol Dames & Moore
Section 5.2	SENES Consultants Limited
Section 5.3	URS Norecol Dames & Moore
Volume 6:	SENES Consultants Limited

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VOLUME 2 – SAMPLING AND ANALYSES

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In particular we wish to highlight the contribution of David Orava of SENES Consultants Limited (Water Sampling, Solids Sampling, and Geophysics and Remote Sensing), Annette Smith of URS Norecol Dames & Moore and Randy Baker of EVS Environment Consultants (Biological Sampling) and Rikkert (Rik) Vos of BC Research Inc. (Chemical Analysis) in the preparation of Volume 2 of the Manual.

At the request of the MEND Secretariat detailed reviews were carried out by:

Howard Barrie	Terraquest Ltd.
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While considerable progress has been made in tackling the problems of acidic drainage, major challenges remain. Comments on this document and other aspects of acidic drainage should be sent to:

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DISCLAIMER

The primary purpose in producing this manual is to provide a succinct summary of the extensive work completed by MEND and MEND 2000 on the processes of acid generation from sulphur-bearing minerals and sulphide wastes in a manageable single reference document. A secondary objective is to provide additional recommendations on the application of currently available technologies. The result is a detailed reference on sampling and analyses, prediction, prevention, control, treatment and monitoring of acidic drainage. The information provided is based on the opinions of the authors of the particular sections and should not be construed as endorsement in whole or in part by the various reviewers or by the partners in MEND (the Government of Canada, Provincial Governments, the Mining Association of Canada, contributing mining companies and participating non-governmental organizations).

The user of this guide should assume full responsibility for the design of facilities and for any action taken as a result of the information contained in this guide. The authors and Natural Resources Canada (through the Mine Environment Neutral Drainage (MEND) and MEND 2000 programs) make no warranty of any kind with respect to the content and accept no liability, either incidental, consequential, financial or otherwise arising from the use of this publication.

PREFACE

Acidic drainage¹ has been identified as the largest environmental liability facing the Canadian mining industry, and to a lesser extent, the public through abandoned mines. This liability is estimated to be between \$2 billion and \$5 billion Canadian, depending on the sophistication of treatment and control technology used. There are numerous examples throughout the world where elevated concentrations of metals in mine drainage have adverse effects on aquatic resources and prevent the reclamation of mined land. Metal leaching problems can occur over an entire range of pH conditions, but are commonly associated with acidic drainage. In North America acidic drainage has resulted in significant ecological damage and multimillion-dollar cleanup costs for industry and governments.

The Canadian Mine Environment Neutral Drainage (MEND) Program was formed in 1989, to develop scientifically-based technologies to reduce or eliminate the liability associated with acidic drainage. This nine-year volunteer program established Canada as the recognized leader in research and development on acidic drainage for metal mines. Through MEND, Canadian mining companies and federal and provincial governments have reduced the liability due to acidic drainage by an estimated \$340 million. It is also acknowledged that the reduction in liability is significantly higher than this quoted value, with a minimum of \$1 billion commonly accepted. This is an impressive return on an investment of \$17.5 million over nine years. A three-year program, called MEND 2000, was initiated in 1998 to further confirm MEND-developed reclamation technologies in the field. The key to MEND 2000 was technology transfer – providing state-of-the-art information and technology developments to users and to ensure that the information is clearly understood, particularly for newly-developed technologies.

THE MEND MANUAL

More than 200 technology-based reports were generated from the MEND and MEND 2000 programs. These reports represent a comprehensive source of information, however, it is not practical for users to have on hand or assimilate all the detailed information. For this reason, a single source of information on acidic drainage and on the results of MEND research is needed which is complimentary to many detailed technical reports. The MEND Manual describes the MEND-developed technologies and their applicability in terms of cost, site suitability and environmental implications - **a "toolbox" of techniques and options.**

The objective of the manual was to summarize work completed by MEND in a format that would provide practitioners in Canadian industry and government with a manageable single reference document. The document is not a “How to” manual. It is a set of comprehensive working

¹ The terms “acidic drainage”, “Acid Mine Drainage” (AMD) and “Acid Rock Drainage” (ARD) are used interchangeably throughout the manual to describe effluent generated from the oxidation of sulphide minerals

references for the sampling and analyses, prediction, prevention, control, treatment and monitoring of acidic drainage. The document provides information on chemistry, engineering, economics, case studies and scientific data for mine and mill operators, engineering design and environmental staff, consulting engineers, universities and governments.

The MEND Manual consists of six volumes. The information found in each volume is as follows:

Volume 1: Condensed “stand-alone” summary of the Manual.

Volume 2: Sampling and Analyses

- Water and solids sampling
- Biological sampling
- Geophysics and remote sensing
- Chemical analyses for water and solids

Volume 3: Prediction

- Laboratory static and kinetic geochemical tests methods
- Field methods
- Modelling

Volume 4: Prevention and Control

- Water covers
 - Non-oxidized and oxidized waste materials
- Dry covers
 - Soil and organic covers
- Disposal technologies
- Saturation (elevated water table)
- Blending and layering
- Separation and segregation
- Backfilling (in-pit) and co-disposal
- Permafrost

Volume 5: Treatment

- Active treatment methods
 - Chemical treatment
 - Metal recovery/recycling
 - Treatment byproducts
- Passive treatment
 - Anoxic limestone drains

- Aerobic wetland treatment systems
- Passive anaerobic treatment systems
- Biosorption treatment methods
- Passive *in situ* treatment methods
- Hybrid active/passive treatment systems

Volume 6: Monitoring

- Monitoring objectives
- Monitoring program design and data management
- Recent developments affecting acidic drainage monitoring

BACKGROUND ACIDIC DRAINAGE FROM SULPHIDE MINERALS

Base metal, precious metal, uranium, diamond and coal mines often contain sulphide minerals, in the mined ore and the surrounding rock. When these sulphide minerals, particularly pyrite and pyrrhotite, are exposed to oxygen and water, they oxidize, and the drainage may become acidic unless sufficient acid-neutralizing minerals such as calcite are present.

The acidic water may contain elevated concentrations of metals and salts. These can include typical major rock constituents (Ca, Mg, K, Na, Al, Fe, Mn) as well as trace heavy elements such as Zn, Cu, Cd, Pb, Co, Ni, As, Sb and Se. Rainfall and snow-melt flush leachate from the waste sites. If acidic drainage is left uncollected and untreated, the drainage can contaminate local water courses and groundwater, affecting plants, wildlife, and fish.

Naturally occurring alkalinity, such as carbonate minerals and carbonate ions in solution may partially or completely neutralize acidity *in situ*. The resulting leachate is non-acidic with very low iron concentrations¹ but can contain elevated concentrations of sulphate, calcium and magnesium.

Neutralization by reactions with acid consuming minerals (carbonate minerals in particular) may result in low concentrations of dissolved metals due to the low solubility of metal carbonates, basic carbonates, hydroxides and oxyhydroxides at pH 6 to 7.

DURATION

The lag time for acid drainage to appear (if at all) is controlled by the concentration and reactivity of the iron sulphides, and the availability of carbonate minerals. Acid may be generated and released by high sulphur wastes having small amounts of carbonate minerals a few days after exposure. Low sulphur (< 2%) wastes with some carbonate may not release acid for years or decades.

¹ Under anoxic conditions Fe will remain in solution in its reduced state

Once acidic oxidation of iron sulphide minerals is initiated the rate tends to increase until a peak is reached. The general trend is for a long-term decrease in acidity release. As the readily available mineral-grains are consumed, the reactive surface shrinks and oxidation product coatings limit reactivity. The rate of decrease is determined by numerous factors but mainly the reactivity of the sulphide minerals, the size of particles, and the availability of reactants (i.e. oxygen and other oxidants). The decrease in oxidation rates may not be apparent in mine waste drainage because oxidation products are stored and released over a long period during flushing events at a rate controlled by the solubility of the oxidation products.

SEASONAL EFFECTS

Under all climatic regimes, release of acidity is controlled, to varying degrees by seasonal precipitation patterns (e.g. transport medium). Under uniform precipitation conditions, the acid load and concentrations leached from a reactive waste are constant. As precipitation patterns vary, the following is observed:

- During dry spells, base flow conditions develop. A small proportion of the reactive surfaces are leached which allows oxidation products to build up in unleached sections;
- As infiltration increases (either due to snow pack melting or increased rainfall), a greater degree of leaching may occur due to rinsing of greater reactive surface areas. The contaminant load and usually the concentration increases;
- As wet conditions persist, the load leached decreases due to removal of acid products and flows are diluted resulting in lower concentrations; and
- When dry conditions are re-established, loads may be similar or lower than wet conditions but concentrations may increase.

SOURCES

Acidic drainage may originate from a variety of natural and man-made sources. Potential natural sources can include:

- Talus;
- Runoff from rock faces; and
- Groundwater seeps.

Man-made sources can include:

- Mines and associated facilities;
- Road cuts and fill;

- Quarries; and
- Other construction fill.

Mines are the major source of acidic drainage primarily because sulphide minerals are concentrated in geological environments containing ore deposits. In addition, rock removal and processing occurs on a large scale, and the methods involved (from blasting to processing) result in particle size reduction thereby increasing the surface area available for reactions. Some significant natural and non-mining sources of acidic drainage have also been documented. For example, at the Halifax International Airport in Nova Scotia, remedial measures are necessary to treat acidic drainage from excavated slates.

At active mine sites (and many inactive mine sites), systems are operated to collect and treat effluents and seepage, and prevent downstream environmental impacts. In some instances, acid generation may persist for hundreds of years following mine closure. The operation of treatment plants for very long periods of time is clearly not desirable. In addition, conventional water treatment technologies produce sludges with low solids content. In some extreme cases, the volume of sludge produced from the acidic drainage effluent can exceed the volume of tailings and/or waste rock. Storage capacity could become an issue for decommissioned mine sites.

LIABILITY ASSOCIATED WITH ACIDIC DRAINAGE

CANADA

Estimates for Canada in 1986 showed that acid generating waste sites totaled over 12,000 hectares of tailings and 350 million tonnes of waste mine rock. These wastes were observed to have mainly accumulated in the previous fifty years of mining. This survey did not represent the entire Canadian inventory, since it did not include abandoned mine sites for which responsibility had reverted to the responsible government authority.

The Canadian mine waste inventory was updated by CANMET in 1994 by surveying mining companies and provincial databases (MEND 5.8e). The results of this survey are summarized in Table 1. A complete national database on mine wastes has never been completed, although several provinces and territories have made considerable progress in defining their own mine waste inventories.

Using a wide variety of nationwide sources, estimates were made of the amount of acid-producing mine wastes (Table 2). Estimates of acid-producing and potentially acid-producing wastes are less accurate than the mine wastes for the following reasons:

- Only a portion of tailings and waste rock piles may be potentially acid producing;
- Some, or all, of the wastes may be stored in a way to eliminate acid potential; and
- Acid production may appear decades after the waste was produced.

Table 1
Estimates of Mine Wastes in Canada

	Tailings (tonnes * 10⁶)	Waste Rock (tonnes * 10⁶)
Newfoundland and Labrador	600	600
Nova Scotia	20	50
New Brunswick	80	30
Québec	1,900	2,700
Ontario	1,700	130
Manitoba	200	100
Saskatchewan	400	50
British Columbia	1,700	2,600
Territories	200	30
Canada	6,800	6,290

Table 2
Canadian Acid-Generating Wastes

	Tailings (tonnes * 10⁶)	Waste Rock (tonnes * 10⁶)
Newfoundland and Labrador	30	-
Nova Scotia	10	40
New Brunswick	80	30
Québec	250	70
Ontario	1,000	80
Manitoba	200	70
Saskatchewan	70	20
British Columbia	200	420
Territories	60	20
Canada	1,900	750

A summary of the estimated existing liability associated with acid-producing mine wastes is shown in Table 3. The assumptions made to calculate the reclamation and maintenance costs for the various options are presented in MEND 5.8e.

Table 3
Liability for Acidic Drainage from Mine Wastes

Waste	Options	\$Billions
Tailings	Collect, Treat	1.5
	Water Cover	1.5
	Dry Cover	3.2
Waste Rock	Collect, Treat	0.4
	Dry Cover	0.7
	Relocate to Pit	2.1

The liability was estimated to be between \$1.9 billion and \$5.3 billion, depending on the sophistication of treatment and control technology selected. The most economical strategy to meet environmental objectives may be to collect water and treat it for a very long time, but such practice raises concerns about treatment product disposal and sustainability of the process.

WORLDWIDE

In the United States approximately 20,000 kilometres of streams and rivers have been impacted by acidic drainage, 85-90% of which receive acidic drainage from abandoned mines (Skousen 1995). Although there are no published estimates of total U.S. liability related to acidic drainage, several global examples indicate the scope of the issue:

- Leadville, a Superfund site in Colorado, has an estimated liability of US\$290 million due to the effects of acidic drainage over the 100-year life of the mine;
- The Summitville Mine, also in Colorado, has been declared a Superfund site by the U.S. Environmental Protection Agency (USEPA). The USEPA estimated total rehabilitation costs at approximately US\$175 million;
- More than US\$253 million dollars have been spent on Abandoned Mine Lands reclamation projects in Wyoming (Richmond 1995);
- At an operating mine in Utah, U.S. regulators estimate the liability to be US\$500-US\$1,200 million (Murray *et al.* 1995);
- The Mineral Policy Center in the US has estimated that there are 557,000 abandoned mines in 32 states, and that it will cost between US\$32 - \$72 billion to remediate them (Bryan 1998); and
- Liability estimates for Australia in 1997 and Sweden in 1994 were \$900 million and \$300 million respectively (Harries 1997; Gustafsson 1997).

Based on these data, as well as the number of new mining projects under development, and mine sites in regions not mentioned above (Europe, South America, Africa), the total worldwide liability is estimated to be around US\$100 billion.

MINE ENVIRONMENT NEUTRAL DRAINAGE (MEND) PROGRAM

In the 1970s and early 1980s, the Canadian mining industry and the government of Canada conducted research into methods of establishing sustainable vegetative growth on tailings and waste rock. At that time, closure of mine sites involved recontouring and revegetation for stability and erosion control. It was believed, at the time, that this technology would also address acidic drainage and allow the sites to be abandoned without future liability. Very successful revegetation methods were developed, and many sites were revegetated. However, after several years, the quality of water drainage from vegetated sites had not significantly improved, and mine site operators were faced with the prospect of operating water treatment plants indefinitely.

In response, the Canadian mining industry initiated a task force in 1986 to research new methods to remediate acid generating mines sites. The task force consisted of a steering committee and a technical working group, with representation from the mining industry, Energy, Mines and Resources, Environment Canada, British Columbia, Manitoba, Ontario, Québec and New Brunswick. It was referred to as the RATS (Reactive Acid Tailings Stabilization) task force. Its recommendations were published in July 1988 (MEND 5.5.1), and were implemented by the Mine Environment Neutral Drainage (MEND) program. Provincial groups worked with MEND to coordinate research. Provincial initiatives included:

- British Columbia - British Columbia Acid Mine Drainage (BC AMD) Task Force,
- Ontario - MEND Ontario (MENDO); and
- Québec - Programme de Neutralisation des eaux de drainage dans l'environnement minier (NEDEM Québec).

The initial MEND research plan was based on a five-year budget of \$12.5 million (MEND 5.5.1).

Three years into the program, the original "RATS" plan was revised and a "Revised Research Plan" was produced. This plan expanded MEND to a 9-year program and the partners agreed to an expanded budget of \$18 million (MEND 5.7.1). Planned funding for MEND was divided equally between the three major partners; the mining industry, the federal government and five provincial governments. When MEND ended in December 1997, the two levels of government together with the Canadian mining industry had spent over \$17 million within the MEND program to find ways to reduce the estimated liability (Table 4).

Table 4
Funding Contribution by MEND Partners

Partners	Spent (\$M)	Funding (%)
Federal government	6.3	37
Mining industry	6.7	39
Provinces	4.1	24

ORGANIZATION OF THE MEND PROGRAM

Two important objectives for MEND Program were established:

- To provide a comprehensive, scientific, technical and economic basis for the mining industry and government agencies to predict with confidence the long-term management requirements for reactive tailings and waste rock; and
- To establish techniques that will enable the operation and closure of acid generating tailings and waste rock disposal areas in a predictable, affordable, timely and environmentally acceptable manner.

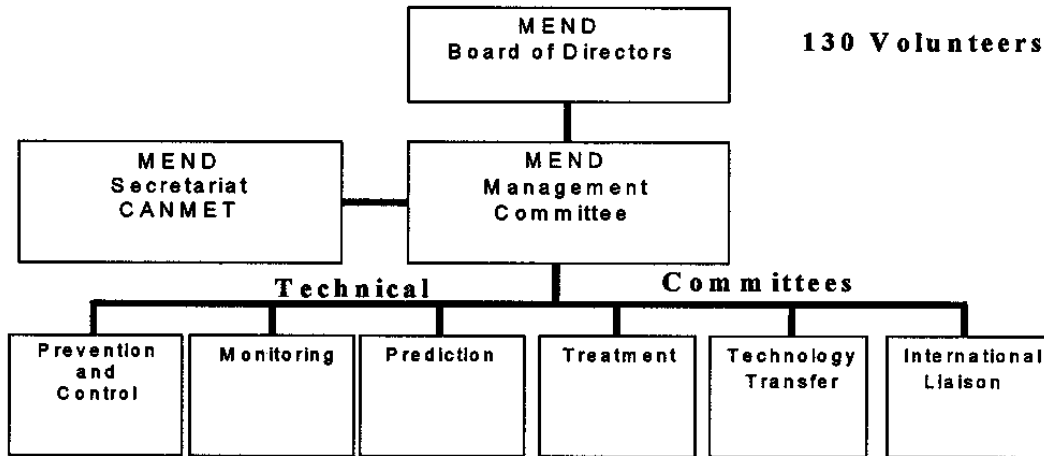
To ensure transparency of the program, it was also recommended that all research reports produced be made available to the partners and the public. Prior to their release the reports were critically reviewed and edited to enhance credibility and provide quality.

MEND adopted an organizational structure that included a Board of Directors, a Management Committee and several technical committees and a coordinating secretariat (Figure 1). The roles of these components were as follows:

- The Board of Directors provided vision and approval of yearly plans and budgets;
- The Management committee provided day-to-day management of the program; and
- The technical committees addressed technological issues and solutions.

The Secretariat ensured coordination of the elements within, and external to MEND. An important role of the Secretariat was to provide program and project management.

Figure 1: MEND Organization



MEND relied heavily on the 130 volunteer representatives of the different participating agencies: regulators, mining company managers and engineers, non-government organizations (NGOs) and government officials and scientists.

MAJOR ELEMENTS AND RESULTS OF THE CANADIAN RESEARCH

MEND organized its work into four technical areas: prediction, prevention and control, treatment and monitoring. The four technical committees were also involved in technology transfer and international activities.

Over 200 projects were completed. Some of the highlights of the MEND Program include:

Prediction and Modelling

- **Field studies of several waste rock piles provided important understanding for development of prediction techniques.** One of the most important observations was that waste rock piles accumulate extensive quantities of oxidation products and acidity that can be released to the environment in the future (MEND 1.14.3; MEND 1.41.4).
- **Geochemical and physical characteristics of a waste rock pile, from its origin in underground workings to its disassembly and placement underwater in a nearby lake was completed.** This study provided qualitative and quantitative information on mass transport and water infiltration within a waste rock pile. Geochemical processes were

dependent on physical factors such as channeling or stratification within the dump (MEND 1.44.1).

- **Laboratory and field prediction tests for waste rock and tailings have been investigated and further developed.** These tests include static and kinetic tests, mineralogical evaluations and oxygen consumption methods.
- **An "Acid Rock Drainage Prediction Manual" for the application of chemical evaluation procedures for the prediction of acid generation from mining wastes was produced (MEND 1.16.1b).**
- **Advances in the prediction of drainage quality for waste rock, tailings and open pit mines have been made.** A tailings model (RATAP) was distributed and a geochemical pit lake model was developed (MINEWALL). A critical review of geochemical processes and geochemical models adaptable for prediction of acidic drainage was completed (MEND 1.42.1).
- **Models that will predict the performance of dry and wet covers on tailings and waste rock piles are available (WATAIL, SOILCOVER).**

Prevention

- **Prevention has been determined to be the best strategy.** Once sulphide minerals start to react and produce contaminated runoff, the reaction is self-perpetuating. Also, at some mine sites, acidic drainage was observed many years after the waste pile had been established. With many old mine sites, there may be no "walk-away" solution;
- **In Canada, the use of water covers and underwater disposal are being confirmed as the preferred prevention technology for unoxidized sulphide-containing wastes.** A total of 25 reports and/or scientific papers have been prepared on subaqueous disposal (MEND 2.11). A generic design guide was developed (MEND 2.11.9). The guide outlines the factors involved in achieving physically stable tailings, and discusses the chemical parameters and constraints that need to be considered in the design of both impoundments, and operating and closure plans.
- **Underwater disposal of mine wastes (tailings and waste rock) in man-made lakes is presently an option favored by the mining industry to prevent the formation of acidic drainage.** At the Louvicourt Mine (Québec) fresh, sulphide-rich tailings have been deposited in a man-made impoundment since 1994. Laboratory and pilot-scale field tests to parallel the full-scale operation and evaluate closeout scenarios are ongoing (MEND 2.12.1).

- **The use of water covers to flood existing oxidized tailings can also be a cost effective, long lasting method for prevention of acid generation.** Both the Quirke (Elliot Lake, Ontario) and Solbec (Québec) tailings sites were subjects of MEND field and laboratory investigations (MEND 2.13.1 (Quirke); MEND 2.13.2 (Solbec)). These sites were decommissioned with water covers and are presently being monitored. Where mining wastes are significantly oxidized, laboratory results have shown that the addition of a thin sand or organic-rich layer over the sulphide-rich materials can prevent or retard diffusion of soluble oxidation products into the water column.

Control

- **Dry covers are an alternative where flooding is not possible or feasible.** MEND has extensively investigated multilayer earth covers for tailings and waste rock (e.g. Waite Amulet and Les Terrains Aurifères (tailings) and Heath Steele (waste rock): 3-layer systems). These type of covers use the capillary barrier concept and although they are effective, they are also costly to install in many areas of Canada.
- **Innovative "dry" cover research is indicating that a range of materials, including low cost waste materials from other industries (crude compost, lime stabilized sewage sludge, paper mill sludge) may provide excellent potential for generating oxygen-reducing surface barriers.** This technology would see the application of one waste to solve a problem of other wastes.
- **Non acid-generating tailings can be used as the fine layer in composite moisture-retaining surface barriers.** Laboratory studies have confirmed that sulphide-free fine tailings offers some promising characteristics as cover materials (MEND 2.22.2). Barrick's tailings site in Northwest Québec, Les Terrains Aurifères, is the first full-scale demonstration project of using tailings in a cover system (MEND 2.22.4). A second site, Québec crown-owned Lorraine, has also been rehabilitated using the same closure technique.
- **The first full-scale application in Canada of a geomembrane liner for close-out was completed in 1999 at Mine Poirier in Northwest Québec.** Performance monitoring of the close-out scenario to evaluate the liner is ongoing (Lewis and Gallinger 1999).

Disposal Technologies

- Several other disposal technologies that will reduce acid generation and have been investigated include:

- **Permafrost in northern environments.** Permafrost covers approximately 40% of Canada, and cold conditions inhibit oxidation. Predictive methods have been researched. Although acid generation is common in cold environments, it occurs when exposed sulphides are warmed to temperatures above freezing (MEND 1.61.1-3; MEND 1.62.2).
- **Blending and segregation (or layering).** Technology is defined as the mixing of at least two rock waste types with varying acid generation potential, neutralization potential and metal content to produce a pile that has seepage water quality acceptable for discharge without additional measures (MEND 2.37.1; MEND 2.37.3).
- **Elevated water table in tailings.** This technique offers a method of inhibiting the oxidation of sulphides through the effective saturation of pore spaces. It may be applied as one component of a multi-component reclamation strategy (MEND 2.17.1).
- **In-pit disposal following mining.** Mined-out pits can provide a geochemically stable environment for wastes and can be a focal point in mine rehabilitation. The addition of buffering material may be required (MEND 2.36.1).
- **Depyritized tailings as cover materials.** Laboratory and field tests are showing that depyritized tailings have excellent potential as covers. Economic analyses have indicated that hydraulic placement will be necessary to be cost effective (MEND 2.22.3).

Lime Treatment

- **Studies conducted to date support the view that sludges will remain stable if properly disposed.** Concerns had been raised with regard to the long-term chemical stability and the potential liability arising from dissolution of heavy metals contained in the sludge (MEND 3.42.2). Other findings include:
 - Optimum conditions will depend on site-specific factors e.g. pH, metal loading chemistry;
 - Modifications to the treatment process (e.g., lime slaking, pH adjustment, mixing, aeration, flocculent addition) can influence operating costs, sludge volumes, and metal release rates (Zinck and Aubé 1999);
 - The method of disposal of the sludge will affect its long-term stability. Aging can promote recrystallization which improves sludge stability;
 - Codisposal of sludges with other mining wastes requires further study; and

- Leach test protocols need to be developed specifically for lime treatment sludges.
- **The status of chemical treatment and sludge management practices was summarized in a reference document (MEND 3.32.1).**

Passive Treatment

- **In Canada, experience indicates that passive systems do have specific applications for acid mine drainage (AMD) treatment.** These applications range from complete systems for treating small seeps to secondary treatment systems such as effluent polishing ponds. Alone, they cannot be relied upon to consistently meet AMD discharge standards. Large-scale passive systems capable of handling the low winter temperatures, high metal loads, and fluctuations in flow rates associated with the spring freshet have yet to be implemented.
- **The status of passive systems for treatment of acidic drainage was summarized in a reference document (MEND 3.14.1).**

Monitoring

- **Several guides are available to assist in the development of acidic drainage monitoring programs.** An important MEND deliverable is MEND 4.5.4, *Guideline Document for Monitoring Acid Mine Drainage*. This document is designed to serve as a single source introductory guide to a wide range of AMD monitoring concerns, while also providing users with information on literature sources for site-specific concerns and emerging monitoring techniques. Monitoring requirements are addressed for both source and receiving environments, with receiving environment concerns restricted to freshwater systems.

Other guideline documents include a field sampling manual (MEND 4.1.1) that presents an approach to assist people in selecting the appropriate methodologies for the sampling of tailings solids, liquids and pore gas. A comprehensive list and description of sampling techniques, and a guide to waste rock sampling program design for the exploration, operation and closure phases of a mining project is produced in MEND 4.5.1-1. Available sampling techniques for waste rock is given in MEND 4.5.1-2.

At the conclusion of the MEND program, a “tool box” of technologies has been developed to assist the mining industry in addressing its various concerns related to acidic drainage, and in significantly reducing its estimated liability. A particularly important outcome has been the development of a common understanding among participants, inasmuch as it has allowed operators to take actions with greater confidence and to gain multi-stakeholder acceptance more rapidly.

NEW IDEAS

In 1992, a Task Force was formed to solicit and nurture innovative new ideas. An additional goal was to encourage researchers from outside the general area of mining environment to becoming involved in acid drainage research. The resulting technology would need to be reliable, inexpensive, permanent, and widely applicable. The innovator had to demonstrate the relevance of the idea at the concept level, which would then be the basis for proceeding to a more detailed development project.

A two-page proposal format was developed and distributed across Canada. New ideas were solicited in two rounds. A total of 135 proposals were received and 18 were funded. Up to \$10,000 was provided for the review and the development of the concepts. Table 1.4-1 lists the new ideas projects funded by the Task Force.

Table 5
New Ideas Projects

New Idea #	Project Title
01	Status of AMD Research in the U.S.
02	Permafrost to Prevent AMD
03	Low Cost Wax Cover
04, 21	Chemically Modified Clay Cover
05	Ferric Phosphate Coating of Pyrrhotite
06	State of Art of Japanese Technology
07	Formation of Hardpan in Pyrrhotite Tailings
08	Passivation of Sulphide Minerals
09, 22	Selective Ion Exchange Resin
10	Chelating Ribbons
11	Comingled Waste Disposal
12	Chelating/Membrane Filtration
23	Sprayed Polyurethane Covers
24	Literature Review: Foam Flotation
25	Limestone Precipitation Layer in Coal Wastes
26	Ion Flotation for Zinc Recovery

The eighteen New Ideas projects cost about \$230k. Although most of the new ideas were innovative and applicable and provided useful information, they did not achieve the objective of providing a solution to the problem of acidic drainage. However, at least three had potential applications (sprayed polyurethane, modified clay and permafrost) and three yielded useful state-of-art reviews (U.S. research, foam flotation and Japanese technology). Also, a large number of additional researchers were made aware of the acidic drainage problem, and some may in due

course make useful contributions. Finally, the endeavour increased MEND's certainty that a magic answer was not overlooked.

TECHNOLOGY TRANSFER

Technology transfer activities were expanded in the later years of the program. The dissemination of information on developed technologies to the partners and the public was a major function of the program. A MEND 2000 Internet site (<http://mend2000.nrcan.gc.ca>) was established and is updated with current information on technology developments. The site provides report summaries, the MEND publication list, information on liabilities, case studies, and conference and workshop announcements. MEND and MEND 2000 hosted several workshops per year at various locations across Canada. Proceedings for the workshops on chemical treatment, economic evaluations, in-pit disposal, dry covers, monitoring, case studies of Canadian technologies, research work in Canada, and risk assessment and management are available from the MEND Secretariat.

MEND participated in the organization of several International Conferences on the Abatement of Acid Rock Drainage (ICARDs) held in 1991 (2nd – Montreal), 1994 (3rd - Pittsburgh) and 1997 (4th -Vancouver).

Other technology transfer initiatives included:

- MEND videos are available in English, French, Spanish and Portuguese. They describe technological advances relating to the prediction, prevention and treatment of acidic drainage from mine sites;
- The MEND Manual that summarizes all of the MEND and MEND-associated work on acidic drainage from mine wastes;
- The Proceedings of the 4th International Conference on Acid Rock Drainage are available on CD-ROM;
- About 200 reports completed during MEND and MEND 2000;
- MEND reports on CD-ROM. A project to have the key MEND reports available on CD-ROM will be completed in 2001; and
- National case studies on acidic drainage technologies.

THE MEND MODEL

MEND has been described as a model way for governments and industry to cooperate in technology development for advancing environmental management in the mining industry.

Decisions are now being made based on findings from scientific research. Reasons for this include:

- The high return on the investment targeted and achieved, in terms of knowledge gained and environmental and technical awareness of the scope of the acidic drainage problem and credible scientific solutions;
- The partnership and improved mutual understanding developed between the two levels of government, the mining industry and NGOs in search of solutions to a major environmental problem;
- The secretariat group which coordinated activities, managed the accounting, reporting and technology transfer;
- The peer review process that was both formal and informal, and resulted in enhanced credibility of the information base; and
- The approach taken for transferring the knowledge gained during MEND.

In large part as a result of MEND, it was shown that new mines are able to acquire operating permits faster and more efficiently than before since there are now accepted acidic drainage prevention techniques. As an example, the Louvicourt mine in northwest Québec adopted MEND subaqueous tailings disposal technology and has been able to progress from the exploration phase to an operating mine within 5 years, with a reduced liability of approximately \$10 million for the tailings impoundment. Similar benefits are reported for existing sites in the process of decommissioning. MEND has also fostered working relationships with environmental groups, ensuring that they are an integral part of the process.

MEND 2000

MEND concluded on December 31, 1997. However, the partners agreed that additional cooperative work was needed to further reduce the acidic drainage liability and to confirm field results of MEND-developed technologies. MEND 2000 was a three-year program that officially started in January 1998. The program was funded equally by the Mining Association of Canada (MAC) and Natural Resources Canada, a department of the Canadian government. The objectives of MEND 2000 were to:

- Transfer and disseminate the knowledge gained from MEND and other related acidic drainage projects;
- Verify and report the results of MEND developed technologies through long-term monitoring of large scale field tests;
- Maintain links between Canadian industry and government agencies for information exchange and consensus building; and

- Maintain linkages with a number of foreign government and industry driven programs (e.g. International Network on Acid Prevention (INAP), the Mitigation of the Environment Impact from Mining Waste (MiMi - Sweden), and the Acid Drainage Technology Initiative (ADTI - USA).

An important function of MEND is technology transfer. All research results must be effectively communicated to industry, government agencies and the public if the program is to continue to achieve the desired results.

CONCLUSION

The benefit of the MEND programs has come through the sharing of experiences, the thorough evaluation of technologies and their incremental improvement. Mining companies and consultants have acquired more capabilities to deal with water contamination from mine wastes, including acid generation. No dramatic technological breakthrough other than water covers has been achieved. Nonetheless, Canadian industry reports that a significant reduction in liability is predicted. An evaluation of MEND in 1996 concluded that the estimated liability had been reduced by \$340 million, for five Canadian mine sites alone (MEND 5.9). It is also acknowledged that the reduction in liability is significantly higher than this quoted value, with a minimum of \$1 billion commonly accepted. The same study concluded:

- There is a much greater common understanding of acidic drainage issues and solutions;
- The research has led to reduced environmental impact;
- There is increased diligence by regulators, industry and the public; and
- The work should continue with strong international connections.

As a result of MEND and associated research, technologies are in place to open, operate and decommission a mine property in an environmentally acceptable manner, both in the short and long term.

MEND is an example of a successful, multi-stakeholder program addressing a technical issue of national importance, and has been a model for cooperation between industry, environmental groups and various levels of government.

MEND AND RELEVANT PUBLICATIONS

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2.0 SAMPLING AND ANALYSIS

2.1 INTRODUCTION

The techniques that are now being used to predict, prevent and control, and treat acidic drainage represent a vast improvement over those available only a decade ago. Science-based techniques are now effectively applied routinely across Canada and internationally. The best application of these technologies requires reliable, quality data obtained through appropriate sampling and analysis techniques. This volume reviews sample collection and analysis methods that were assessed/used by MEND and others as part of their studies into the prediction, prevention and control, and treatment of acidic drainage.

This volume is intended to serve as a general reference to readers with regards to the methods that are used to collect samples for acidic drainage related study purposes. Given the complexities inherent in collecting samples for scientific analyses under diverse conditions, this volume cannot specifically indicate all of the aspects that need to be considered when collecting a sample. However, to assist readers in their sampling activities, this volume provides general guidance by identifying available sampling methods and discussing selected, relevant sampling issues. To further assist readers Volume 6.0 – Monitoring addresses the development of acidic drainage and environmental monitoring strategies. Properly designed monitoring programs assist mine personnel in understanding the state of the acid generation process and its effects (if any), as well as the effectiveness of measures used to prevent or control acidic generation.

While the collection and analysis of samples was not a primary focus of MEND, it did make important contributions in this area. Relevant MEND projects have involved the sampling and analysis of tailings, ore and waste rock, pore waters and gases, treatment sludges, sediments, surface and ground water, and fish and benthic organisms. The numerous sampling methods employed in MEND projects include: 1) methods that are widely accepted and used in other fields; 2) modified sampling methods; 3) new methods that are better suited for the collection of samples for acidic drainage related investigations; and 4) quality assurance/quality control measures.

Data requirements for acidic drainage studies range from regional geology and mineralogy through local meteorology to water quality and effects on the receiving environment. Mine site staff typically develop site-specific electronic databases to enable them to statistically analyse the environmental data, characterize effects (e.g. seasonal effects), and identify data trends.

Sampling related documents available from MEND and the BC AMD Task Force are listed in Table 2.1-1.

**Table 2.1-1
Sampling Projects Completed by MEND and the BC AMD Task Force**

MEND Project	Title
4.1.1	Field Sampling Manual for Reactive Sulphide Tailings
4.5.1-1	Review of Waste Rock Sampling Techniques
4.5.1-2	Handbook for Waste Rock Sampling Techniques
4.5.2*	Field Quality Assurance/Quality Control (QA/QC) Protocols for Monitoring and Predicting Impacts of Acid Rock Drainage
4.5.4	Guideline Document for Monitoring Acid Mine Drainage Appendix A – Technical Summary Notes
4.6.1	Applications of Geophysical Methods for Monitoring Acid Mine Drainage
4.6.2**	Continuous Monitoring of AMD – Literature Review
4.6.3	Application of Remote Sensing and Geophysics to the Detection and Monitoring of Acid Mine Drainage
4.6.4**	Piezocene Technology – Demonstration Project
4.6.5a,c	A Survey of <i>In Situ</i> Oxygen Consumption Rates on Sulphide Tailings: Investigations on Exposed and Covered Tailings
4.6.5b	A Rapid Kinetic Technique for Measuring Reactivity on Sulphide Waste Rock: The Oxygen Consumption Method
4.7.1*	Monitoring Acid Mine Drainage
4.7.2*	Literature Review for Biological Monitoring of Heavy Metals in Aquatic Environments
4.8.2	Evaluation of an Underwater Monitoring Probe for Locating and Estimating the Impact of Groundwater Discharges to Surface Waters Adjacent to Potential Sources of Acid Mine Drainage
MA-1	Environmental Monitoring of Uranium Mining Wastes Using Geophysical Techniques Phase 1 – A Comparison and Evaluation of Conductivity and Resistivity Methods to Monitor Acid Mine Drainage from Uranium Waste Rock Piles and Tailings Areas

* BC AMD Task Force Report.

** Open file report

The balance of this volume is organized as follows:

- Section 2.2, Water Sampling, deals with surface water flow and chemistry, and groundwater flow and chemistry;
- Section 2.3, Solids, studies tailings, waste rock, mine surfaces, treatment sludge, and drainage sediments sampling;
- Section 2.4, Biological Sampling, examines benthic invertebrates, fish, periphyton, and plankton sampling;
- Section 2.5, deals with Geophysics and Remote Sensing; and
- Section 2.6, Chemical Analysis, looks at chemical analysis of water samples, chemical analysis of solids samples, and quality assurance and quality control.

2.2 WATER SAMPLING

This section addresses the collection of water samples and the measurement of water flow rates.

Water quality data obtained from the analysis of water samples are used to monitor and assess changes in the quality of drainage (i.e. seepage, runoff, streamflow) from a source. The values of water quality parameters (i.e. pH, metals, acidity) can be interpreted based on an understanding of acid generation theory and used to assess the state of the acid generation process at the source. As examples, these data could be applied to monitor: for the initial signs of acidic drainage from a source that is potentially acid generating; or the quality of water from a decommissioned mine waste management area to demonstrate that the measures taken to prevent or control acidic drainage have and continue to be effective.

It is important to understand the water balance of an acidic drainage source. Water inputs to a source include, but are not limited to, precipitation, snowmelt and runoff from adjacent surfaces. Water losses typically include evaporation, transpiration, losses to surface water drainage courses and water bodies, and losses to the groundwater. The local meteorology needs to be taken into consideration when determining the water balance as water inputs and losses are subject to seasonal effects.

2.2.1 SURFACE WATER

2.2.1.1 Surface Water Flow Measurement (Hydrology)

I. Discussion of Theory

Measurements of surface water flow to/from a source are used to determine water balances and calculate contaminant loadings.

II. Discussion of MEND Research

MEND 4.5.1-2, *Handbook for Waste Rock Sampling Techniques*, reviews the monitoring of surface water flows around waste rock piles. The report indicates that instantaneous flow measurements in a stream/channel should be conducted at a location that has the best cross-section for measurement. When procedures are followed by experienced technicians, the flow measurements can have an accuracy within five percent of the true value 95% of the time. Continuous stage (water level) measurements can be converted to streamflow using a stage-discharge curve. The accuracy of streamflow data depends on the accuracy and stability of the stage-discharge relationship at the measurement location and the frequency of discharge measurements. About ten stage/discharge measurements are typically required to establish a stage-discharge curve.

III. Applications and Limitations

Manual flow monitoring has the advantage that it is less likely to fail in comparison to automated sampling. The disadvantage is that measurements are obtained less frequently in comparison to electronic monitoring devices.

IV. Base Method

The most common method to monitor surface water flow is to use a water depth-flow rate rating curve which correlates the depth of flow to the flow rate based on measurements of both water depth and flow over a range of flows at the location of interest. The flow is estimated for the rating curve using a current velocity meter and measurements of the cross-sectional area of the stream. The location of a flow measurement station needs to be selected to avoid backwater effects or other conditions that can induce errors. Once a rating curve is developed, only water depth is required for flow measurement. Water depths are commonly measured manually using a staff gauge.

V. Variations

A V-notch weir may be used to translate the depth of moving water to a flow rate without the need for developing a rating curve. For continuous flow measurements, float, pressure or electronic depth measuring devices can be connected to automatic recorders.

Solar power cell panels or small water-powered generators have been used at a few remote sites to provide power to sampling and monitoring equipment.

VI. Cost

Installation costs for a V-notch weir range from \$200 to \$2,000. The cost of electronic flow meters range upwards from \$2,000.

2.2.1.2 Surface Water Chemistry

I. Discussion of Theory

Surface water is sampled to assess water quality parameters, and to provide data required for contaminant loading calculations. Water released to the receiving environment may also be sampled for toxicity testing purposes.

II. Discussion of MEND Research

Acceptable concentrations of contaminants are specified in surface water protection legislation and mine permits and licenses. These limits are scientifically-based and intended to protect aquatic life in the receiving environment, and downstream water use.

MEND 4.5.4, *Guideline Document for Monitoring Acid Mine Drainage*, serves as a single source introductory guide for a range of acidic drainage monitoring concerns. The report is structured to provide a guide for the design and implementation of monitoring programs from the perspective of the development of a new mine. The recognition of acidic drainage potential and the integration of acidic drainage monitoring as part of an overall environmental monitoring program during the pre-operational phase can minimize acidic drainage effects and optimize sampling and cost-efficiency. MEND 4.5.4 succinctly reviews surface water sampling methods. The BC AMD Task Force, *Field Quality Assurance/Quality Control (QA/QC) Protocols for Monitoring and Predicting Impacts of Acid Rock Drainage* (1992), reports on the selection of sampling sites, sample replication and frequency, technician training, sample collection, and sample preservation.

III. Applications and Limitations

Surface water quality samples are collected using grab and composite samples, with grab samples most commonly used. The advantage of manually collected grab and composite samples is that field analysis can be done immediately. For programmable samplers, a delay between the collection of a sample and analysis can affect results.

Seepage may be naturally diluted by surface runoff or wash-through flow associated with precipitation events. Therefore, recording the location, time and rainfall prior to, and during, sampling is also important for seepage sampling.

IV. Base Method

Samples should be collected as follows:

1. Use of sample bottles, or containers specifically assigned for the collection and transfer of samples to the sample bottles. The bottles, containers, and caps must be clean and free from contaminants including dust. Sample collection containers and sample bottles should be field flushed whenever possible at least three times using the surface water that is to be sampled;
2. Appropriate sample containers, preservation methods and storage times should meet acceptable protocols, as listed in Table 2.2-1. Polyethylene bottles are acceptable for most acidic drainage water quality parameters;
3. Sample bottles should be well labelled and indicate the sample location, the time of sampling, the name of the sampler, and the required analyses. Field notes should be made in a field book and include the information recorded on the sample bottle labels, as well as a description of the sampling location. If possible, a sketch of the site could be included so that the site can be identified with certainty in the future should the need arise. Other information such as visual observations, weather conditions, air and water temperature, and field instrument measurements (i.e. electrical conductance, dissolved

- oxygen, pH, water temperature) should be recorded neatly and legibly. Information such as duplicate samples, trip blanks, field blanks, should be clearly noted in the field book;
4. Samples should be identified using a coding system. Coding systems can be quite useful in later identifying the location of the sample, the month and year of the sample, and other information. Codes can also facilitate later sorting and assessment of the data. The use of codes also avoids the problem of having data from many samples referred to, as an example, "No. 1";
 5. Samples should be taken from the middle of the flow stream if possible, and at mid-depth. Care must be used to collect a fresh sample and not stir up sediments and introduce contaminants into the sample collection area. As such, people standing in a stream should stand downstream of the sampling station and minimize disturbance to the water to be sampled; and
 6. Surface water samples are not filtered when the total concentration (dissolved and suspended components) is of interest.

Water samples can be collected from a water column using discrete samplers such as Van Dorn, and Kemmerer samplers or pumps. If a pump is used, a peristaltic pump is preferable as they are less vulnerable to contamination. Composite samples can be obtained from a water column using a depth integrating sampler. MEND 4.5.4 notes that the analysis of composite samples should be carefully reconsidered in light of the loss of information relating to variable water chemistry due to water column stratification.

Laboratory analyses for common water quality parameters are fairly standard, however limits of detection need to be specified to ensure that the data can be compared to allowable limits or established water quality objectives. As an example, if the measured concentration of copper is to be compared to a water quality objective of 0.005 mg/L, the limits of detection need to be 0.005 mg/L or lower.

Laboratory analyses of water samples commonly involve the following parameters:

- pH;
- Major ions including sulphate;
- Conductivity;
- Acidity;
- Alkalinity;
- Total dissolved solids (TDS);
- Total suspended solids (TSS);
- Elemental scan of metals; and
- Eh, Redox potential

Table 2.2-1
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	X	Unpreserved	7 days
TSS		X	X	Unpreserved	7 days
Acidity		X	X	Unpreserved	24 hours
Alkalinity		X	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	X	Unpreserved	7 days
Sulphate		X	X	Unpreserved	7 days
Nitrate		X	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 ₂ SO ₄ +K ₂ Cr ₂ O ₇	1 month
Uranium		X	X	HNO ₃	6 months
Radionuclides ⁽²⁾		X	X	HCR 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.

Source: Modified from MEND 4.5.1-1, Table 2.2.3

Electrical conductance, pH, temperature and dissolved oxygen should be measured in the field and measured again in the laboratory to detect possible changes during sample transport and handling. Electrical conductance can also be monitored continuously and used to detect changes in water quality (MEND 1.14.3e).

Samples have a limited life span and as such, analytical analyses need to be completed within allowable times from sample collection. Immediately upon collection, samples should be placed in a cooler (ideally at 4°C) for transportation and storage. Samples should be shipped to the analytical laboratory as soon as possible. Samples should be preserved as indicated in Table 2.2-1.

Samples for dissolved metals should be filtered using a 0.45 µm acid-rinsed filter prior to preservation. Field filtration is preferable to filtration in the laboratory due to possible changes during transport and handling.

V. Variations

Conventional surface water quality data is not likely to represent trace metal biological availability. In many cases, the availability of trace metals to aquatic organisms is significantly different from the measured total or dissolved metal concentration. A recently developed gel-sampler described by McNee and Martin (1999a,b) addresses this issue by accumulating biologically-available metals (i.e. the fraction of metal that is both dissolved and uncomplexed) onto an ion-specific resin. The ion-specific nature of the resin is beneficial as particulate and strongly-complexed metals, which are in forms that may be non-toxic to biota, are not accumulated. McNee and Martin (1999a,b) report that the gel-sampler involves the use of a polyacrylamide gel layer to quantitatively control metal transfer from the surrounding water to a trace-metal absorbing, gel-embedded resin. Advantages of the gel-sampler include:

- Direct measurement of trace metals;
- Preservation and direct determination of metal speciation; and
- Elimination of contamination during sampling.

Numerous technical studies have demonstrated that placing fresh sulphide-rich tailings under water mitigates acid drainage generation. Adverse impacts to water quality may occur if the wastes are not kept underwater, but are instead subjected to regular cycles where they become exposed and then resubmerged. As part of a study to assess the importance of maintaining a water cover over sulphide mine wastes, Pedersen *et al.* (1999) investigated the release of copper and zinc from contaminated shallow sediments in Lago Junin located in the Peruvian altiplano. The researchers assessed the post-placement cycling of lake sediment metals and nutrients and their exchange in the overlying water column through high resolution sampling of the lake bottom water and the sediment pore water using dialysis arrays (peepers) and sediment cores.

The samplers were deoxygenated prior to use to avoid oxidation artifacts. The peepers were positioned by a diver and the deionized, distilled water in the peeper cells was allowed to reach diffusive equilibrium with the pore water and lake bottom water over 14 days. Upon retrieval:

- The pore waters were subsampled in a nitrogen environment for determination of dissolved metals, sulphate and hydrogen sulphide;
- The metals samples were preserved by acidification to pH 2 using nitric acid; and
- The sulphate samples were frozen and samples to be analyzed for hydrogen sulphide were fixed using 2 M Zn-acetate.

Pedersen *et al.* (1999) describes the analytical methods used, and Pedersen *et al.* (1993) explains the techniques used to core and extrude the lake bottom sediments and collect pore water.

Drainage does not have to be acidic to be a concern. Depending upon the characteristics of the mine waste, there may also be a need to sample neutral mine drainage. Neutral mine drainage has a neutral range pH and contains elevated concentrations of sulphate and other contaminants released from sulphide oxidation and neutralization processes. Examples of neutral mine drainage are shown in Table 2.2-2.

Table 2.2-2
Examples of Neutral Mine Drainage

	Waste Rock Uranium Ronneburg Germany	Waste Rock Uranium Aue Germany	Waste Rock Gold Kyrgyzstan	Large Coal Discard Dump South Africa	Small Coal Slurry & Discard Dump South Africa
Location	Dump Seepage (mean) (1989-95)	Dump Seepage (mean) (1993-96)	Intermittent Seepage (July-Aug, 1998)	Collection Ditches (1997)	Collection Ditches (1998)
pH	7.51	7.65	7.3 to 8.0	7.9 to 8.6	7.1 to 8.4
Sulphate	26,208	3,714	2,510 to 3,581	146 to 7,720	4,510 to 6,140
Iron	0.56	0.69	0.19 to 4.74	0.1 to 2.5	0.12 to 39.8
Calcium	377	321	124 to 314	51 to 474	332 to 490
Magnesium	6947	634	140 to 752	20 to 471	243 to 362
Aluminum	0.63	0.84	0.04 to 0.82	0.2 to 3	0.1
Nickel	0.707	0.038	0.07 to 0.31	0.05	0.01
Manganese	15.95	0.06	1.14 to 4.02	0.05 to 0.64	0.36 to 13.9
Zinc	0.225	0.06	0.001 to 0.008	0.04	0.01 to 0.04

Source: Modified from Pettit *et al.* (1999)

Water sampling in the receiving environment is required to meet both regulatory monitoring requirements and environmental monitoring programs established by mine operators. Downstream sampling is likely to include the collection of surface water, sediment and benthic samples, and other water samples for acute toxicity tests. These activities are largely focussed

on providing data to demonstrate that fish, fish habitat and other water uses in the downstream receiving environment are protected.

Papineau *et al.* (1999) reports that the Aquatic Effects Technology Evaluation (AETE) Program (1994-1998) evaluated methods to assess the impacts of mine effluent on receiving waters. AETE 4.1.4, *AETE Program Synthesis Report*, addresses the following four guidance questions: 1) Are contaminants getting into the system? 2) Are contaminants bioavailable? 3) Is there a measurable biological response? and 4) Are the contaminants in the system causing the observed response? Recommended methods, or tools, suitable for use in providing answers to these questions are summarized in Table 2.2-3. AETE 4.1.4 and Papineau *et al.* (1999) note that while the results of the AETE program identify a suite of reliable tools and methods that should be suitable for use in a routine monitoring program, other tools not recommended by AETE may be appropriate for more detailed site-specific applications.

VI. Cost

The cost to collect a surface water sample is highly variable and dependant upon the time required to access the sampling station and collect the sample.

Table 2.2-3
Summary of Suitable Routine Monitoring Tools Recommended by the AETE Program

Question	Toolbox	Tool	Recommendation ¹	
Are contaminants getting into the system?	Effluent chemistry	Chemical parameters	Yes	
		Effluent acute toxicity	<i>Daphnia</i> IQ test	No
		Microtox acute test	No	
		Rototoxki F test	No	
		Thamnotoxkit F	No	
		Toxichromotest	No	
		Rainbow trout	Yes	
		<i>Daphnia magna</i>	Yes	
	Water chemistry	Total metal concentrations	Yes	
		Dissolved metal concentrations	No*	
	Sediment chemistry	Substrate mapping	Surface sediment collection	Yes
			Sediment cores	No*
		Total metal concentrations	Partial metal concentrations	No
			Pore water	No*
Are contaminants bioavailable?		Aquatic plants	Metal concentrations	No
			Molluscs	Tissue metal concentrations
	Fish tissues	Organ tissue metal levels	Yes	
		Tissue metallothionein levels	No	

Table 2.2-3 (Cont'd)
Summary of Suitable Routine Monitoring Tools Recommended by the AETE Program

Question	Toolbox	Tool	Recommendation ¹	
Is there a measurable response?	Effluent sublethal toxicity	Fathead minnow	Yes	
		<i>Ceriodaphnia dubia</i>	Yes	
		<i>Selenastrum capricornutum</i>	Yes	
		<i>Lemna minor</i>	Yes	
		Algae multi-species test	No	
		Microtox chronic	No	
		Mutotox chronic	No	
		Nematode survival	No	
		Rainbow trout embryo	No	
		Sediment toxicity	<i>Chironomus riparius</i>	Yes
	<i>Hyalella azteca</i>		Yes	
	<i>Tubifex tubifex</i>		No*	
	Microtox solid phase		No	
	Aquatic plants	Phytoplankton community structure	No	
		Periphyton community structure	No	
		Macrophyte community structure	No	
		Biochemical indicators	No	
		Benthic invertebrates	Mollusc growth	No
			Fitness parameters	No
			Community composition	Yes
Fish survey	Artificial substrates	No		
	Rapid assessment procedures	No		
	Biochemical indicators	No		
	Histopathology	No		
	Fish organ size	Yes		
	Fish growth	Yes		
	Abundance indicators	Yes		
	Community indicators	No*		
Are contaminants causing this response?	Pairwise comparisons of the above toolboxes	Toxicity versus biology correlations	Yes+	
		Toxicity versus biology	Yes+	
		Chemistry versus toxicity	Yes+	

Notes: Yes = recommended as a suitable tool for routine monitoring.
 No = not recommended as a suitable tool for routine monitoring.
 No* = not recommended for routine monitoring but may have application in more detailed site-specific investigations.
 Yes+ = the concept of pairwise comparisons and Sediment Quality Triad is supported by AETE where the necessary data are available and adequate, but they are not considered monitoring tools.

Source: Modified from Papineau *et al.* (1999)

VII. MEND and Relevant Publications

- MEND 1.14.2b 1997. Sampling and Monitoring Data from the Mine Doyon South Waste Rock Dump (1990 to 1995). September.
- MEND 1.14.3e 1996. Peer Review of MEND Studies Conducted from 1990 to 1994 on Acid Mine Drainage at Mine Doyon South Waste Rock Dump. November.
- MEND 2.11.1c 1992. Chemical Diagenesis of Submerged Mine Tailings in Benson Lake and Natural Sediments in Keogh Lake, Vancouver Island, British Columbia. June.
- MEND 4.5.1-1 1994. Review of Waste Rock Sampling Techniques. June.
- MEND 4.5.1-2 1994. Handbook for Waste Rock Sampling Techniques. June.
- MEND 4.5.4 1997. Guideline Document for Monitoring Acid Mine Drainage. Appendix A – Technical Summary Notes. October.
- AETE 4.1.4 1999. AETE Program Synthesis Report of Selected Technologies for Cost-Effective Environmental Monitoring of Mine Effluent Impacts in Canada. March.
- BC AMD Task Force 1992. Field QA/QC Protocols for Monitoring and Predicting Impacts of Acid Mine Drainage.
- McNee, J.J. and Martin, A.J. 1999a. *The Measurement of Biologically-Available Metals – A New Approach.* In: Proceedings of the 6th International Conference on Tailings and Mine Waste '99. Fort Collins, CO. 24 to 27 January. pp. 639-646.
- McNee, J.J. and Martin, A.J. 1999b. *The Measurement of Biologically-Available Metals in Aquatic Systems – A New Approach.* In: Sudbury '99 – Mining and the Environment II Conference Proceedings. Sudbury, Ontario. 13 to 17 September. Vol 3, pp. 1217-1224.
- Papineau, J., Campbell, D., Trudel, L., Wren, C. and Béchar, G. 1999. *Synthesis of Selected Technologies for Cost-Effective Environmental Monitoring of Mine Effluent Impacts in Canada.* In: Sudbury '99 – Mining and the Environment II Conference Proceedings. Sudbury, Ontario. 13 to 17 September. Vol 3, pp. 951-959.

Pedersen, T.F., Martin, A.J. and McNee, J.J. 1999. *Contrasting Trace Metal Dynamics in Contaminated Lago Junin, Peru and Submerged Tailings Deposits in Canadian Lakes: The Importance of Permanent Submergence*. In: Sudbury '99 – Mining and the Environment II Conference Proceedings. Sudbury, Ontario. 13 to 17 September. Vol 1, pp. 165-176.

Pedersen, T.F., Mueller, B., McNee, J.J. and Pelletier, C.A. 1993. *The Early Diagenesis of Submerged Sulphide-Rich Mine Tailings in Andersen Lake, Manitoba*. Canadian Journal of Earth Sciences. Vol 30, pp. 1099-1109.

Pettit, C.M., Scharer, J.M., Chambers, D.B., Halbert, B.E., Kirkaldy, J.L. and Bolduc, L. 1999. *Neutral Mine Drainage*. In: Sudbury '99 – Mining and the Environment II Conference Proceedings. Sudbury, Ontario. 13 to 17 September. Vol 2, pp. 829-838.

2.2.2 GROUNDWATER

2.2.2.1 Hydrogeology

I. Discussion of Theory

There is a need to obtain an understanding of groundwater flow and quality as groundwater represents a potential pathway for the transfer of acidic drainage contaminants to the receiving environment.

Techniques for groundwater sampling and flow modelling are well developed. In-depth studies in these areas tend to be complex and are likely to be carried out by hydrogeologists and other specialists. Readers interested in learning more about hydrogeology can refer to Freeze and Cherry (1979).

II. Discussion of MEND Research

Groundwater flow estimation is an area where a considerable body of knowledge and established methods existed prior to MEND. Standard methods were used in MEND projects where groundwater flow was measured.

III. Applications and Limitations

The migration of leachate from mine wastes can be a concern particularly when leachate constituents may migrate to surface waters. Groundwater discharges to surface waters occur naturally in many geologic settings through submerged joints, fractures, and bottom sediments. The zone of groundwater discharge can be identified using recently developed techniques, and the contaminant flux can be measured.

An aquifer's hydraulic conductivity can be determined by a variety of techniques including empirical methods, *in situ* slug tests, and *in situ* pumping tests. Empirical methods from grain size are only approximations and should only be used for materials with low silt or clay content. Slug tests are relatively inexpensive but may not characterize bulk conditions. Pumping tests are more costly but are better for estimating average conditions in an aquifer.

Hydraulic conductivities derived from pumping tests may not be applicable over large areas due to geologic variability.

IV. Base Method

MEND 4.5.4 succinctly addresses the measurement of groundwater flows, and the measurement of groundwater contaminant seepage to surface waters. Selected aspects are reiterated below.

Groundwater flow velocity is calculated using differences in water level elevations from a network of monitoring wells (piezometers) and permeability data. Mini-piezometers were used in a test program to track tracers in groundwater movement in thickened tailings (MEND 2.23.2c).

Tracer studies can be applied to determine flow rates, dispersion and some physico-chemical characteristics of the surrounding formations. The advantages and drawbacks of tracer studies, which involve the injection of a dye/salt in a well and the timing of its arrival at downgradient monitoring well(s), are listed in Table 2.2-4.

**Table 2.2-4
Advantages and Disadvantages of Tracer Studies**

Tracers	Advantages	Disadvantages
<u>Dyes:</u> Uranine, Rhodamine B, Suforhodamine G Extra	Easy to use and safe. Concentrations may be measured in the field.	Dyes may be affected by pH, temperature or absorbed by clays and organic soils.
<u>Strong Electrolytes:</u> Sodium Chloride Potassium Chloride Ammonium Chloride Lithium Chloride	May be measured in the field or laboratory using electrical conductivity or resistivity. Lower concentrations may be measured by atomic absorption spectroscopy.	Requires large amounts of salts if ordinary analytical methods are used.
<u>Radioactive Isotopes:</u> Tritiated Water Iodine Ion Others	May be used in small quantities that have no effect on the physical or chemical properties of the water. Concentrations easily measured by sophisticated equipment.	May pose some radiation hazard (except for tritiated water). Requires expensive detection equipment.
<u>Detergents:</u> Alkylbenzol-sulphonates	Easy to use and safe.	May be confused with sewage related detergents. Disperses aggregated soils thereby changing permeabilities.

Source: MEND 4.5.4

A zone where contaminated groundwater discharges to a stream can be identified by bracketing the suspected point of seepage with upstream and downstream stations and analyzing the water samples for contaminant markers (e.g. conductivity). A zone of groundwater seepage into a river or lake can be identified using either a seepage meter or an electrical conductance bottom contacting probe.

A seepage meter can be used to measure the rate of groundwater discharge, and to collect a sample of the groundwater discharge. Seepage meters consist of a collection chamber that is open at one end and a sample hole/port at the other end. To collect a sample, the open end of the sampler is pushed into the sediments and left in place until the groundwater discharge flushes the chamber. A clean collapsed sample bag is then attached to the sample port and filled with groundwater.

An electrical conductance bottom-contacting probe (commonly known as the sediment probe) is towed by a small boat and dragged along river or lake bottom in areas where groundwater discharge is suspected. Instrumentation in the probe can measure pH, conductivity and radiation. The data is continuously recorded using a recorder located in the boat, and the boat position is identified using a shore-based electronic survey instrument. The probe has been shown to be a practical reconnaissance method for locating contaminated groundwater discharges to larger surface water bodies.

MEND 4.8.2 evaluated the use of the sediment probe over 21 line-kilometres of lake and river bottom near mine properties in Timmins and Sudbury, Ontario. The sediment-probe method was applied to locate eight areas of leachate discharge. Some targets were confirmed by measuring the conductivity of pore water 20 to 120 cm below the water/sediment interface. Other targets were confirmed using seepage meters to obtain direct measurements of contaminant flux, or through measurements of the upward gradient, hydraulic conductivity and the solute chemistry.

V. Variations

The hydrogeologic conditions within tailings deposits and waste rock dumps can be assessed using hydrological techniques.

MEND 2.23.2ab, also Woyshner and St-Arnaud (1994), describe their investigative methodology for hydrogeological and hydrometeorological monitoring, and their findings regarding the hydrogeology and water balance of the Kidd Metallurgical Division's thickened tailings deposit in Timmins, Ontario. The field program included a hydrometeorological monitoring station, piezometers and measurements of moisture content, hydraulic head and hydraulic conductivity. The hydraulic gradients indicated that the pore water in the saturated zone tends to migrate longitudinally with a low average linear velocity of 12 cm/yr. At the top of the thickened tailings mound, the capillary zone (e.g. top of the vadose zone) was observed to be less than a metre

from the tailings surface. From the perspective of closure planning, these hydrogeological conditions are beneficial because only the near-surface, unsaturated and uncovered layer of tailings are available for oxidation.

Newman *et al.* (1997) describe the results of a multi-phase research program which consisted of field and laboratory investigations to characterize waste rock followed by a column study and numerical modelling to investigate possible mechanisms for preferential flow in unsaturated, layered conditions. The results show that in unsaturated layered systems such as waste rock piles, water may be transported preferentially through the fine-grained wastes rather than through the coarse-grained waste layers as often presumed.

VI. Cost

The cost of measurement of water levels in wells is mainly comprised of labour, which will vary widely depending on well site accessibility. For hydraulic conductivity testing, a rough estimate of slug pumping testing costs is \$200 per borehole - excluding the cost of the borehole. Difficult site access or low hydraulic conductivities increase costs.

VII. MEND and Relevant Publications

- MEND 2.23.2ab 1993. Hydrologic and Hydrogeologic Evaluation of the Thickened Tailings Disposal System at Kidd Creek Division, Falconbridge Limited. October.
- MEND 2.23.2c 2000. The Verification of Modelled Pore Water Movement Within Thickened Tailings Using Tracers at the Falconbridge Limited Kidd Metallurgical Division, Timmins, Ontario. May.
- MEND 4.5.4 1997. Guideline Document for Monitoring Acid Mine Drainage. October.
- MEND 4.8.2 1994. Evaluation of an Underwater Monitoring Probe for Locating and Estimating the Impact of Groundwater Discharges to Surface Waters Adjacent to Potential Sources of Acid Mine Drainage. March.

Freeze, R.H. and Cherry, J.A. 1979. Groundwater. Prentice-Hall Inc.

Newman, L.L., Herasymuik, G.M., Barbour, S.L., Fredlund, D.G. and Smith, T. 1997. *The Hydrogeology of Waste Rock Dumps and a Mechanism for Unsaturated Preferential Flow*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 2, pp. 551-565.

Woyshner, M.R. and St-Arnaud, L.C. 1994. *Hydrogeological Evaluation and Water Balance of a Thickened Tailings Deposit Near Timmins, Ontario, Canada*. In: Proceedings of the International Land Reclamation and Mine Drainage Conference and the 3rd International Conference on the Abatement of Acidic Drainage. Pittsburgh, PA. 24 to 29 April. Vol 2, pp. 198-207.

2.2.2.2 Chemistry

I. Discussion of Theory

Groundwater sampling provides data regarding the quality and migration of contaminants. This type of information is typically obtained at mine waste management areas.

II. Discussion of MEND Research

Groundwater sample collection methods were identified as part of MEND 4.5.1-1 and 4.5.1-2. Methods for the collection of groundwater samples from saturated and unsaturated zones are summarized in Table 2.2-5.

III. Applications and Limitations

Subsurface water within tailings and in waste rock piles can be subdivided into the zone of saturation (or groundwater) and the overlying vadose zone. The sampling of the groundwater and vadose zone pore water within mine waste deposits is complicated by the likelihood that they are not in equilibrium, *in situ*, with the atmosphere. As such, geochemical composition can be altered (i.e. pH change, precipitate formation) with exposure to atmospheric oxygen when samples are retrieved to surface. Common sampling techniques include the sampling of wetted waste rock, gravity lysimeters, tailings core squeezing, and the use of pore water suction samplers.

When contaminants migrate through the groundwater regime, some contaminants can be conservative (e.g. travel at the same rate as the groundwater) while the migration of other contaminants can be retarded. This needs to be considered in the selection of sampling locations, and in the review of sampling results.

IV. Base Method

Groundwaters from the saturated zone within a tailings area and from upgradient and downgradient areas are sampled from piezometers or monitoring wells using a wide variety of bailers, suction-lift pumps, submersible pumps, and other devices. The sampling methods and their applications and limitations are described in Table 2.2-5.

**Table 2.2-5
Groundwater Sample Collection Methods**

Type	Application	Limitations
Saturated Zone		
1) Bailers	<ul style="list-style-type: none"> Simple, inexpensive method for collection of samples 	<ul style="list-style-type: none"> Samples are highly disturbed and must be extensively handled during filtration Can be time consuming in small diameter wells
2) Depth-specific bailer	<ul style="list-style-type: none"> Simple, inexpensive method less disruptive than bailer 	<ul style="list-style-type: none"> Requires relatively large diameter wells
3) Syringe sampler	<ul style="list-style-type: none"> Allows collection of samples without exposure to the atmosphere and allows filtration down-the-hole Can collect samples from any depth 	<ul style="list-style-type: none"> Only small volumes of pore water are collected in each syringe Requires piezometers greater than 3 cm diameter
4) Suction-lift pumping	<ul style="list-style-type: none"> For collection of relatively large volumes of water from shallow depth Permits use of inline filters to reduce sample handling 	<ul style="list-style-type: none"> Sampling limited to water depths less than 8 m
5) Submersible pumps	<ul style="list-style-type: none"> For collection of large volume samples from depths greater than 8 m 	<ul style="list-style-type: none"> Requires relatively large diameter wells Costly
6) Air-lift	<ul style="list-style-type: none"> For collection of water samples from conventional wells or special air-lift samplers No limitation on depth of water 	<ul style="list-style-type: none"> Samples can be highly disturbed
7) Inertia pumping system (Waterra)	<ul style="list-style-type: none"> Low cost, unlimited depth, no power requirements, dedicated instalment (no cross-contamination), direct filtering capabilities 	
Unsaturated Zone		
8) Suction lysimeters	<ul style="list-style-type: none"> For collection of pore water samples from unsaturated tailings solids samples 	<ul style="list-style-type: none"> Reliable only in relatively coarse sandy materials
9) Core squeezing	<ul style="list-style-type: none"> For collection of pore water from tailings solids samples by squeezing or displacement 	<ul style="list-style-type: none"> Destructive sampling, monitoring at precisely the same location is not possible

Source: MEND 4.5.1-1, Table 2.2.4.

Pore water and groundwater are filtered to remove suspended solids. Groundwater samples should be filtered prior to preservation using a 0.45 µm filter. Groundwater filters should not be reused.

The electrical conductance, pH, water temperature and dissolved oxygen concentration of groundwater samples should be measured in the field. The laboratory analyses of groundwater samples commonly includes: pH, major ions including sulphate, acidity, alkalinity, total dissolved solids, total suspended solids, and elemental metal scan.

Samples have a limited life span and should be shipped to the analytical laboratory as soon as possible. Detection limits need to be specified, and protocols followed as discussed previously in Section 2.2.1.2, Surface Water Chemistry.

V. Variations

MEND 2.23.2d and Al *et al.* (1994) describe a study in which tailings pore water geochemical data were collected in the vadose and saturated zones at several locations in the Kidd thickened tailings impoundment in Timmins, Ontario. Their investigative methodology is instructive and the key aspects are reiterated below for reference by readers:

- Vadose zone pore water was sampled by collecting cores in thin-walled aluminum casings. Pore water was squeezed from 20 to 25 cm long core lengths having a 7.62 cm diameter;
- Saturated zone pore water was collected using a peristaltic pump with polyethylene lines from polyethylene-lined stainless steel or PVC, single-completion drive-point piezometers installed between the water table and the base of the tailings. The piezometers were bailed dry prior to sampling;
- Vadose zone pore water pH, conductivity and Eh measurements were made at least three times during sampling. Saturated zone pore water pH and Eh measurements were made in a sealed flow-through cell that was maintained at the groundwater temperature; and
- Pore water samples were filtered through 0.45 μm cellulose acetate filters and split. One volume was acidified with 12 N analytical grade HCl to a pH of <1 for cation analysis. An unacidified volume was submitted for anion analysis. Samples were kept refrigerated until analyzed.

Contaminated groundwater can discharge to surface waters. MEND 4.8.2 evaluates a new method for locating and estimating the impact of contaminated groundwater discharges to surface waters. The method involves towing an electrical-conductance, bottom contacting probe (known as a sediment probe) behind a boat in areas of lakes and streams where it is suspected that acidic drainage impacted groundwater discharges to surface water. The method depends on two conditions: 1) the contaminant plume must differ from the surface water in electrical conductivity; and 2) the groundwater signature must be present in the sediment within centimetres of the receiving surface waters. This technique has been used to locate areas of leachate discharge which were then quantitatively characterized.

VI. Cost

The key components of the cost of groundwater sampling are labour and filters. The labour cost is dependent upon the time required to access the sampling locations, purge wells, and collect and ship the samples. The cost of a filter for field filtering of a groundwater sample is about \$50.

VII. MEND and Relevant Publications

- MEND 1.14.2b 1997. Sampling and Monitoring Data from the Mine Doyon South Waste Rock Dump (1990 to 1995). September.
- MEND 2.23.2d 1995. A Geochemical, Hydrogeological and Hydrological Study of the Tailings Impoundment at the Falconbridge Limited, Kidd Creek Division Metallurgical Site, Timmins, Ontario. October.
- MEND 4.5.1-1 1994. Review of Waste Rock Sampling Techniques. June.
- MEND 4.5.1-2 1994. Handbook for Waste Rock Sampling Techniques. June.
- MEND 4.8.2 1994. Evaluation of an Underwater Monitoring Probe for Locating and Estimating the Impact of Groundwater Discharges to Surface Waters Adjacent to Potential Sources of Acid Mine Drainage. March.

Al, T., Blowes, D.W., and Jambor J.L. 1994. *The Pore-Water Geochemistry of the Cu-Zn Mine Tailings at Kidd Creek, Near Timmins, Ontario, Canada*. In: Proceedings of the International Land Reclamation and Mine Drainage Conference and the 3rd International Conference on the Abatement of Acidic Drainage. Pittsburgh, PA. 24 to 29 April. Vol 2, pp. 208-217.

2.3 SOLIDS SAMPLING

2.3.1 TAILINGS

I. Discussion of Theory

Tailings are sampled for a variety of reasons, the main ones are to assess the potential for acidic drainage generation, and to investigate conditions *in situ*. The following subsections describe a range of techniques that are used to sample tailings solids, including submerged tailings, as well as pore water, pore gases, and measure tailings properties *in situ*. Some of the techniques can also be applied to assess conditions *in situ* after the completion of closure works (e.g. after the construction of a dry cover over tailings).

Tailings sampling can present a number of challenges with regards to:

- Safe access for people and equipment over tailings surfaces;
- Obtaining representative and undisturbed samples including samples collected at depth;
- Interpreting data - this highlights the need to use acceptable sampling techniques; and
- Obtaining data at a reasonable cost.

Tailings are crushed rock particles - a waste by-product from the comminution of ore. Conventional unthickened tailings typically have a grain-size distribution that ranges from medium sand to clay sized particles, with 70 to 90% of the tailings solids measuring less than 74 μm (200 mesh) in size. During conventional tailings placement, beach type deposits are formed as the particles are hydraulically separated by grain size, density and shape. In contrast, thickened tailings (e.g. tailings thickened to ≥ 50 wt% prior to discharge) do not segregate but remain homogeneous when placed (MEND 2.23.2c).

The geochemical conditions within sulphide tailings may change with time depending upon the tailings characteristics and the tailings disposal strategy used. The following aspects need to be considered when selecting sampling and analytical techniques, and evaluating results:

- When tailings are initially deposited, the pore water quality would be expected to be that of the mill water used to hydraulically transport the tailings. Tailings deposited subaerially and exposed to the atmosphere may generate acid prior to closure depending on the reactivity of the tailings. The oxidation of fresh tailings placed under a water cover would be expected to be inhibited;
- Should it occur, the oxidation of exposed tailings will produce free and metal acidity by-products that may be buffered *in situ* by available alkalinity in pore water and carbonate minerals present in the tailings. Oxidation is likely to occur at the exposed tailings surface,

with oxidation by-products migrating laterally and vertically through pore water movement. This effect has been observed at historic tailings sites where sulphides in the near surface layer of exposed tailings have oxidized over a period of decades, while tailings at depth remain unoxidized. At these sites, pore water quality at depth is often impacted as a consequence of the downward migration of contaminants (i.e. dissolved metals, free acidity) in pore water; and

- The oxidation of sulphide tailings capped using an engineered dry cover would be expected to be effectively controlled to very low levels over the long term.

II. Discussion of MEND Research

MEND projects have included the preparation of a field sampling manual for tailings, and a range of technical studies which involved the sampling and analysis of tailings solids, pore water, and pore gases. In addition, MEND projects have applied *in situ* monitoring techniques, typically used outside the mining sector, to characterize tailings. This included the use of tracers to verify the predicted movement of pore water in thickened tailings (MEND 2.23.2c).

The *Field Sampling Manual for Reactive Sulphide Tailings* (MEND 4.1.1) presents an approach that can be used to select appropriate methodologies for the sampling of tailings solids, liquids, and pore gases. The selection process uses classification index charts and a flowchart which are categorized on the basis of:

- The phase of the sample;
- Sample position relative to the water level;
- Equipment power requirements;
- Degree of required isolation from sources of contamination; and
- Acceptable degree of disturbance to the sample during its collection.

The above report includes technical descriptions of sampling equipment, listings of advantages and disadvantages, and comments on the suitability of the equipment for collecting samples for microbiological and geochemical analyses.

BC AMD Task Force (1992), Field QA/QC Protocols for Monitoring and Predicting Impacts of Acid Rock Drainage, discusses the sampling of tailings solids, and sampling design, sample size, and quality control aspects.

The influence of pore space saturation on inhibiting sulphide oxidation is reasonably well-understood. MEND 2.17.1 assessed the use of an elevated water table in tailings as an effective means of controlling acid generation.

MEND projects which include significant tailings sampling or *in situ* monitoring components are reviewed in the following subsections.

III. Applications and Limitations

Tailings are primarily sampled to provide materials for static and column tests and hence determine the acid generation potential. For proposed operations, tailings samples are obtained from pilot plants.

Obtaining a representative sample of tailings is challenging, and as such, a statistically-based number of tailings samples are typically collected. Sample site selection should account for particle segregation, and the possible concentration of sulphides in a particular grain size range. Factors that affect sulphide and buffering mineral distributions within an impoundment are largely site-specific. A sampling procedure should be well-developed prior to sampling, and a meaningful sampling strategy should:

1. Clearly establish the sampling objectives;
2. Select a sampling strategy that will meet the objective;
3. Follow the strategy and periodically review it;
4. Optimize the sampling program where practical; and
5. Periodically revisit and reassess the adequacy of the objectives.

Tailings submitted for acid/base accounting (ABA) or column testing are typically also characterized for their particle size distribution, mineralogy, density, moisture content and age.

As in all sampling programs, it is important to document the sampling program so that the location sampled can be identified with confidence at some later date, and the sample collection and analysis procedure can be reassessed should the need arise.

As an example, a collaborative project (MEND 2.12.1) assessed the effectiveness of subaqueous tailings disposal within test cells at the Louvicourt Mine located near Val d'Or, Québec. Several ARD characterization tests were completed using the prospective sulphidic tailings during the environmental permitting of the mine in the early 1990's. The material selection and sampling procedure is reiterated below.

1. Tailings Sampling

Fresh, unoxidized mill tailings were collected from the backfill circuit of the Louvicourt mill between May and June, 1995 (MEND 2.12.1e). Ten 35-gallon drums were filled in parallel over one month, with tailings taken from the circuit and added to each drum every week. The length

of the sampling period was chosen based on the observed variation in tailings composition and ensured that a representative sample of the total tailings was obtained.

A layer of process water was maintained over the tailings while filling the drums, during shipping and on receipt prior to column loading, to minimize oxidation of the fresh tailings. Additional process water, obtained from the mine, was used to slurry the tailings before placing them in the columns.

2. Tailings Analyses

Tailings from each of the 10 drums were allowed to settle for one month after receipt and then sampled using 2.5 cm (1 in) diameter cores to assess the degree of variability between barrels and to obtain a composite sample. Three cores were taken from each barrel and combined. The core samples were extruded using nitrogen and the composite samples dried at 70°C under inert conditions. The composite samples from each barrel were characterized for particle size distribution and chemical composition to assess the homogeneity of the tailings amongst barrels. Based on these results, the contents of the barrels were individually slurried and then loaded into the columns. The tailings are typical products of moderate milling, with the majority of the material in the silt to fine-sand size range.

The size distribution analysis indicates that on average greater than 50% by weight of the tailings are finer than 20 µm, while greater than 98% by weight are less than 150 µm (Figure 2.3-1).

The average analytical results from the 10 composite core samples for a selected number of analytes are given in Table 2.3-1. The tailings contain an average of 17.2% S (ranging between 16.0 - 19.4%) and 19.8% Fe (ranging between 17.2 - 20.8%) (MEND 2.12.1e). These values are consistent with those reported for four tailings samples obtained during the same month of sampling for humidity cell tests including; 15.8% S (ranging between 15.0 - 17.4%), 21.0% Fe (ranging between 20.1 - 22.5%), 0.11% Cu and 0.36% Zn (MEND 2.12.1d).

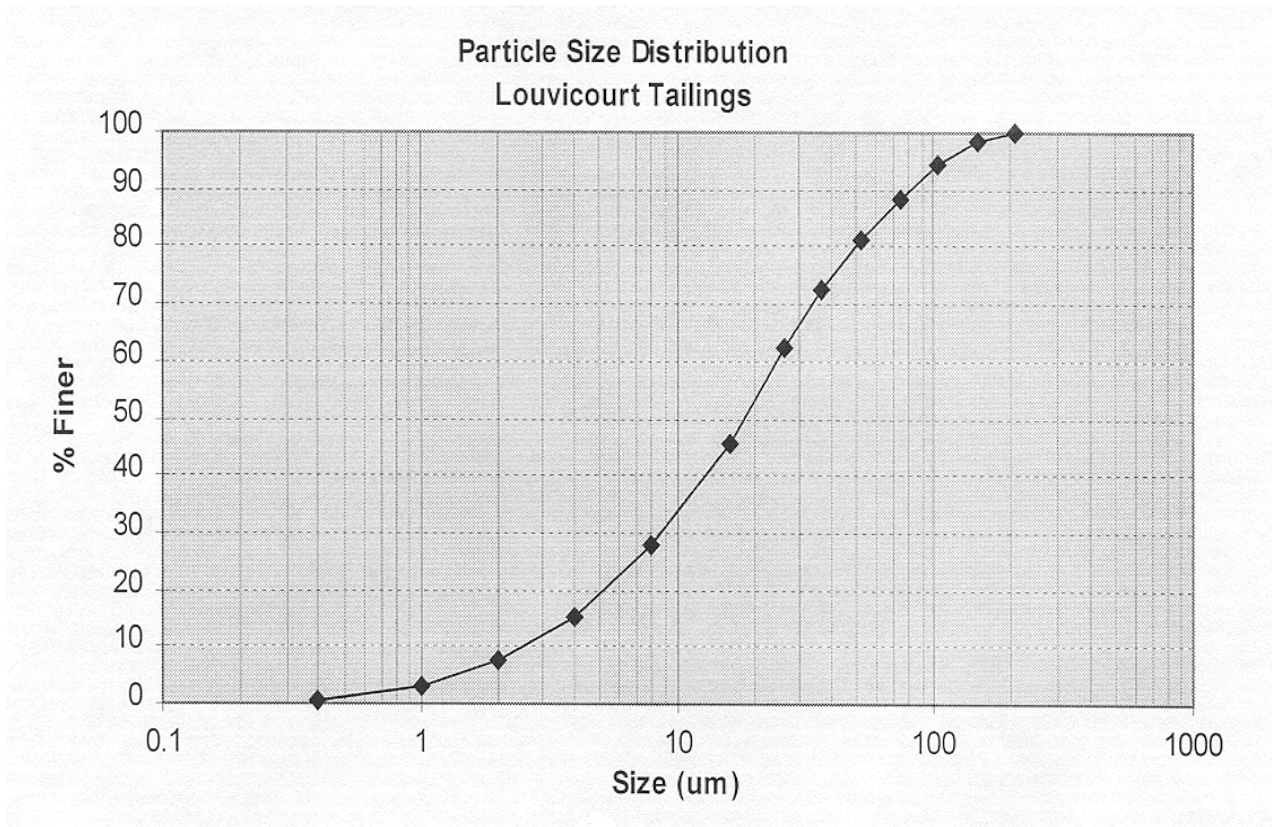
Table 2.3-1
Chemical Analysis of Louvicourt Tailings

Analyte	S	Fe	SO ₄	Al	As	Ca	Cu	Mg	Mn	Pb	Zn
% in Tails	17.2	19.8	0.68	3.8	0.064	1.6	0.092	2.4	0.17	0.065	0.33

Source: MEND 2.12.1e

Whole rock analysis and mineralogical characterization were carried out on fresh tailings samples representative of the two field test cells (MEND 2.12.1e). The samples were studied by a combination of scanning electron microscopy, X-ray micro analysis, image analysis and X-ray powder diffraction techniques. The tailings are fine grained and are characterized by high SiO₂

Figure 2.3-1 Average Particle Size Distribution of Louvicourt Tailings



Source: MEND 2.12.1e

(34 - 45 wt%), Fe (14.5 - 21.1 wt%) and S (9.0 - 17.6 wt%), with the bulk sulphur values tied to sulphide minerals. Pyrite is the dominant sulphide and constitutes 16 - 54 wt% of the samples.

Pyrrhotite, chalcopyrite, sphalerite, arsenopyrite and galena occur in trace quantities. The dominant carbonate minerals are ankerite and magnesian siderite while silicate minerals include quartz, micas, chlorite and feldspars. The tailings exhibited significant heterogeneity in geochemistry and mineralogy.

The Modified ABA test (MEND 1.16.1b) was conducted on the tailings head sample. The test results gave a neutralizing potential of 49 kg CaCO₃ equivalent per tonne of tailings. Using the average values of 17.2% and 0.68% for total sulphur and sulphate respectively, the net neutralization potential of the tailings is calculated to be -466 kg CaCO₃ equivalent per tonne of tailings (MEND 2.12.1e). Thus, while the tailings have some neutralizing capacity, they have a high potential for acid generation.

IV. Base Method

Samples of tailings solids, pore water and pore gases collected for physical, chemical and microbiological analyses should be of high quality with minimal disturbance. Optimum methods for the collection of high quality samples depend on site-specific conditions and equipment availability, and as such, sampling methods need to be selected based on conditions at the site.

MEND 4.1.1, *Field Sampling Manual for Reactive Sulphide Tailings*, can be used to select the appropriate sampling method. High quality samples are obtained by minimizing sample disturbance and contamination. One potentially significant source of sample disturbance and contamination, is exposure of samples collected from chemically reducing (anoxic) environments to the atmosphere.

The manual presents a series of reference indexes and a flowchart which can be used to identify a suitable sampling method. Sampling methods are categorized based on:

- The position of the sample location relative to the water level;
- The degree of sample disturbance; and
- Sampling equipment requirements.

Descriptions of the sampling equipment, including their advantages and disadvantages, are provided in the field sampling manual. MEND 4.1.1 is straightforward to use as indicated by the following examples.

Example 1: High integrity solid and liquid samples are required from the edge of a tailings pond to determine the acid generation potential of the solids and the groundwater quality immediately below the water table. The water table is approximately 4 m below the surface.

Figure 2.3-2 lists the available methods for both solids and liquid samples in the subsurface. For liquid samples, a high degree of isolation from the atmosphere is desired (Figure 2.3-3). For the solids sample, methods resulting in a low degree of sample disturbance during collection are required (Figure 2.3-4). Both heavy and light powered equipment are available for the study (Figure 2.3-5). Figure 2.3-6 simplifies the overall selection process.

Based on the above, a split-spoon sampler within a hollow stem auger would be used to obtain the solid samples at specific depth intervals. The liquid samples would be obtained from an observation well installed after solid sampling. The groundwater sample would be obtained using a piston pump sampler.

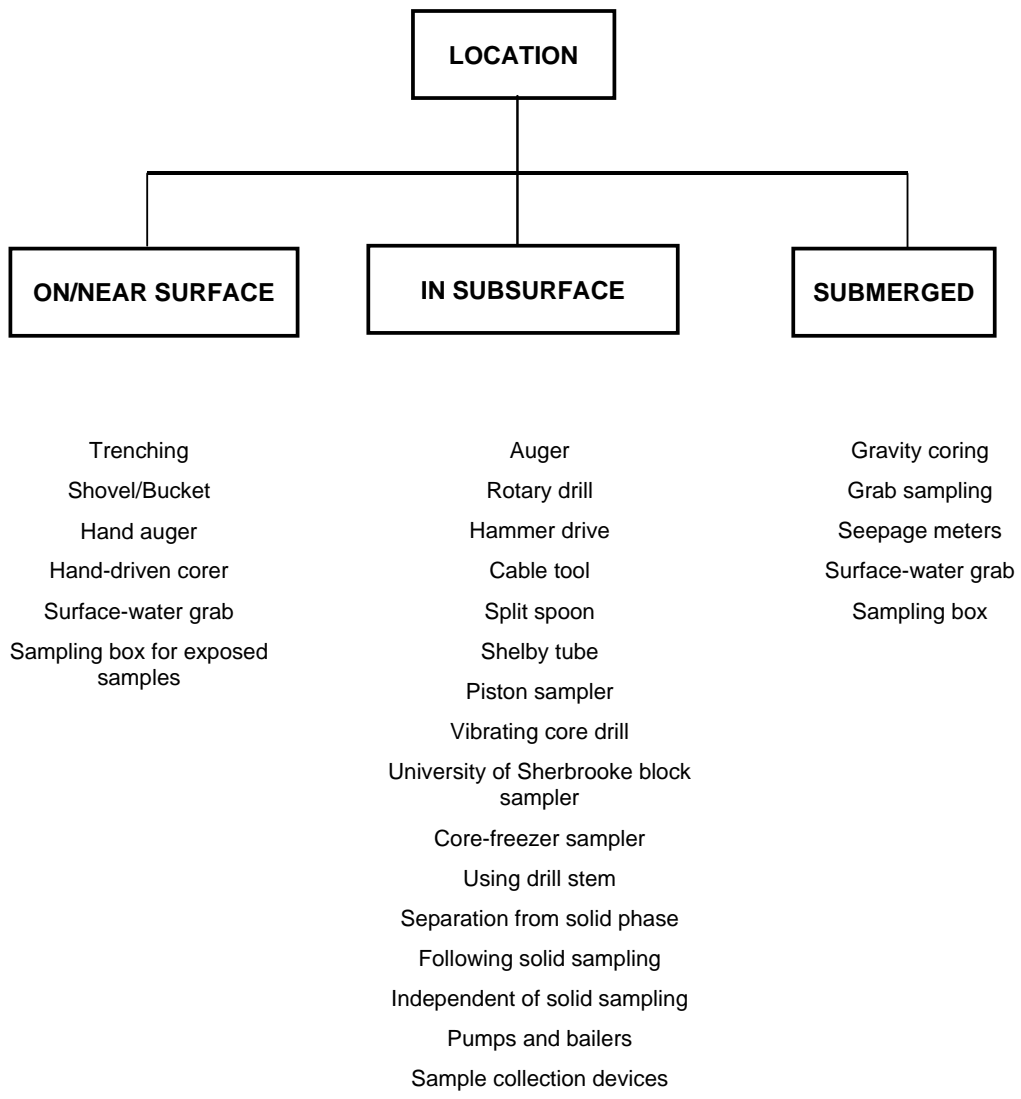
Example 2: Solids sampling at the surface of a tailings impoundment is required to determine the acid generation potential of the solids. The surface is not stable for equipment. The degree of sample disturbance, or degree of isolation from the environment, is not important for this program, the budget is minimal.

A shovel can be used (Figure 2.3-6).

Example 3: A high quality liquid sample is required to determine the water chemistry in the vadose zone.

A high quality teflon suction lysimeter could be used (Figures 2.3-3, 2.3-6).

Figure 2.3-2 Location of Desired Sample Relative to Land/Water Surface



Source: MEND 4.1.1, Index 2-2

Figure 2.3-3 Degree of Desired Isolation from the Atmosphere and Other Contamination⁽¹⁾

LOW	HIGH
<p>Solids</p> <ul style="list-style-type: none"> Auger flights Rotary drill Hammer drive Cable tool Trenching Grab sampling Sampling box for submerged sampling <p>Liquids</p> <ul style="list-style-type: none"> In-filling of drill stem Centrifugation Pressurized consolidation Pore water displacement Monitor well Suction lysimeter Surface-water grab Wash-boring/jetting Centrifugal pump Gas-driven pumps Bailer, single-valve <p>Pore-Gas</p> <ul style="list-style-type: none"> Port extended beyond drill stem 	<p>Solids</p> <ul style="list-style-type: none"> Split spoon (with inner liner) Shelby tube, sealed Piston sampler Vibrating coring, with inner liner Gravity coring, submerged, with liner University of Sherbrooke block sampler Core-freezer sampler Sampling box for exposed samples <p>Liquids</p> <ul style="list-style-type: none"> Advance intake beyond drill stem Piezometer Seepage meter Peristaltic pump Piston pump Bladder pump WaTerrapump Syringe sampler Bailer, double valve (with modifications) <p>Pore-gas</p> <ul style="list-style-type: none"> Single port Multiple port Closed-circuit port Syringe sampler Autoanalyzer

Notes: ⁽¹⁾ This rating is qualitative in nature and will vary with equipment, site conditions and operator

Source: MEND 4.1.1, Index 2-4

Figure 2.3-4 Degree of Sample Disturbance during Collection⁽¹⁾

LOW	MODERATE	HIGH
<p>Solids</p> <ul style="list-style-type: none"> Split spoon Shelby tube Piston sampler University of Sherbrooke block sampler Vibratory coring Hand-driven core Gravity coring, submerged Sampling box for submerged sampling Sampling box for exposed samples <p>Liquids</p> <ul style="list-style-type: none"> Surface-water grab Streambed seepage meter Peristaltic pump Piston pump Bladder pump Syringe sampler Bailer, double valve <p>Pore-gas</p> <ul style="list-style-type: none"> Closed-circuit (with autoanalyzer) Closed-circuit (with syringe) Single-level port (with syringe) Multiple port (with syringe) 	<p>Solids</p> <ul style="list-style-type: none"> Rotary drill, core barrel Hammer drive Trenching Grab sampling, submerged Shovel/bucket Core-freezer sampler <p>Liquids</p> <ul style="list-style-type: none"> Advance intake beyond stem Pressurized consolidation Porewater displacement Monitor well installation Piezometer installation Suction lysimeter Centrifugal pump Gas-driven pumps (double tube, triple tube) WaTerra pump Bailer, single valve <p>Pore-gas</p> <ul style="list-style-type: none"> Withdrawn from advanced intake beyond stem Single-level port (with autoanalyzer) Multiple port (with autoanalyzer) Collector for migrating pore gas 	<p>Solids</p> <ul style="list-style-type: none"> Auger Rotary drill Cable tool Hand auger <p>Liquids</p> <ul style="list-style-type: none"> In-filling of stem Centrifugation Wash-boring/jetting Gas-driven pumps (single tube) <p>Pore-gas</p>

Notes: ⁽¹⁾ This rating is qualitative in nature and will vary with equipment, site conditions and operator

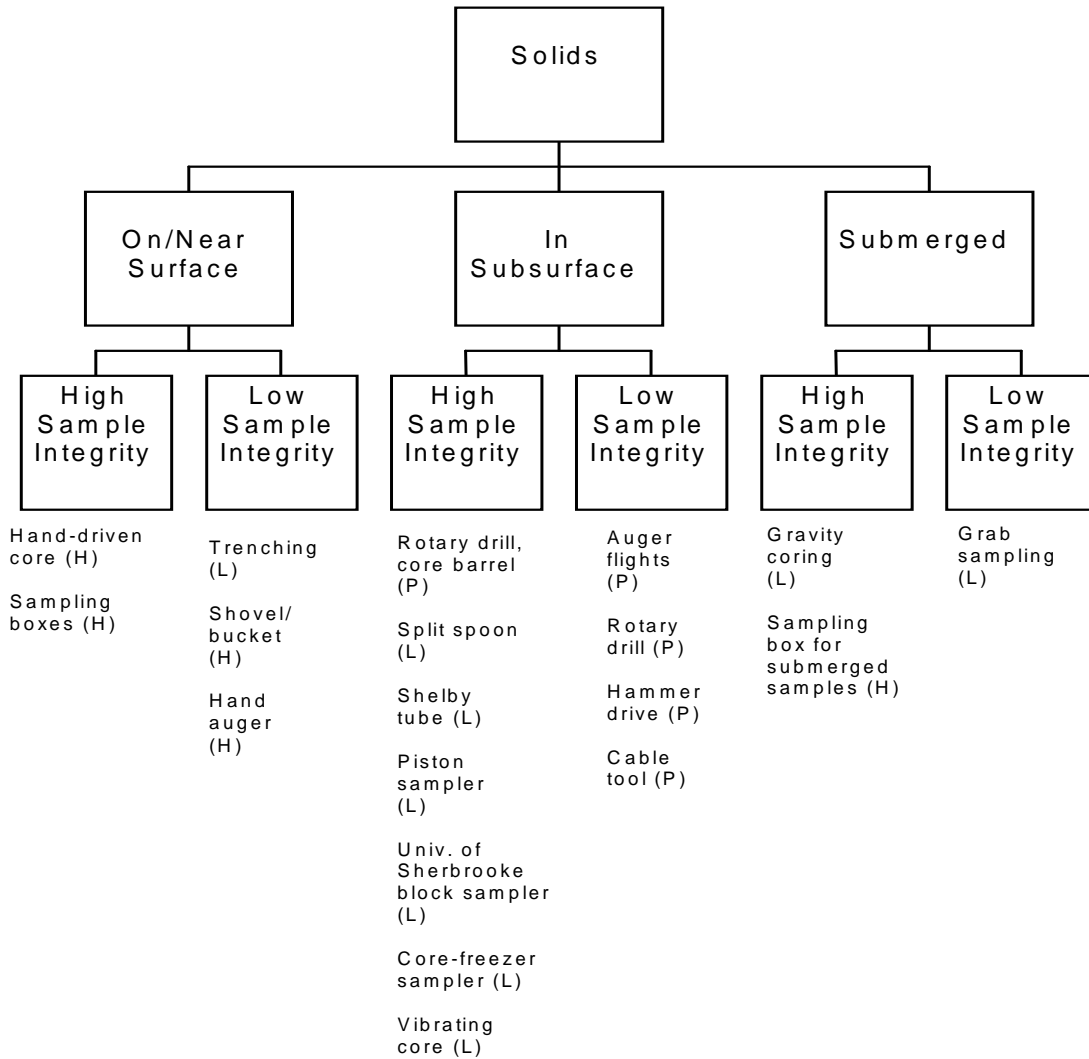
Source: MEND 4.1.1, Index 2-5

Figure 2.3-5 Extent of Available Powered Equipment

HEAVY-POWERED	LIGHT-POWERED	HAND OPERATED
<p>Auger Rotary drill Hammer drill Cable tool Water sampling using drill stem Pore gas sampling using drill stem</p>	<p>Trenching Split spoon Shelby tube Piston sampler Vibrating coring Gravity coring University of Sherbrooke block sampler Core-freezer sampler Grab sample of submerged samples Water sample by electrical or gas-driven pumps Pore-gas sampling/analysis by autoanalyzer</p>	<p>Shovel/bucket Hand auger Hand-driven coring Gravity core submerged Sampling box for submerged sampling Sampling box for exposed samples Surface water grab Streambed seepage meter Water sample by WaTerra pump Water sample by bailer Pore-gas sample by syringe</p>

Source: MEND 4.1.1, Index 2-3

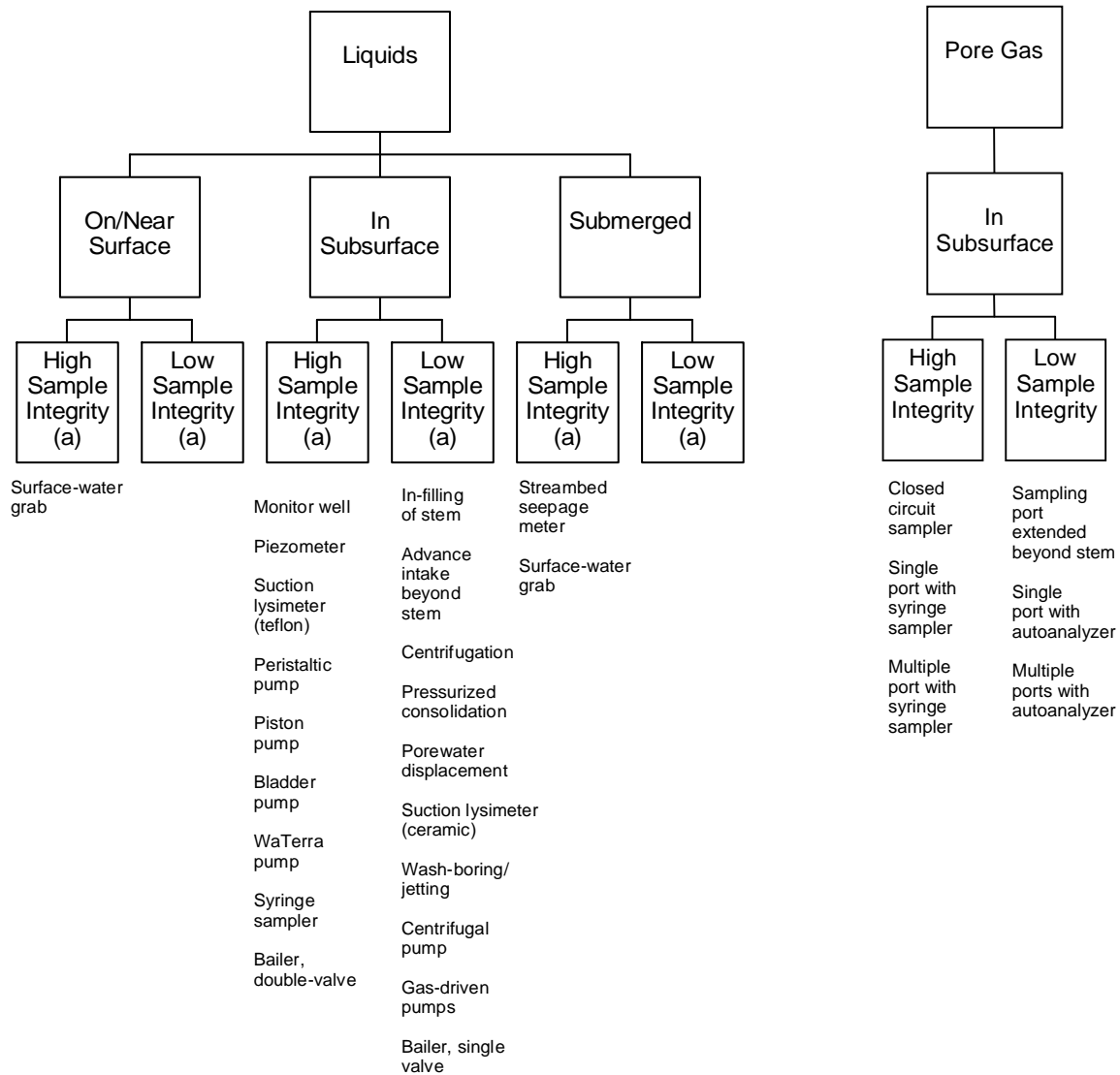
Figure 2.3-6 Flowchart for Sampling Methods – Solids, Liquids and Pore Gas⁽¹⁾



Notes: ⁽¹⁾ This rating is qualitative in nature and will vary with equipment, site conditions and operator
 H – Handheld sampler
 L – Light powered
 P – Heavy powered

Source: MEND 4.1.1, Index 2-6

Figure 2.3-6 Flowchart for Sampling Methods – Solids, Liquids and Pore Gas⁽¹⁾



Notes: ⁽¹⁾ This rating is qualitative in nature and will vary with equipment, site conditions and operator

Source: MEND 4.1.1, Index 2-6

V. Variations

For readers interested in learning more about tailings sampling this subsection reviews:

- Selected actual tailings sampling and analysis programs; and
- Additional methods used to sample oxygen consumption at the surface of tailings (or cover), and measure tailings properties *in situ*.

1. The sampling of tailings for possible use in a cover

At times, there may be a need to sample clean (non-reactive) tailings and characterize them for possible use in engineered cover systems. In such cases, tailings solids samples may be collected for static, leachability and physical parameter testing. As an example, Bussière and Aubertin (1999) carried out an *in situ* investigation where clean tailings were used in the moisture retaining layers of covers in experimental cells (MEND 2.22.2c). Cover monitoring included volumetric water content, matric suction and oxygen flux measurements, and the chemical analysis of the leachate. Time domain reflectometry was applied to measure the volumetric water content. Matric suction was measured in each layer using Watermark sensors and Jet Fill tensiometers. The oxygen consumption method was used to measure the decrease in oxygen concentration in vertical stainless steel tubes, which served as gas containment chambers. The tests lasted two-hours, and were used to develop an oxygen flux value which reflects the rate of sulphide oxidation and hence the cover performance.

The oxygen consumption method provides a quantitative assessment of *in situ* oxidation rates in tailings (MEND 4.6.5). The results can provide immediate feedback on the oxidation status of a tailings impoundment and be used to calibrate predictive models that require reaction rates as input. The method is relatively new and until recently measurements were available at only a few field sites where research was conducted during method development (MEND 4.6.5ac and MEND 4.6.5b).

2. Sampling to investigate the presence of sulphate-reducing bacteria

Fortin (1999) sampled mine tailings impoundments in the area of Timmins, Ontario, and investigated the presence of sulphate-reducing bacteria and their role in iron and sulphur cycling. The samples were collected from diverse physico-chemical conditions which included oxic and acidic environments. In the study:

- Tailings samples were collected at two types of sites (with and without vegetation);
- Tailings samples were aseptically sampled for bacterial enumeration at each 5 cm along a 60 cm deep profile; and
- The tailings were immediately placed in sterile, airtight containers and kept on ice until the analysis. Enumeration was completed within a week after sampling.

3. In situ geotechnical and geochemical measurements

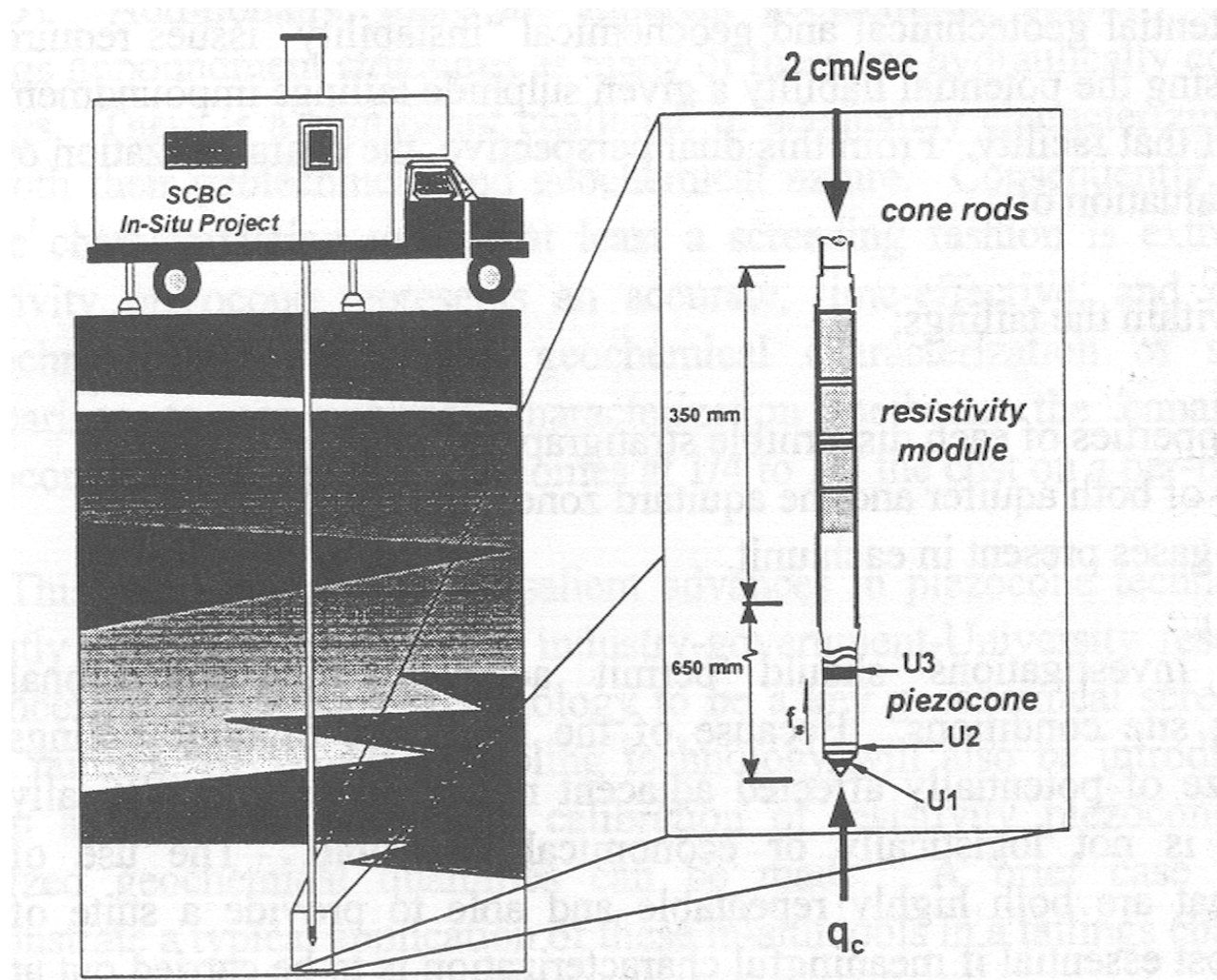
The stratigraphy of tailings and changes in characteristics with depth and across a tailings basin are often of interest. Robertson *et al.* (1997), also MEND 4.6.4, reviewed the use of piezocone technology to provide *in situ* geotechnical and geochemical data for sulphide tailings. The electronic cone penetration test with pore water measurement is recognized as a stratigraphic logging tool for most soil conditions. Geophysical techniques that are used with piezocones include geophones for downhole and/or cross-hole seismic wave measurements and resistivity modules that allow induced-polarization measurements. A resistivity module can be used to assess groundwater quality by measuring the bulk soil resistivity. Piezocone technology is well-suited for use in mine tailings where data can be obtained regarding:

- The stratigraphy of the tailings;
- The relative geotechnical properties of each discernible stratigraphic unit;
- The hydraulic properties of aquifer/aquitard zones; and
- The nature of pore fluid/gases in each discernible stratigraphic unit.

The cone penetration test (CPT) typically involves the use of a 35.7 mm diameter (10 cm² area) cone tip that is pushed into the ground using rods at a constant rate of 2 cm/sec or roughly a metre per minute (Robertson *et al.* 1997). The resistance to the penetration of the cone is continuously measured during the test. In addition, measurements are made of the resistance to penetration of a 150 cm² friction sleeve located behind the cone tip. The CPT concept is illustrated in Figure 2.3-7. Standard piezocones provide measurements of tip resistance, friction sleeve stress, and pore pressure response at the cone tip face, and immediately behind the cone tip and friction sleeve. Stratigraphic interpretation based on tip, sleeve and pore pressure measurements allow layers to be discerned to within a few centimetres. Data on the rate of excess pore pressure dissipation can be used to estimate hydraulic conductivity. Equilibrium pore pressure data can be used to estimate the pressure head distribution within the saturated zone.

The resistivity piezocone also allows electrical resistance to current flow in the ground to be measured on a continuous basis. The resistivity piezocone (RCPTU), developed at the University of British Columbia, consists of a resistivity module installed behind a standard piezocone (Campanella and Weemes 1990). Bulk resistivity trends can be used to indicate if ARD dissolution constituents (e.g. sulphate), which have an effect on electrical resistivity measurements, are present at or above background values. Robertson *et al.* (1997) indicate that RCPTU screening in combination with discrete water samples provides a rapid and cost-effective means of undertaking geoenvironmental characterizations, and is well-suited for the monitoring of groundwater quality at sulphide tailings impoundments.

Figure 2.3-7 Cone Penetration Test Concept



Source: Robertson *et al.* (1997)

In situ tailings pore water samples can be obtained at desired depths using the commercially available BAT system - named after its inventor, Bengt Arne Torstensson (1984). Robertson *et al.* (1997) describe a modified BAT discrete-depth pore water sampler that allows more accurate and feasible sampling in higher total dissolved solids conditions that are typically encountered when sampling tailings pore water. Field measurements of pore water samples obtained using the BAT system should include pH, conductivity and temperature.

Robertson *et al.* (1997) assessed the capability of piezocone technologies with regards to soil characterization issues including tailings. Their assessment is reproduced in Table 2.3-2.

**Table 2.3-2
Piezocone Technology Rating**

Characterization Issue	RCPTU/BAT Water Sampler
Stratigraphic interpretation	Excellent capability
Static/Dynamic Geotechnical Parameters <ul style="list-style-type: none"> • Strength • Modulus • Liquefaction susceptibility 	Excellent capability Excellent capability Excellent capability
Hydrogeological Parameters <ul style="list-style-type: none"> • Hydraulic conductivity • Hydraulic gradients • Geochemical gradients 	Excellent capability Excellent capability Good capability
Information from Bulk Conductivity/Resistivity <ul style="list-style-type: none"> • Total dissolved solids • Specific ion detection • Sulphate anion concentration • LNAPL detection (**) • DNAPL detection (**) 	Excellent capability Poor to good capability Good to excellent capability Good capability Excellent capability
Pore Fluid Geochemistry(*) <ul style="list-style-type: none"> • Total dissolved solids • Specific ion discrimination • LNAPL discrimination (**) • DNAPL discrimination (**) 	Excellent capability Excellent capability Excellent capability Good capability

Note: LNAPL: Light Non-Aqueous Phase Liquid
DNAPL: Dense Non-Aqueous Phase Liquid
* With post-testing laboratory analyses.
** Not discussed in paper by Robertson *et al.* (1997). Organic contaminants are insulators and result in very high bulk resistivities.

Source: Robertson *et al.* (1997)

4. Sampling for mineralogical assessments

Woyshner *et al.* (1997) assessed post-closure monitoring data from the historic Millenbach tailings area near Rouyn-Noranda, Québec that had been decommissioned through the use of a composite clay cover. Samples of waste rock and tailings were obtained from beneath the cover. The leachable materials that were present in secondary mineral form, generally as oxides and sulphates, were evaluated using elemental and mineralogical analyses. Elemental composition was determined using acid digestion and ICP methods. Mineralogy was determined using X-ray diffraction (XRD). Pyrite was the only sulphide mineral identified in the study through XRD, and its composition was quantified using sulphur analysis results.

Woyshner *et al.* (1997) used the sulphate analysis results to quantify the sulphate mineral composition which was then compared to geochemical modelling results. Modelling had indicated that the sulphate concentration in the tailings pore water would be controlled by gypsum, and that ferric iron oxides (e.g. $\text{Fe}(\text{OH})_3$) would dominate. The quantity of iron oxide was estimated by subtracting pyrite iron from the total iron as determined by the ICP analysis. The predicted depth-weighted average level of iron oxide was 2% as $\text{Fe}(\text{OH})_3$. Given the low level and the amorphous nature of the iron oxide minerals, they were not detected using XRD. Calcite was detected in trace amounts and quantified using data from the inorganic carbon analysis. Feldspars and chlorite which provide additional buffering capacity, but with slower kinetics, were detected in trace to minor amounts.

5. Tailings lysimeters

Lysimeters are used to assess the oxidation process under field conditions. MEND 2.45.2 and Hanton-Fong *et al.* (1997) describe a detailed hydrochemical study that compares the geochemical evolution of pore water from low sulphur tailings to that from higher sulphide tailings. The study involved the use of three 10 m x 15 m field lysimeters that contained low sulphur tailings (0.35 wt% S), main tailings (0.98 wt% S) and total tailings (2.3 wt% S). The low sulphide tailings were obtained from a pilot scale test at the INCO Clarabelle Mill in Copper Cliff, Ontario (MEND 2.45.2).

6. Sampling of pore water in submerged tailings

Several MEND projects have investigated the post-depositional geochemical behaviour of submerged tailings. The sampling of submerged tailings was completed using a variety of techniques, with the use of the sediment corer and peepers representing the most elaborate and rigorous technique. A peeper, or dialysis array sampler, is based on diffusion-controlled transport where chemical equilibrium occur across a dialysis membrane between the pore water and the water in the sampler. Peepers are further discussed in Section 2.3.5. Investigative programs that include the use of peepers are described in Volume 4 – Prevention and Control, Water Covers, Section 4.2.

VI. Cost

The cost of sampling tailings is highly variable and dependent upon the objectives of the sampling and analysis program, site conditions, and sampling requirements (e.g. shallow or deep samples).

VII. MEND and Relevant Publications

MEND 1.16.1b	1991. Acid Rock Drainage Prediction Manual. March.
MEND 2.12.1c	To be published in 2001. Subaqueous Disposal of Reactive Mine Tailings – Louvicourt Mine Test Cells – Geochemical Sampling and Analysis.
MEND 2.12.1d	To be published in 2001. Reactivity Assessment and Subaqueous Oxidation Rate Modelling for Louvicourt Tailing.
MEND 2.12.1e	To be published in 2001. Evaluation of Man-Made Subaqueous Disposal Option as a Method of Controlling Oxidation of Sulphide Minerals: Column Studies.
MEND 2.17.1	1996. Review of Use of an Elevated Water Table as a Method to Control and Reduce Acidic Drainage from Tailings. March.
MEND 2.22.2c	1999. Études sur les barrières sèches construites à partir de résidus miniers, Phase II – Essais en place. novembre.
MEND 2.23.2c	2000. The Verification of Modelled Pore Water Movement Within Thickened Tailings Using Tracers at the Falconbridge Limited Kidd Metallurgical Division Timmins, Ontario. May.
MEND 2.45.2	1997. Separation of Sulphides from Mill Tailings – Field. September.
MEND 4.1.1	1989. Field Sampling Manual for Reactive Sulphide Tailings. November.
MEND 4.6.4	1994. Piezocone Technology – Demonstration Project. Open file report.
MEND 4.6.5ac	1997. A Survey of <i>In Situ</i> Oxygen Consumption Rates on Sulphide Tailings: Investigations on Exposed and Covered Tailings. November.
MEND 4.6.5b	1997. A Rapid Kinetic Technique for Measuring Reactivity on Sulphide Waste Rock: The Oxygen Consumption Method. December.

BC AMD Task Force 1992. Field Quality Assurance/Quality Control (QA/QC) Protocols for Monitoring and Predicting Impacts of Acid Rock Drainage.

Bussière, B. and Aubertin, M. 1999. *Clean Tailings as Cover Material for Preventing Acid Mine Drainage: An In Situ Experiment.* In: Sudbury '99 – Mining and the Environment II Conference Proceedings. Sudbury, Ontario. 13 to 17 September. Vol 1, pp. 19-28.

Campanella, R.G. and Weemees, I. 1990. *Development and Use of an Electrical Resistivity Cone for Groundwater Contamination Studies.* Canadian Geotechnical Journal. Vol 27, No. 5, pp. 557-567.

Fortin, D. 1999. *Microbial Sulfate Reduction in Active and Abandoned Mine Tailings Impoundments in the Timmins Area, Ontario, Canada.* In: Sudbury '99 – Mining and the Environment II Conference Proceedings. Sudbury, Ontario. 13 to 17 September. Vol 1, pp. 137-143.

Hanton-Fong, C.J., Blowes, D.W. and Stuparyk, R.A. 1997. *Evaluation of Low Sulphur Tailings in the Prevention of Acid Mine Drainage.* In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 2, pp. 835-847.

National Uranium Tailings Program. 1985. Uranium Tailings Sampling Manual. NUTP-1e.

Nicholson, R.V. 1996. *Oxygen Consumption Measurements for Mapping and Monitoring of Sulphide Tailings and Covers.* In: MEND Workshop on Dry Cover Technologies for Acid Mine Drainage. Sudbury, Ontario. 15 to 16 April.

Robertson, J.D., Kuit, W.J., Campanella, R.G., Frew, D., McLeod, H.N. and Davies, M.P. 1997. *The Use of In Situ Testing for the Characterization of Sulphide Mine Tailings.* In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 4, pp. 1761-1777.

Torstensson, B.A. 1984. *A New System for Groundwater Monitoring.* Groundwater Monitoring Review. Fall, pp. 131-138.

Woyshner, M.R., St-Arneault, C. and St-Arnaud, L.C. 1997. *Five Years after Covering Tailings and Waste Rock with a Composite Soil Cover: A Case Review and Water Quality Predictions at the Millenbach Site near Rouyn-Noranda, Québec.* In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 4, pp. 1673-1690.

2.3.2 WASTE ROCK

I. Discussion of Theory

Waste rock is typically sampled to assess the potential for acidic drainage through a variety of analyses including; chemical composition, mineralogy, static acid generating potential or net neutralization potential, hardness/weathering, and particle size distribution. Dynamic tests to determine acid generation are also utilized - these tests are discussed in Volume 3.0 – Prediction.

There can be a wide variation in the nature of waste rock at a mine, depending on the geology and mineralogy surrounding the mineral deposit. Waste rock may be sampled before, during or after it is disposed. Ideally, sampling should take place before the rock is excavated. The advantage of sampling before the rock is blasted/excavated is that it is much easier to define the geological units, and to ensure that each unit is adequately characterized by the sampling. Once the units are characterized, the mine plan can be used to predict the waste rock dump composition.

After waste rock has been disposed in a dump, it is much more difficult to characterize the geological units. Mixing and segregation of rock types occurs, and is dependent on the waste rock excavation sequence and type of dump construction. Also, there are difficulties in sampling any part of the dump but the near surface.

Regardless of when the waste rock samples are taken, an important step in the collection of geologic data is the sampling procedure. A meaningful sampling strategy should:

1. Establish the objectives;
2. Select a sampling strategy to meet the objectives;
3. Periodically review the sampling strategy;
4. Optimize the sampling; and
5. Periodically review the adequacy of the objectives.

II. Discussion of MEND Research

MEND 4.5.1-1, *Review of Waste Rock Sampling Techniques*, provides a comprehensive list and description of sampling techniques, and a guide to waste rock sampling program design for the exploration, operation and closure phases of a mining project. MEND 4.5.1-2, *Handbook for Waste Rock Sampling Techniques*, summarizes currently available sampling techniques.

Waste rock sampling programs often involve more than the collection of waste rock. As an example, the South Waste Dump located at La Mine Doyon near Rouyn-Noranda, Québec has been extensively characterized (MEND 1.14.2).

The South Dump has been the focus of numerous MEND investigations. The investigations have included: drilling and sampling of the rock dump materials; piezometer, lysimeter and thermocouple installations; sampling of acidic drainage, groundwater and pore water; collection of gas samples within the dump; collection of microbiological specimens; measurement of surface temperatures and temperature profiles in the dump; and collection of climatic and hydrologic data. The laboratory and analytical studies carried out included: characterization of the physico-chemical and mechanical properties of the different types of waste rock; water chemistry analyses including rapid chemical techniques to monitor acid mine drainage; hydrology and water budget studies; geotechnical and hydrological studies including evaluation of dry barriers; extensive studies of mineralogy and geochemical processes; microbiological enumeration and diversity studies; and predictive modelling of acid mine drainage processes including heat transfer analysis. An important objective of the above studies was to measure the physical and chemical properties of an actual waste dump and to identify key processes contributing to the generation of acidic mine drainage.

MEND 1.14.2b presents a compilation of chemical and mineralogical data for the South Waste Dump. Sampling data includes flow measurements, total dissolved solids, effluent density, conductivity, pH, acidity, sulphate, and metal concentrations. The data assessment includes: chemical analyses of sampled leachate; a discussion of water quality in the unsaturated zone; mass balance calculations based on the chemical data; and chemical composition calculations based on common physical parameters.

MEND 1.14.2e involved the sampling of groundwater and the culturing of isolates taken from wells at depths of 30.5 to 42.5 m. An innovative bacteria trap device was developed and used in this study. The traps, which included particles of pyrite, sphalerite, chalcopyrite or sulphur, were used to attract and collect microorganisms in the sampling wells.

In MEND 1.14.3E (French version is 1.14.3F), the studies carried out at the South Dump were reviewed by experts. The overall conclusions were that the Mine Doyon study provides a new understanding of some specific technical issues and represents a thorough and exceptionally well-documented case study.

The South Dump is estimated to contain approximately 21 million tonnes of waste rock including 1.05 million tonnes of pyrite - equivalent to an average pyrite content of 4.5%. The key aspects of the field instrumentation and monitoring program for the rock dump as outlined by Poirier and Roy (1997) are:

- Instrumentation was installed in the South Waste Dump in 1990 to provide additional data on oxidation conditions. Six boreholes were drilled and equipped with two monitoring wells, a thermistor string (typically 11 thermistors/hole), and gas sampling tubes (to 8 depths);

- Twelve gravity lysimeters were subsequently installed in two, five metre deep excavations, along with three groups of suction lysimeters. In addition, weirs were installed in ditches that collect runoff from the rock dump to allow for flow measurements. Each of the ditch weir stations consisted of a V-notch weir, a conductivity meter, a flow meter and a data logging system. The weir data allowed seasonal variations in acidity and flow to be characterized;
- Monitoring commenced in 1991. A typical chemical analysis of the leachate sampled in the saturated zone of the monitoring wells located within the waste rock is presented in Table 2.3-3. The elevated aluminum concentrations measured in samples from Boreholes 2 and 3 may have resulted from the dissolution of aluminosilicate minerals present in sericitic schists;

Table 2.3-3
1996 Water Quality in the Saturated Waste Rock Zone
(Boreholes 2-4, South Waste Dump, La Mine Doyon)

Borehole Number	pH	Acidity (mg CaCO ₃ /L)	TDS (mg/L)	Al (mg/L)	SO ₄ ²⁻ (mg/L)	Fe ²⁺ (mg/L)	Fe ³⁺ (mg/L)	Fe tot. (mg/L)
2	2.52	93,387	142,443	9,630	106,419	10,742	2,975	13,717
3	2.47	134,969	198,575	12,367	130,967	13,950	2,545	16,495
4	4.45	2,639	4,425	54	3,401	260	0	260

Source: Poirier and Roy (1997)

- Thermistor data were recorded monthly. Values as high as 65°C were recorded inside the rock dump with seasonal variations observed in the topmost 8 m layer; and
- The field program additionally included an assessment of bacterial activity within the South Waste Dump. Four types of microorganisms, *Thiobacillus ferrooxidans*, *Leptospirillum ferrooxidans*, *Thiobacillus thiooxidans* and *Thiobacillus acidophilus*, were isolated from the borehole drill cuttings. In addition, bacteria traps consisting of chunks of local sulphides were placed in the boreholes to collect microorganisms for 40 days. It was concluded from field observations that bacterially catalyzed oxidation was occurring.

Thermally driven convection is a key mechanism controlling oxygen flow through a waste rock dump. Hot air chimneys and snow-free zones were observed on the waste rock dump surface and frequently near the top of the dump slopes at the South Dump (Poirier and Roy 1997). An airborne infrared thermographic survey confirmed that air entry occurs at the dump base and hot air exits along the upper rim around the dump. The thermal data was used in MEND 1.14.2 to develop a conceptual model for air convection within the rock dump.

In another study, Martin *et al.* (1999) carried out acid rock drainage assessment programs at the Kuntor Gold Mine, Kyrgyzstan and the Bogoso Gold Mine, Ghana. Their experience highlights the need to tailor the details of a program to meet site-specific requirements. The aspects addressed at each of the mine sites are shown in Table 2.3-4, and reviewed below.

Table 2.3-4
ARD Assessment Program Elements

Element	Kumtor	Bogoso	Comments
Review of Existing Data	√	√	Previous ARD studies, geological information, environmental data, mining and rehabilitation plans were reviewed to develop field and laboratory programs, and were essential to ARD assessments.
Field Program			
Waste Rock			
On-site review of geology	√	√	Distribution of rock types, sulphides and neutralizing minerals both within waste dumps and <i>in situ</i> . Geological staff at both sites provided assistance.
Sample collection and description	√	√	Sample locations based on goals of each program. Samples collected from the surface of existing dumps and pits. At both sites existing borehole samples were also used, which proved beneficial to the programs. Descriptions included sample location, rock type, structural deformation, level of oxidation, mineralogy (sulphides, carbonates and other identifiable minerals), colour, etc.
Field tests paste pH/conductivity	√	√	Useful at both sites for gaining an understanding of sulphide oxidation/acid neutralization while field program still in progress.
Water – Seepage and Downstream Environment			
Field pH and conductivity	√	√	Essential at both sites for locating areas of sulphide oxidation and ARD while the field program was ongoing.
Sample collection	√	√	Targeted seepage from waste rock dumps for both sites. Downstream results were available from existing monitoring programs, however at Bogoso some downstream samples were taken to provide additional parameters and as a QA/QC check.
Laboratory Program			
QA/QC Program	√	√	Recommend inter-laboratory QA/QC program.
Waste Rock			
ABA	√	√	To characterize ARD potential of various rock types and locations. An alternate ABA test was conducted on a subset of the samples to provide additional information on neutralization potential (NP).
NAP	√	√	At Kumtor net acid production (NAP) test was conducted to determine suitability as a quick laboratory test for ongoing ARD characterization. At Bogoso, NAP test was conducted to relate previous ARD studies to present study.
ICP metals	√	√	To determine metals of potential concern.
Gold	√	√	To relate ABA and metals to ore, low grade and waste categories.
Major elements	√	X	Used in geochemical modelling for Kumtor.
Dynamic testwork	X	X	Conducted in previous studies for Kumtor. Not necessary for Bogoso as existing dumps/pits are full-scale dynamic tests.
Cover Material Testwork	X	√	Carried out for Bogoso to determine effectiveness of oxide waste as a cover to limit oxygen and water infiltration to waste rock.
Water Samples ICP metals, sulphate	√	√	Collected at both sites to determine significance of ARD in terms of metal release. Used at Kumtor to calibrate geochemical model.
Geochemical Modelling	√	X	Used at Kumtor to evaluate the potential for ARD and to predict seepage quality. Not necessary at Bogoso based on rehabilitation plans.
ARD Assessment	√	√	Interpretation and presentation of results, discussion of potential ARD management strategies, conclusions and recommendations.

Source: Martin *et al.* (1999)

At Kumtor, mining activities are undertaken at a single open pit that commenced commercial production in 1997. The study at this site focussed on the continued ARD assessment of the waste rock to allow for the ongoing management of the waste rock as the pit is mined. Waste rock was sampled on a regular pattern at all waste rock dumps and within the pit to ensure that an unbiased snapshot of the waste rock at the time of sampling was obtained. The surface samples had been recently excavated and were relatively unweathered.

In contrast, the Bogoso Mine is located in a tropical environment with high precipitation levels and consists of a series of open pits that have been operated since 1990. The ARD assessment focussed on evaluating the environmental impacts of the waste rock dumps and open pits, and on reclamation strategies to minimize these impacts. Preferential weathering of acid neutralizing minerals is a major factor affecting ARD at the site. Oxide waste rock was not sampled in detail as it was not an ARD concern. As well, the large number of pits and waste rock dumps required prioritization of sampling sites. Rock samples that had not been weathered (i.e. reverse circulation drill cuttings and recently excavated materials) were targeted where possible to avoid the complications of interpreting weathering effects.

III. Applications and Limitations

The processes that control sulphide oxidation within existing waste rock piles can be assessed on a site-specific basis through the use of instrumentation for data collection purposes. Smolensky *et al.* (1999) describe an extensive drilling and geochemical characterization program which included eight instrumented boreholes in the Nordhalde, which is the second largest waste pile in the Ronnenburg uranium district (former East Germany). Eight instrumented boreholes were installed in the waste pile which has a pyrite content of 1 to 2%. The researchers report that:

- The boreholes were drilled to depths of 8 to 75 m in waste rock using a dry rotary air blast method and cased with 194 mm OD pipe;
- Instrumentation included gas sampling and pressure monitoring tubes, thermistors and cables taped to a 40 mm OD HDPE pipe with open tube ports and the thermistors positioned at selected intervals. The HDPE pipe/instrumentation assembly was wrapped with filtercloth at the tube port locations;
- The instrumentation assemblies were lowered in the casings, then centred and capped at the collars. A filling tube was used to backfill the boreholes, with port locations surrounded by quartz sand and gravel between bentonite seals; and
- Automatic data recorders stored temperature and pressure data for the monitoring ports on an hourly basis. Oxygen concentrations were measured manually on a working day basis using a TESTO 346 Analyser. In addition, site meteorological data was recorded on a half-hourly basis.

Representative sampling of waste rock after a dump is constructed can be a very challenging task. The British Columbia Ministry of Energy and Mines carried out a program which involved the sampling and examination of waste rock dumps in British Columbia (Price and Kwong 1997). The objectives of the program were to:

- Document the rate and form of weathering in different geologic materials and in dumps of different ages;
- Test a range of analytical procedures; and
- Consider how the results from the above mentioned objectives can be applied to improve the accuracy and to facilitate drainage chemistry predictions.

A number of procedures and findings related to the sampling of waste rock are summarized.

- The proportion of fines and the particle size distribution of waste rock within a dump are determined by blast features, the materials handling methods used in excavating and depositing the waste, the rock strength and competency, and weathering (Price and Kwong 1997). The compositional differences between the particle size fractions are a result of variations in strength, cohesion and weatherability, and secondary weathering product accumulation in fine particle size fractions. The BC study involved the sampling of fines-containing portions of waste rock dumps, typically on terraced dump benches. Particles less than 10 cm in diameter were sampled from backhoe or hand-dug trenches. The objective of sampling was to collect waste samples that represented the range in weathering rate and not to predict the performance of the whole site.
- Sample variability was identified based on differences in geological and physical properties and particle size distribution. Significant weathering of aged waste rock particles was identified by red or yellow staining indicative of iron oxidation and ferric iron precipitation. Based on an analysis of the data, Price and Kwong (1997) concluded that:
 - There are differences between pH measurements made on pulverized materials and on surface rinse pH;
 - There are differences in the composition of different particle size fractions; and
 - A whole sample assay is inadequate as a means of characterizing weathering. It is important to separately analyze a fine particle size fraction (e.g. <2 mm) when evaluating the effects of weathering.

IV. Base Method

Waste rock may be sampled before, during, or after it is disposed. A primary objective in sampling is to collect a sufficient number of representative samples to obtain the required precision. Sampling is preferably performed on *in situ* rock during the exploration, development and operation stages of mining, usually in conjunction with sampling to assess the economic

potential of the ore body. If the waste rock of concern is an existing pile, and records and samples from exploration and operation of the mine do not exist, then the waste rock piles will in most cases need to be sampled.

For sampling of *in situ* rock, a statistically sufficient sampling of each physical and chemical geological unit is required to ensure that the units are adequately characterized. The accepted methods of geostatistical ore reserve estimation can be followed to characterize *in situ* waste rock. The method should be suitable and cost-effective to use for waste rock. Advice and assistance should be sought from the geologists and mine engineers involved in assessing the ore deposit.

The determination of what constitutes a “representative sample” of a waste rock pile is a challenging task. A record of the placement of waste rock in the pile is useful for determining how to sample the pile. Both horizontal and vertical characterization are required, however drilling into the pile may be difficult and may not result in representative samples. Waste rock piles are, by nature of construction, heterogeneous; sampling should be sufficient to ensure that the waste pile can be adequately characterized by homogenous regions. It must be decided which characteristics of waste rock 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. General sampling guidelines are listed below:

- 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;
- Mathematical formulations can be applied to determine the required number of samples. Techniques which suggest that the number of samples can be based upon the size of the geological unit may not be applicable in all cases;
- A staged program is warranted. Analyses of the initial sampling provides guidance as to how many additional samples may be required and which geological units/strata should be re-sampled. The input of the geologist/engineer assessing the mineral deposit 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 should 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 which is comprised of one rock type. Compositing may be useful when a large number of samples are available for acidic drainage 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 to provide a sample of adequate size for testing;

- The objectives of the sampling program must be defined prior to sampling;
- 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 more sampling would be required than if all reactive waste was to be disposed of below water;
- Existing mine block models are useful in defining zones of waste rock and their mining sequence;
- Sample size is important and should be evaluated in the first stage of sampling through the collection of duplicates. Sampling errors will result if the sample is large enough to occasionally include a particle of the component of interest, but too small to ensure that the particles are frequent enough to eliminate subsampling variability;
- Fresh rock should be collected if the rock mass under consideration is unweathered. If weathered rock samples are collected, this must be taken into account when evaluating test results; and
- Drilling into a waste rock dump can be difficult, depending on the nature of the waste rock. At Mine Doyon, sampling of the South Waste Dump was performed using a drill equipped with an ODEX bit. This drilling method was efficient, with good penetration rates, and excellent recovery without sample contamination.

Waste rock characterization is likely to be part of the mine design process. For example, Higgs *et al.* (1997) describe the use of lithology and geochemical tests for classification and the planning of the Eskay Creek Mine where the potential for acidic drainage was one of the earliest environmental issues raised. ARD assessment work was carried out in parallel with a constantly evolving mine plan. The approach was conducted using a committee of representatives from the regulatory agencies, Homestake Canada Inc. (the owner of the property) and its consultants. The approach allowed the design and interpretation phases of the work to be successively reviewed and approved.

The Eskay Creek deposit is a volcanogenic massive sulphide deposit. A mudstone formation hosts the orebody in which the hangingwall and footwall are andesite and rhyolite respectively. The geological characterization of the deposit included (Higgs *et al.* 1997):

- The geological identification and description of samples;
- Mineralogy;
- Alteration assemblages;
- Weathering potential;
- Sample location and relationship to orebody;
- Static and kinetic test data;

- Neutralization Potential (NP) to Maximum Potential Acidity (MPA) ratios;
- Ore geometry and depositional history; and
- The mine development plan.

Subsequent to the review of the above information, the mine plan was revised and resources were focussed as follows:

- The hangingwall andesite was found to have an overall positive net neutralizing potential. Its use for infrastructure construction (e.g. waste dump pad construction) was further assessed in Phase 1;
- In Phase 2, samples of massive and brecciated rhyolite were obtained from drill core, exploration adit development and underground sampling. The net NP was shown to shift from positive to negative when the massive rhyolite was compared to the brecciated rhyolite; and
- A temporary waste rock dump containing predominantly rhyolite that had been excavated in 1990-91 became acidic in 1992. The Phase 3 test program used to characterize and prevent acid generation included:
 - The collection of seven waste rock samples from different locations in the temporary dump. Each sample was classified with regards to rock type, degree of oxidation and relative portion of the dump that it represented. Paste pH and NP were used to derive a correlation between paste pH and lime demand for neutralization; and
 - A 300 kg sample of highly oxidized waste rock was collected from one location. The sample was then split into 6 to 7 kg aliquots for testing purposes. The data were used to develop a strategy to neutralize the acidity when the waste rock was relocated.

Higgs *et al.* (1997) derived the following recommendations based on their experience at Eskay Creek:

- Place the emphasis on compiling geological and geochemical information to support program design and interpretation. Combine a number of interpretation and predictive tools to assess the acidic drainage potential at each site;
- Use plan views and sections to illustrate drill holes, ore zone, geology, alteration halos, sample location ABA data, location of existing and proposed development and other pertinent information. These plots assist in establishing an accurate spatial relationship between mine development and waste generation;
- Conduct petrographical, chemical and physical tests on the target waste and ore zones using the section plots and correlate this information with deposit geology and proposed mine plan(s);

- Collect and archive samples along with detailed physical and chemical alteration information. This will allow the test results to be confirmed and re-visited should the mine plan change while the ARD program is in progress;
- Evaluate disposal options for all waste materials early in the project, with emphasis on subaqueous disposal of waste rock and tailings in natural or man-made impoundments if these materials are potentially acid generating; and
- Maintain flexibility in design and operation to accommodate unexpected changes in waste characteristics after start-up.

V. Variations

MEND 4.6.5b and Anderson *et al.* (1999) describe an experimental method that was developed to evaluate the rate of oxygen consumption of rock and drill core samples. The method, referred to as the oxygen consumption method, involves placing a moist waste rock sample in a gas-tight reaction vessel and then monitoring the gas-phase oxygen concentration for 2 to 3 days at constant temperature and moisture content conditions. As part of the research, the influence of particle size, sulphur content, inoculation with *Thiobacillus ferrooxidans*, and temperature on the oxygen consumption rate was also investigated. The researchers concluded that:

- The rate of oxygen consumption was a non-linear inverse function of the particle size with the rate increasing as the particle size decreased. This relationship was observed for both inoculated and uninoculated waste rock samples. These experimental results confirm the importance of fine particles in terms of acid generation potential in waste rock piles;
- Waste rock samples inoculated with *Thiobacillus ferrooxidans* has significantly higher oxygen consumption rates. After inoculation at temperatures of 20 and 30°C, the rate increased by a factor of 2 to 10, with more significant increases related to pyrite compared to pyrrhotite. At lower temperatures, inoculation did not appear to have an effect on the rate of oxygen consumption; and
- The oxygen consumption rate increased with temperature in the range of 20 to 30°C consistent with temperature effects for oxidation of sulphide minerals.

MEND 4.6.5b and Anderson *et al.* (1999) report that the oxygen consumption method was successfully adapted for use with waste rock and provides a direct measure of the intrinsic kinetics of sulphide oxidation in waste rock material. The method is simple, rapid and inexpensive with the capability of performing multiple tests simultaneously. These tests can also be used to complement those from more traditional humidity cell and column test results and can form the basis of a larger database to provide statistical evidence of variability within waste rock materials for which a large number of samples may be justified.

Site-specific assessments of waste management options completed prior to the permitting of a proposed mine project rely on the use of representative mine rock and tailings samples. As an example, Nicholson *et al.* (1999) assessed the underwater disposal of reactive tailings associated with the proposed Voisey's Bay project. Representative samples of waste rock and tailings were placed in flooded columns, and the chemical composition of the waste pore water and the overlying water column were monitored. The flux of potential contaminants to the water column provided data needed for lake-disposal modelling. The tailings and mill process water used in the study were collected from a pilot milling study. The waste rock was selected from exploration diamond drill core to represent waste rock zones located within the proposed open pit. The disseminated sulphate waste zone was represented by gneiss waste rock zone samples, while the massive sulphide zone was represented by intrusive waste rock samples.

Geophysical techniques that can be used to estimate sulphide content can play a role in characterizing *in situ* rock that will become waste rock as a deposit is mined. Two such techniques are induced polarization (IP) for disseminated sulphides, and electromagnetics (EM) for more massive sulphides. These techniques can be used to extrapolate the results of physical sampling of boreholes (Section 2.5).

The characteristics and distribution of carbonate minerals in waste rock are studied to better understand the alkalinity available to buffer acid generation. In 1998, Paktunc investigated mineralogical constraints in acid-base accounting (ABA) testing and, in particular, on measurements of the Neutralization Potential (NP), and interpreted what static test results mean with respect to predicting acid generation. One potential source of error in NP measurements is determining the contribution from the dissolution of non-carbonate minerals. As non-carbonate sources of alkalinity may not be readily available to neutralize acidity in the field, it is important to:

- Select representative samples of tailings and rock for ABA testing; and
- Determine the mineralogical composition of samples submitted for ABA testing.

Personnel responsible for the collection of samples need to be aware that uncertainties in NP measurements can arise due to the mineral composition of a sample, and the particle size-mineralogical relationship in a sample. The sources of neutralization potential and acid potential (AP) in ABA tests depend upon the sample mineralogy. A static testing technique based on bulk dissolution can provide a reasonable estimate of the acid generating potential of the tailings on rock samples in most cases. However, the influence of mineralogy needs to be considered when assessing ABA test results. As examples:

- In conventional ABA testing, AP is calculated using sulphur content and it is assumed that the sulphur is present as pyrite. If the sample tested also contains pyrrhotite, the AP could be

overestimated by up to 1.5 times. Paktunc (1998) indicates that when one or more sulphide minerals are present in a sample, the AP can be calculated as follows:

$$AP = \sum_{s=1}^m \frac{n_s \times 98 \times X_s \times 10}{W_s}$$

where:

AP =	the acid potential in kg H ₂ SO ₄ /t;
n _s =	the number of moles of H ₂ SO ₄ formed by the oxidation of one mole of sulphide minerals;
98 =	the molecular weight of H ₂ SO ₄ ;
10 =	the conversion factor for kg/t units;
X _s =	the weight % of sulphide minerals;
W _s =	the molecular weight of sulphide mineral, s, in gram/mole; and
M =	the number of sulphide minerals in the sample.

- The mineral siderite initially acts as a neutralizing mineral, but after continued dissolution becomes a source of acidity as its ferrous iron by-product is oxidized. As such, siderite's net contribution to NP is zero; and
- Based on stoichiometric requirements, equal moles of calcite and dolomite would be needed to neutralize a given quantity of H₂SO₄. However, dolomite's NP is 1.1 times that of calcite.

The above types of information can only be used to assess NP results if the sample mineralogy is available. Paktunc (1998) notes that based on mineralogical and sample particle size distribution data, NP values can be calculated for individual size fractions. The mineralogical NP calculations could then be used to interpret ABA test results, and assist in evaluating NP and AP within a kinetic framework (e.g. in predictive modelling).

VI. Cost

MEND 4.5.4 (1997) notes that the cost of a drill and operators range from \$50 to \$100/m for a down-the-hole hammer. Typical drilling rate in waste rock is 4 m/hr. A geologist may also be required to supervise the drilling. Test pits in waste rock cost \$300 to \$500/day for a backhoe and a staff geologist with a performance in the range of ten to fifteen 3 m deep pits/day, or two to six 6 m deep pits/day.

VII. MEND and Relevant Publications

- MEND 1.14.2b 1997. Sampling and Monitoring Data from the Mine Doyon South Waste Rock Dump (1990 to 1995). September.
- MEND 1.14.2c 1997. Heat Transfer During Acid Mine Drainage Production in a Waste Rock Dump, La Mine Doyon (Québec). August.

- MEND 1.14.2d 1997. Water Budget for the Waste Rock Dump at La Mine Doyon, (Québec). August.
- MEND 1.14.2e 1997. Diversité microbiologique dans la production de drainage minier acide à la halde sud de la Mine Doyon. August.
- MEND 1.14.3e 1996. Peer Review of MEND Studies Conducted from 1990 to 1994 on Acid Mine Drainage at Mine Doyon South Waste Rock Dump. November.
- MEND 1.14.3f 1996. Revue technique des étude réalisées par NEDEM de 1990 à 1994 sur le drainage minier acide de la halde sud de la mine Doyon. novembre.
- MEND 4.5.1-1 1994. Review of Waste Rock Sampling Techniques. June.
- MEND 4.5.1-2 1994. Handbook for Waste Rock Sampling Techniques. June.
- MEND 4.5.4 1997. Guideline Document for Monitoring Acid Mine Drainage. October.
- MEND 4.6.5ac 1997. A Survey of *In Situ* Oxygen Consumption Rates on Sulphide Tailings: Investigations on Exposed and Covered Tailings. November.
- MEND 4.6.5b 1997. A Rapid Kinetic Technique for Measuring Reactivity on Sulphide Waste Rock: The Oxygen Consumption Method. December.

Anderson, M.E., Scharer, J.M., and Nicholson, R.V. 1999. *The Oxygen Consumption Method (OCM): A New Technique for Quantifying Sulphide Oxidation Rates in Waste Rock*. In: Sudbury '99 – Mining and the Environment II Conference Proceedings. Sudbury, Ontario. 13 to 17 September. Vol 3, pp. 1133-1142.

Gy, P.M. 1979. Sampling of Particulate Materials: Theory and Practice. Elsevier.

Higgs, T.W., Murphy, F.M. and Stewart, C.J. 1997. *ARD Assessment Program from Exploration to Operation: Case Studies from the Eskay Creek Mine*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 1, pp. 385-398.

Martin, J.C., Halbert, B.E. and Anderson, M.E. 1999. *Acid Rock Drainage Assessment Programs at the Kumtor Gold Mine, Kyrgyzstan, and the Bogoso Gold Mine, Ghana*. In: Sudbury '99 – Mining and the Environment II Conference Proceedings. Sudbury, Ontario. 13 to 17 September. Vol 1, pp. 281-290.

Nicholson, R.V., Rinker, M.J., Williams, G.M., Napier, W.A. 1999. *Assessment of Water Quality Associated with Underwater Disposal of Tailings and Waste Rock from the Voisey's Bay Project, Labrador, Canada*. In: Sudbury '99 – Mining and the Environment II Conference Proceedings. Sudbury, Ontario. 13 to 17 September. Vol 1, pp. 127-136.

Paktunc, A.D. 1998. Mineralogical Constraints on the Determination of Neutralization Potential and Prediction of Acid Mine Drainage. CANMET Report, Mining and Mineral Sciences Laboratories.

Poirier, P.J. and Roy, M. 1997. *Acid Mine Drainage Characterization and Treatment at La Mine Doyon*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 4, pp. 1485-1497.

Price, W.A. and Kwong, Y.T.J. 1997. *Waste Rock Weathering, Sampling and Analysis: Observations from the British Columbia Ministry of Employment and Investment Database*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 1, pp. 31-45.

Smolensky, J., Hockley, D., Lefebvre, R. and Paul, M. 1999. *Oxygen Transport Processes in the Nordehalde of the Ronnenburg Mining District, Germany*. In: Sudbury '99 – Mining and the Environment II Conference Proceedings. Sudbury, Ontario. 13 to 17 September. Vol 1, pp. 271-280.

2.3.3 MINE SURFACES

I. Discussion of Theory

Geochemical processes within tailings, waste rock piles, ore stockpiles, and in mines (e.g. pit walls and underground mine workings) can be acidic drainage sources. To better understand and predict water chemistry in and around mines, MEND in co-operation with the British Columbia Acid Mine Drainage Task Force sponsored the MINEWALL project (MEND 1.15.2). It involved a literature review, a geochemical assessment of Equity Silver Mines' Main Zone Pit in British Columbia, the development of a computer code (MINEWALL 1.0 (Morin 1990)) to predict pit-water chemistry, and recommendations for pit-water quality assessment studies (MEND 1.15.2c). MINEWALL 1.0 was refined under the direction of MEND and the BC AMD Task Force to produce MINEWALL 2.0.

II. Discussion of MEND Research

MEND 1.15.2a serves as the user's manual for MINEWALL 2.0. The fundamental objective of MINEWALL 2.0 is to provide an empirical tool to forecast chemical conditions within a mine.

MEND 1.15.2c assesses the application of MINEWALL 2.0 to the following three mines in British Columbia: Placer Dome's Equity Silver Mines Main Zone Pit, BHP Canada's Island Copper Mine Pit, and Noranda's Bell Mine. MEND 1.15.2b, *Literature Review and Conceptual Models*, presents the case studies and conceptual models upon which the MINEWALL 2.0 design was based.

III. Applications and Limitations

The MINEWALL 2.0 code can be run with a minimum of data to simulate geochemical processes within a mine. The results are dependent upon the representativeness of the input data. The site-specific predictive modelling completed in MEND 1.15.2c indicate the challenges that may be encountered in using MINEWALL 2.0. These challenges largely relate to sampling for the purposes of obtaining representative data.

At the Equity Silver Mines, Main Zone Pit, four MINEWALL monitoring stations were established with an additional station in the adjacent pit to define unit-area reaction rates (Morin 1990). Three of the stations were considered representative based on single rinse events and provided data for unit-area reaction rate calculations. As these stations were rinsed once, reaction rates over time remain unquantified. In addition, assumptions needed to be made regarding the availability and reactivity of the neutralization potential of the rock surfaces. The major input parameters that could not be measured/estimated were the percentages of the rock surfaces that were; 1) regularly flushed, 2) periodically flushed, and 3) not flushed. These percentages were determined by calibrating the MINEWALL 2.0 program to field pH conditions and adjusting the percentages to obtain reasonable matches of predicted and operational pH.

The MINEWALL 2.0 modelling of Noranda's Bell Mine demonstrated the sensitivity of the predictive program to surface reaction rates. The rates of acid generation and neutralization were based on a comparison of predicted and measured field values. The percentages of rock surfaces that are flushed regularly, periodically and not flushed were determined to be 18%, 2%, and 80% respectively.

In the MINEWALL 2.0 modelling of BHP Canada's Island Copper Mine Pit, the percentage of rock units was estimated based on an investigation of one area of the pit. The best-fit calibration of rock surfaces that are flushed regularly, periodically and not flushed were 30%, 5%, and 65% respectively.

IV. Base Method

Mine surface sampling includes pit wall washing where the resulting drainage from a rock face, fractured rock, etc. is sampled. The rock surfaces are characterized to provide supplementary information for predictive modelling purposes.

V. MEND and Relevant Publications

MEND 1.15.2a 1995. MINEWALL 2.0 User's Manual. September.

MEND 1.15.2b 1995. MINEWALL 2.0 Literature Review and Conceptual Models. September.

MEND 1.15.2c 1995. Application of MINEWALL 2.0 to Three Minesites. September.

Morin, K.A. 1990. Acid Drainage from Mine Walls: The Main Zone Pit at Equity Silver Mines. Report for the BC AMD Task Force and MEND (Associate Project).

Morin, K.A. and Hutt, N.M. 1995. *MINEWALL 2.0: A Technique for Predicting Water Chemistry in Open-Pit and Underground Mines*. In: Sudbury '95 – Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 3, pp. 1007-1016.

2.3.4 TREATMENT SLUDGE

I. Discussion of Theory

Treatment sludge is a by-product of the chemical treatment of acidic drainage. Sludge sampling and analyses are undertaken to obtain data on the chemical (i.e. metal content) and physical characteristics of the sludge, and its stability, and to provide a scientific basis for sludge management.

II. Discussion of MEND Research

MEND projects, in particular MEND 3.42.2a, have reviewed sludge production and disposal options.

III. Applications and Limitations

MEND 3.42.2a, *Characterization and Stability of Acid Mine Drainage Treatment Sludges*, and Zinck (1997) describes a project that involved the sampling and characterization of fresh and aged sludge collected from 11 sites including base metal, uranium, gold and coal mines. Fresh (i.e. end of pipe) and aged (i.e. sludge pond cores) sludge samples were collected to study the effect of natural sludge aging. The experimental procedures used for sample preparation, physical characterization, and chemical, mineralogical, thermal and leachability analyses as described in MEND 3.42.2a and Zinck (1997, 1999) would serve as useful references for readers planning a sludge sampling and analysis program.

Aubé and Zinck (1999) investigated the effect of three lime-based AMD treatment processes on the characteristics of the treatment sludge by-product. Raw (untreated) water quality was found to have the greatest influence on the characteristics of sludge. Influent that primarily contain iron tend to form a more stable sludge. The physico-chemical characteristics of the sludges that were characterized are shown in Table 2.3-5.

The treatment process also has an important effect on the sludge density and stability, as most significant density control occurs during sludge formation. As a general remark, lime sludges have a tendency to densify as a result of surface evaporation and freeze-thaw effects. However, even after aging, low density sludges will not attain the percent solids content of high density sludges.

Table 2.3-5
Physico-Chemical Characteristics of Sludges

Site	Mine	Lime-Based Process	Lime Type	Sludge Sample	Density (% Solids)	pH	Particle Size μm , D_{50} (% Solids)
Brunswick	Cu/Zn/Pb	HDS	CaO	Fresh	32.8	10.04	3.1 (24%)
Falconbridge Sudbury	Smelter/Ni	Basic	Ca(OH) ₂	Fresh	3.7	9.45	
				Aged	7.2	9.51	
Geco	Closed	Geco HDS	CaO	Fresh	27.8	9.32	2.7 (16%)
				Aged	60.0	9.32	
Heath Steele	Cu/Zn/Pb	HDS	CaO	Fresh	20.8	9.48	4.1 (16%)
Kidd Creek	Cu/Zn/Pb	Basic	CaO	Fresh	3.4	10.85	
				Aged	4.1	10.56	
Mattabi	Closed	HDS	CaO	Fresh	16.1	9.30	4.7 (16%)
				Aged	22.5	9.95	
Waite Amulet	Closed	HDS	Ca(OH) ₂	Fresh	18.5	8.90	4.7 (6%)
				Aged	24.8	9.62	

Source: Aubé and Zinck (1999)

IV. Base Method

MEND 3.42.2a addresses the need for standardized sampling, handling and characterization protocols for acidic drainage treatment sludges. The composition of treatment sludges varies and is dependant upon the acidic drainage source characteristics and climatic effects. To ensure that representative sludge samples are collected, it is preferable that a suitable sampling protocol is followed and that the sample is properly preserved for analyses. The sludge sampling protocol presented in the MEND 3.42.2a study is described below.

1. Planning the Sludge Sampling Program

Background information regarding the sludge and sludge pond should be assembled. This information can include engineering drawings, the sludge depth profile, and when available, data

on the sludge characteristics. The number of sludge samples required can be estimated using Table 2.3-6.

Table 2.3-6
Number of Samples to be Collected as a Function of Sludge Volume

Sludge Volume Disposed (m ³)	Number of Samples to be Collected
<10,000	3-6 ⁽¹⁾
10,000 - 50,000	7-12
50,001 - 100,000	13-18
100,001 to 1,000,000	19-40
>1,000,000	41 + (volume -1,000,000)/75,000 ⁽²⁾

Notes: ⁽¹⁾ Assumes six samples are sufficient to obtain an acceptable level of confidence for a project of 10,000 m³ (Ocean Chem Sciences Ltd. 1984).
⁽²⁾ Atkinson (1985).

Source: MEND 3.42.2a, Table 5

Sludge sampling stations should be selected after reviewing site-specific information including the pond dimensions and morphology, and the pattern of flows within the pond. Sampling stations can be positioned along sections across the pond, with the section locations based on sludge depth profiles when available.

2. Sludge Sampling

Sampling equipment is commercially available for grab and core sampling. Sampling equipment should be selected with the objective of preventing sludge loss during sampling. In MEND 3.42.2a, a hand corer was determined to be most suitable for collecting sludge cores in the winter through holes augered in pond ice. With a handle extension, a hand corer can be used to sample sludge at depths of 6 m.

In deep water where a hand corer is not practical, a Ballchek corer can be used. A Ballchek corer has a positive sealing mechanism that serves as a check valve to retain sludge in the core tube when the sampler is raised.

Sterile acrylic core tubes were used to contain and store the sampled sludge. A 5 cm I.D. x 50 cm L tube was used with the hand corer, and a 5 cm I.D. x 75 cm L tube was used with the Ballchek corer. Tubes were labelled to indicate the project number, site name and location, date, station number, sampler's name, and the purpose of the sample.

Grab samples of fresh sludge were collected in 20-L HDPE pails. The pails were also used to store the sludge samples.

3. Testing and Analysis of Wet Sludge Samples

Particle Size Distribution

Sludge samples collected for particle size distribution analysis should be stored at 4°C. A sludge having a high iron content should be stored under inert gas conditions in an airtight container to prevent the oxidation of ferrous iron to its ferric state. In addition, high iron sludge should be analyzed as soon as possible following collection.

Particle size analyses need to be carried out using wet sludge. Samplers need to take steps to prevent sludge drying, freezing or thawing as these processes may produce irreversible particle aggregation.

Sludge cores can be homogenized for test purposes. The conventional procedures of quartering, turning the sample over and over with a spatula, and using mechanical mixers can be used to homogenize sludge cores.

Organic Analyses

Deep freezing (e.g. to -80°C) can be used to maintain sludge sample integrity for organic analyses should there be a need to do so.

4. Testing and Analyses of Dry Sludge Samples

Three methods of drying are commonly used to prepare solids samples for analysis; air-drying, oven-drying, and freeze-drying. In MEND 3.42.2, freeze-drying was selected as most suitable for maintaining sludge sample integrity.

The freeze-drying process can be applied to samples of dry sludge and sediments obtained for the analyses of most organic components and inorganic constituents. The process involves the removal of frozen water from the sample through sublimation. Advantages of freeze-drying include:

- Volatile constituent loss is minimized;
- Low temperatures mitigate chemical changes in labile components;
- Most dried sludge particles remain dispersed;
- Particle aggregation is minimized; and
- Oxidation is minimized/eliminated.

Sample preservation technologies are largely intended to retard degradation due to oxidation, microbial processes, and the loss of volatile components. Temperature is an important factor that needs to be considered from the time of sample recovery to sample analyses. As a guide:

- After drying, sludge samples can be stored in containers at ambient or room temperature; and
- Sludge samples for organic and mercury analyses should ideally be stored at 4°C.

Sample storage time can affect physiochemical parameters, and as such, measurements of pH, Eh, temperature and cation exchange capacity should be made in the field whenever possible and immediately after sample recovery. Recommended storage times for different parameters are given in Table 2.3-7.

Table 2.3-7
Sampling Containers and Preservation Methods for Different Parameters
Measured in Sediments

Parameter	Suitable Containers	Preservation	Maximum Storage Time	Comments
Particle size	Polyethylene, Glass, Metal	Wet, 4°C, tightly sealed	14 days	Drying, freezing and thawing cause aggregation of particles
pH, Eh	Bucket or Core	Wet, undisturbed and untreated	Measure in the field	Very difficult and problematic temperature corrections
Metals	Polyethylene or Teflon	Dry (60°C), freeze (-20°C) or freeze dry	6 months	If samples will not be analyzed within 48 hours, they can be freeze dried at -20°C for up to 6 months
Mercury	Glass or Teflon	Freeze, -20°C	1 month	Mercury analysis is performed with wet samples

Source: MEND 3.42.2a (after Mudroch and Azcue 1995), Table C-2

V. MEND and Relevant Publications

MEND 3.42.2a 1997. Characterization and Stability of Acid Mine Drainage Treatment Sludges. May.

Atkinson, G. 1985. ODCA Sampling Project U390, Environment Canada, Environmental Protection Service, Ocean Dumping Program, Internal Document, p. 17.

Aubé, B.C. and Zinck, J.M. 1999. *Comparison of AMD Treatment Processes and Their Impact on Sludge Characteristics*. In: Sudbury '99 – Mining and the Environment II Conference Proceedings. Sudbury, Ontario. 13 to 17 September. Vol 1, pp. 261-270.

Mudroch, A. and Azcue, J.M. 1995. Manual of Aquatic Sediment Sampling. Lewis Publishers, Boca Raton, FL. Chapters 2, 6.

Zinck, J.M. 1997. *Acid Mine Drainage Treatment Sludges in the Canadian Mineral Industry: Physical, Chemical, Mineralogical and Leaching Characteristics*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 4, pp. 1691-1708.

Zinck, J.M. 1999. *The Stability of Lime Treatment Sludges*. In: Proceedings for Calgary '99 and the 101st Annual General Meeting of the Canadian Institute of Mining, Metallurgy and Petroleum. Calgary, Alberta. 2 to 5 May.

2.3.5 DRAINAGE SEDIMENTS (STREAM SEDIMENTS)

I. Discussion of Theory

Contaminants can be transported from an acidic drainage source and slowly accumulated in downstream sediments. The adsorptive capacity of sediments depends on the physical, chemical, and biological conditions of the waterbody. The rate of contaminant burial is reduced by water mixing due to wind energy and turnover events, and bioturbation - sediment movement due to benthic organisms.

Understanding the effect (if any) of acidic drainage contaminants on downstream sediments is important as the sediments are an integral component of the aquatic ecosystem. The tendency of sediments to act as contaminant sinks may produce increased concentrations of contaminants in comparison to the overlying water. Biologically toxic concentrations in sediments would not normally be detected by surface water quality monitoring programs.

II. Discussion of MEND Research

MEND 4.5.4, *Guideline Document for Monitoring Acid Mine Drainage*, includes comprehensive information on sediment monitoring. It identifies the following three broad categories of sediment monitoring.

1. Chemical characterization studies.
2. Investigations of the *in situ* benthic community.
3. Sediment toxicity assays.

Potentially influenced and reference waterbodies should be characterized. Bathymetric maps of potentially impacted and reference lakes in the greater study area will assist in selecting sampling locations. Sediment types, particularly fine sediments, and their distribution within the lakes also need to be identified. Rivers and streams are subdivided into depositional and erosional zones, and the sediment types in each zone are then identified.

Acoustic surveys such as echo soundings, ground penetrating radar, and seismic reflections or refractions can be used to characterize the surficial sediment layer and the underlying sediments. A low intensity sediment sampling program consisting of sample collection along transfers, can be used to identify zones of fine-grained sediment deposition. These zones are often in the deepest areas and represent the greatest potential for contaminant accumulation over the long term.

MEND 4.5.4 notes that as a minimum, the following information should be documented for samples collected during a preliminary sediment characterization program.

Physical logging:

- Equipment used for core collection.
- Name of the operator who collected, handled, and split the core.
- Description of splitting methods.
- Length of the retained core.
- Thickness of sediment units (may be based on colour).
- Consistency (e.g. soupy, soft, medium-firm, etc.).
- Texture (e.g. silty sand, sandy, clay, etc.).
- Structure (e.g. graded bedding, cross bedding, etc.).
- Presence and description of organic matter.
- Odour.
- Appearance of oil, coal dust, ash, etc.
- Presence of carbonates (Mudroch and Azcue 1995).

Recommended additional parameters are:

- Sediment grain size;
 - Important in determining the sorptive capacity (e.g. for heavy metals) of sediments.
 - Used to indicate the potential availability of contaminants to benthic organisms through ingestion of fine-grained materials.
- Total Organic Carbon or % Loss on Ignition;
 - Potential metal-adsorption capacity of the organic load in the sediment.
- Wet Weight/Dry Weight
 - For estimating the wet weight that will meet dry weight analytical requirements.

MEND 4.5.4 describes the development of an operational sediment monitoring program. This includes information regarding the selection of sampling station locations, sample replication requirements, particle size aspects, sample depth profile, where and when to sample, the sampling platform, the selection of sampling equipment, wet weight requirements for samples, and analytes or parameters of interest. Parameters commonly investigated at mine properties involve the visual description (e.g. physical logging) of the sediment, the wet to dry weight ratio, particle size distribution, total organic carbon (e.g. percentage loss on ignition), sulphides, ammonia and metal concentrations. The addition of sediment pH and Eh measurements, and acid volatile sulphide concentrations can be helpful.

III. Applications and Limitations

MEND 4.5.4 describes the requirements of a preliminary sediment survey needed to establish a technical basis for the development of an operational sediment monitoring program. The specific objective of the monitoring program will in turn affect the sediment sampling strategy and the selection of sampling locations. Three possible objectives are indicated in Table 2.3-8.

Table 2.3-8
Operational Sediment Monitoring - Possible Objectives

Objective	Description
1	To monitor the spatial and temporal influence along the drainage from an acidic drainage source
2	To quantify contaminant loadings and determine contaminant budget for a lake
3	To identify or locate sites of contaminated sediments on a quantitative spatial or temporal basis

Source: MEND 4.5.4

IV. Base Method

Sediments are sampled using grab samples and core samplers. Grab samples (Figure 2.3-8) are suitable for the preliminary mapping of surficial sediments and for the collection of samples for gross bulk chemical analysis. Core samplers (Figure 2.3-9) are used when the objective is to characterize the chemical composition of specific horizons.

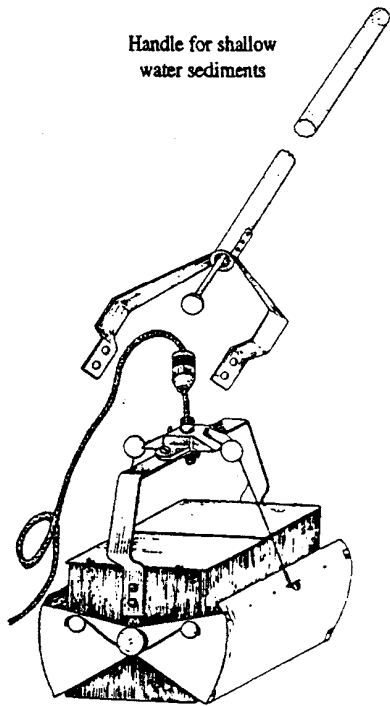
No single sediment sampler is suitable for all conditions.

V. Variations

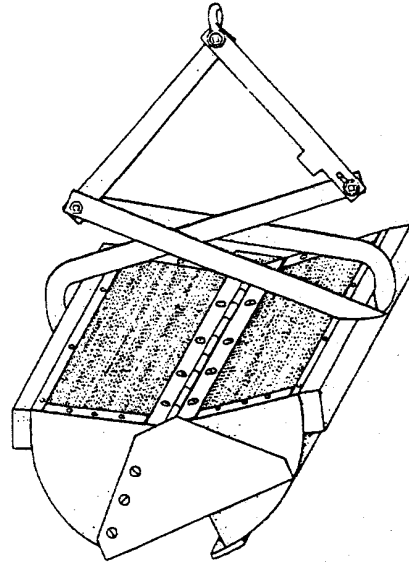
Sediment pore water can be indirectly extracted for analysis from collected sediments using centrifugation and sediment squeezing techniques. The key challenge in analyzing indirect pore water samples is obtaining representative pore water samples that have not been influenced by sediment oxidation. *In situ* and direct pore water sampling techniques are used to minimize the influence of sediment oxidation artifacts. Direct pore water sampling is carried out using suction samplers and dialysis samplers (also known as peepers).

Suction samplers involve the placement of a probe equipped with sampling ports into the sediment. Pore water is drawn through Teflon or ceramic filters in the sampling ports using vacuum pressure generated by a syringe, the release of pressurized gas, or a vacuum pump. A difficulty with these samplers is determining the appropriate pore size for the sampling port filter. Clogging can be problematic if the pore size is too small, and contamination can occur with fine-grained sediment particles when the pore size is too large.

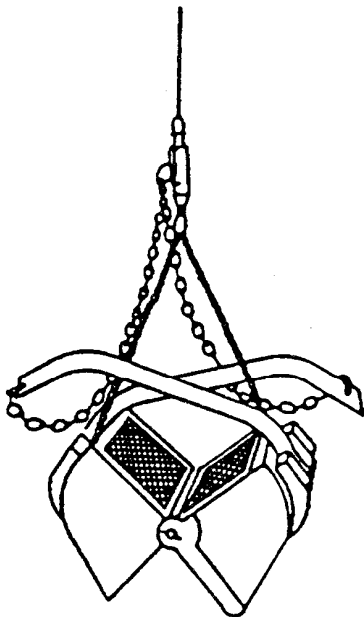
Figure 2.3-8 Commercially Available Grab Samplers



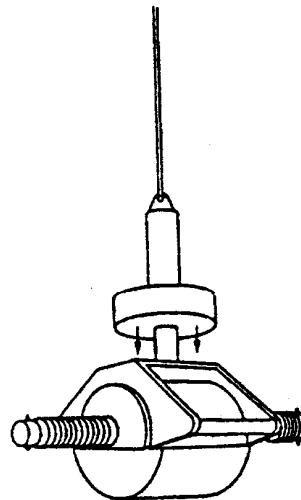
Ekman Grab Sampler



Ponar Grab Sampler



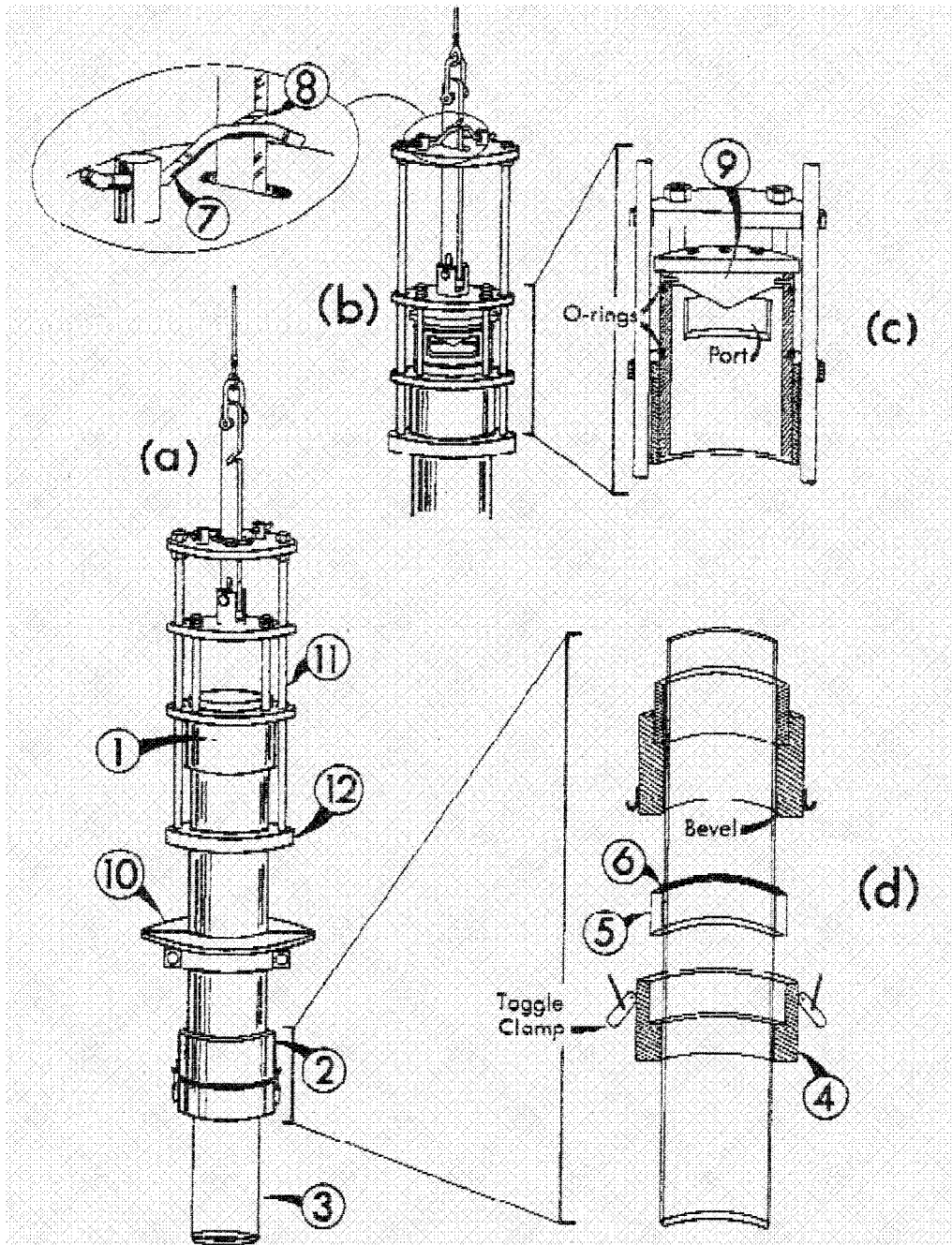
Van Veen Grab Sampler



Shipek Grab Sampler

Source: MEND 4.5.4 (After Merritt and Cummins 1984; Mudroch and Azcue 1995)

Figure 2.3-9 Gravity Corer



Notes: a) Complete corer showing sleeve valve closed b) upper half of corer showing open sleeve valve, two O rings and two ports c) sleeve valve detail d) lower collar detail showing barrel clamping mechanism.

Source: Pedersen *et al.* (1985)

Dialysis samplers use diffusion-controlled transport, where equilibration occurs across a dialysis membrane between the pore water and the water in the sampler. A peeper typically consists of two acrylic sheets; one 1.3 cm thick main body and a 0.3 cm thick cover (Figure 2.3-10). Elongated cells are machined into the main body. A dialysis membrane is placed between the main body and the cover sheet. The cover slots are aligned with the cells in the main body, and the cells are filled with deoxygenated double distilled water. All handling of the peeper prior to placement is done under oxygen-purged conditions. The peeper is driven into the sediments and the water in the cells is allowed to equilibrate over a designated time period (e.g. often 6 to 30 days). Depending on depth, divers may be used to place and retrieve the samplers after the designated testing period. The cells are sampled using a syringe within 5 minutes of the removal of the peeper from the sediments.

VI. Cost

The cost of sediment sampling is largely comprised of labour. Costs vary widely depending on the amount of time required to access the sampling locations, the techniques used to collect the sample, and special procedures required for sample handling and analysis.

VII. MEND and Relevant Publications

MEND 4.5.4 1997. Guideline Document for Monitoring Acid Mine Drainage. October.

AETE 4.1.4 1999. AETE Program Synthesis Report of Selected Technologies for Cost-Effective Environmental Monitoring of Mine Effluent Impacts in Canada. March.

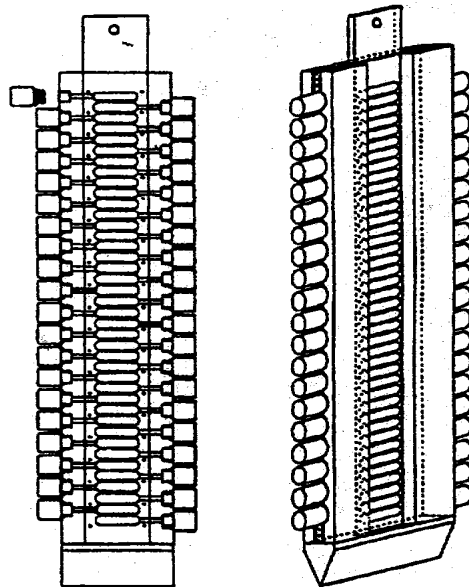
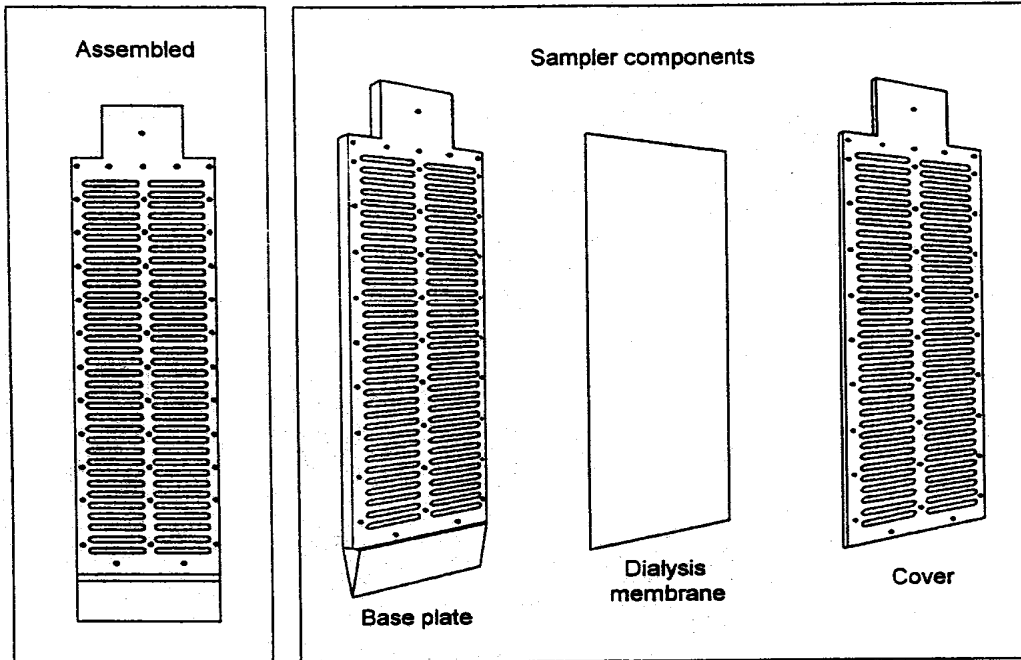
Azcue, J.M., Rosa, R. and Lawson, G. 1996. *An Improved Dialysis Sampler for the In Situ Collection of Larger Volumes of Sediment Pore Waters*. Environmental Technology. Vol 17, pp. 95-100.

Merritt, R.W. and Cummins, K.W. 1984. An Introduction to the Aquatic Insects of North America. 2nd Edition. Kendell Hunt Publ., Dubuque, IA.

Mudroch, A. and Azcue, J.M. 1995. Manual of Aquatic Sediment Sampling. Lewis Publishers, Boca Raton, FL. Chapters 2, 6.

Pedersen, T.F., Malcolm, S.J. and Sholkovitz, E.R. 1985. *A Lightweight Gravity Corer for Undisturbed Sampling of Soft Sediments*. Canadian Journal of Earth Sciences. Vol 22, pp. 133-135.

Figure 2.3-10 Front View and Components of a) Dialyzer (Peeper) Sampler and b) a Volume Enhanced Sediment Pore Water Sampler (VESPOS)



Source: MEND 4.5.4 (After Mudroch and Azcue 1995; Azcue *et al.* 1996)

2.4 BIOLOGICAL SAMPLING

The sampling of biological organisms in aquatic systems is an important component of monitoring programs. Monitoring programs are usually implemented to establish baseline environmental conditions and to detect changes in the species composition, abundance and/or distribution of plants and animals. These kinds of changes are typically monitored in a spatial context, to detect changes between affected and reference or control areas, or in a temporal context, where changes are monitored over time at a discrete location, from a baseline condition. The strength of a monitoring program lies in its ability to detect changes from baseline and differentiate these from natural variability.

MEND projects were conducted using well-established biological sampling methods and protocols, but did not sponsor the development of any sampling procedures.

Cost estimates are highly variable for biological sampling (depending on factors such as site accessibility, program objectives, weather conditions) and therefore were not included.

Biological sampling in water bodies can include periphyton, plankton, benthic invertebrates and fish, in order of ascending trophic level. Although the sampling of benthos and fish is most common, biological sampling is discussed below according to ascending trophic level.

2.4.1 PERIPHYTON

I. Discussion of Theory

Periphyton (algae attached to hard substrates along shorelines of lakes and streams) monitoring is not commonly included in effects monitoring (e.g. ARD) programs. However, periphyton sampling may be included as part of baseline characterization or to investigate mining-related effects or impacts. Periphyton sampling provides information on a major component of the aquatic ecosystem - the primary producers. Sampling can be done to evaluate changes in community structure (species present) or standing crop (chlorophyll α , biomass measured as ash-free dry weight), which is used as an indicator of productivity. Sampling periphyton is useful when there is a concern over increased nutrient levels (e.g. phosphorus leaching in ARD or nitrate loadings from explosives use).

II. Discussion of MEND Research

MEND 4.5.2 includes QA/QC protocols for periphyton sampling.

III. Applications and Limitations

Sampling of periphyton is conducted to acquire information on changes to primary productivity of lakes and streams where there is a concern over increased nutrient concentrations in the water. Sampling of periphyton should be combined with other methods of detecting changes in productivity. Despite the quantitative nature of the method, results can be quite variable depending on a variety of factors and should not be used in isolation to make definitive statements.

The base method described below (for sampling natural substrates) is applicable to sampling periphyton on natural, cobble/stone substrates on the margins of streams and lakes. Sampling of artificial substrates allows sampling in conditions where the base method would not work (e.g. large boulder substrates). Basically, sampling of periphyton involves sampling a known area (the usual unit is cm^2) to remove, enumerate, and measure the biomass of attached algae on a hard surface.

IV. Base Method

The British Columbia Ministry of Environment, Lands, and Parks *Biological Sampling Manual* (Cavanagh *et al.* 1994) describes a base method for sampling periphyton. The basic equipment includes:

- A template for defining the area to be sampled (this can be a flexible piece of plastic or rubber with a square or round hole of known size);
- A toothbrush and sharp blade to scrape algae free from the rock;
- Deionized water; and
- A turkey baster to transfer the sample from the scraping cup to the sample bottle.

The sampling method is as follows:

1. Select rocks that are relatively flat and large enough to accommodate at least three scrapings.
2. Brush and/or scrape algae off the rock, removing it evenly over the defined area. Squirt deionized water into the cup and transfer the water-algae mixture to a pre-labelled sample bottle and repeat.
3. If the algal density is low or patchy, collect at least five scrapings from each rock. Combine the scrapings to form a composite sample.
4. Repeat the procedure using additional rocks. At least five rocks should be used to prepare a composite sample.

Sample preservation depends upon the intended analyses. If chlorophyll α or biomass is to be measured, samples should immediately be placed in the dark (use aluminium foil or a dark coloured plastic garbage bag), and held on ice. As soon as possible after collection, samples should be filtered onto a membrane filter. The membrane filter should be wrapped in a larger (8 to 10 cm) Whatman-type filter and frozen. If the sample is to be analysed for taxonomy, it must be preserved with Lugol's solution (at least 1 mL of Lugol's for 250 mL of sample, more if algal growth is heavy).

V. Variations

Artificial substrates (e.g. clay tiles, plexiglass) can be used as an alternative to sampling natural substrates. These substrates have the advantages of being easier to sample than natural substrates and have less variability due to their uniform texture and history. Ideally, artificial substrate materials should be chosen to resemble the natural substrate and should be placed as close as possible to the natural substrate to ensure they are exposed to similar conditions of light, temperature, current, and water chemistry. Artificial substrates can also be damaged or lost.

VI. MEND and Relevant Publications

MEND 4.5.2 1992. Field Quality Assurance/Quality Control (QA/AC) Protocols for Monitoring and Predicting Impacts of Acid Rock Drainage. BC AMD Task Force Report. March.

AETE 2.3.2. 1997. Technical Evaluation of Monitoring Methods Using Macrophytes, Phytoplankton and Periphyton to Assess the Impacts of Mine Effluents on the Aquatic Environment. November.

Cavanagh, N., Nordin, R.N. and Warrington, P.D. 1994. Biological Sampling Manual. British Columbia Ministry of Environment, Lands, and Parks, Victoria, B.C.

2.4.2 PLANKTON

I. Discussion of Theory

Plankton consists of zooplankton (small, weak swimming animals) and phytoplankton (microscopic algae). Although monitoring of plankton is not often included in effects monitoring programs, such as for ARD, it has potential application when combined with other sampling methodologies, such as changes in benthic community composition. Phytoplankton standing crop and/or community structure could be used in a manner similar to periphyton standing crop and community structure, although this is not common.

II. Discussion of MEND Research

MEND 4.5.4 describes methods of plankton sampling. MEND 4.5.2 includes QA/QC protocols for plankton sampling. In addition, MEND 4.7.6, a review of the potential application of paleolimnology to ARD monitoring, suggested that, where baseline data are lacking, paleolimnological techniques could provide information on the phytoplankton (diatom) community that existed prior to ARD discharge.

III. Applications and Limitations

Sampling of phytoplankton and zooplankton can be applied to situations where it may be difficult to sample for benthos or fish, or to augment these programs. Collection of plankton can be done quickly and easily, and provides quantitative data. However, for these data to be meaningful, a good understanding of baseline conditions must be known, or an adequate reference area should be sampled, such that sufficient data are collected to distinguish possible anthropogenic effects from natural variability. For these data to be meaningful, good taxonomic identification, adequate temporal and spatial coverage and specialized knowledge in this discipline is required. Note that differences in plankton abundance and species composition can vary considerably over time (e.g. seasonally), as well as between lakes and years. Thus a good understanding of seasonal changes in species composition and density of plankters is usually required.

The base methods described below are applicable to sampling zooplankton and phytoplankton in lakes, estuaries and coastal marine areas where the water is relatively calm. Sampling for plankton in flowing water such as streams and rivers is not typically done.

IV. Base Methods

1. Zooplankton

Zooplankton are usually collected with a conical, fine mesh net (plankton tow net) (Figure 2.4-1) that has a specific mesh size (ranging from 64 μm to 256 μm). The mesh size used for a particular project will depend upon the productivity of the water body being sampled and the study objectives. For most studies, the British Columbia Ministry of Environment, Lands, and Parks recommends the smallest mesh size (64 μm) with a net mouth diameter of 20 cm. This provides detailed information on several life history stages of zooplankton, ranging from small juveniles to adults. Larger mesh sizes (e.g. 250 μm) are used to collect only the larger organisms or adult stages for studies requiring less life history information.

The base method for zooplankton sampling consists of vertical plankton hauls at discrete stations. The net is lowered to a specified depth (usually 10 m) and then slowly pulled directly up through the water column at a constant speed. In small lakes, the net is pulled by hand, using a consistent motion to move the net at a speed of approximately 0.5 m/s. In large, deep lakes, a

winch is sometimes required. The actual distance that the net travels through the water must be recorded, and the total volume of water that passes through the net must be calculated using the following formula:

$$V = \pi r^2 d$$

where:

V = volume of water filtered through sampler

r = radius of the net

d = depth of the net at start of vertical haul (total length of course through the water)

Zooplankton samples are preserved in 70% ethanol (70 mL for each 30 mL of sample volume). The density ($\#/m^3$) of zooplankters captured in each vertical haul is calculated based on results of a taxonomic enumeration of the species present. To facilitate data interpretation, only comparisons in density ($\#/m^3$) or biomass (gm dry weight/ m^3) of zooplankton should be made between sampling stations, lakes or years. Duplicate samples should be collected and combined to increase precision.

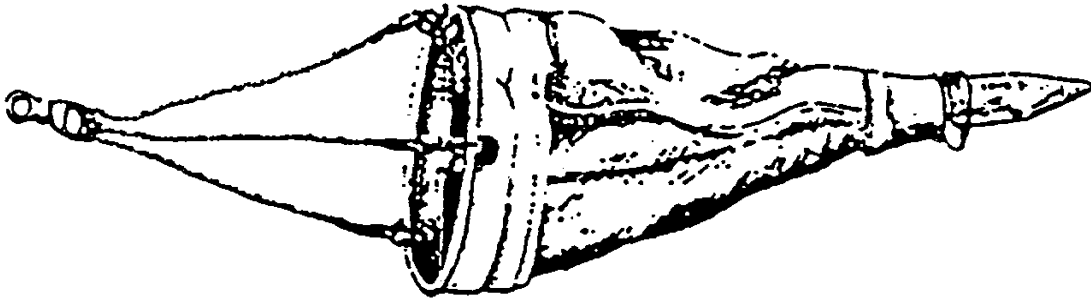
2. Phytoplankton

The base method for phytoplankton sampling involves the use of a van Dorn bottle. A van Dorn sampler consists of a plexiglass container that is open at both ends, armed with plungers that can be triggered to capture a sample of water from a discrete depth. Samples are usually collected just below the surface (also by hand) and at depth (one or more depths may be included in the study design, e.g. above, at or below the thermocline). When the sampler is lowered to a pre-determined depth, a messenger is sent from the surface that triggers the plungers to seal the bottle and capture the water sample. The sampler is then brought to the surface and the samples are preserved in the manner described for periphyton. A small aliquot of water is used by a taxonomist to determine the species composition and relative abundance of phytoplankton species present.

V. **Variations**

As an alternative to vertical tows, zooplankton may be sampled using horizontal or oblique tows, in which various strata of the water body are sampled individually (horizontal tow) or as a composite (oblique tow). These techniques sometimes require specialized equipment that is rigged to the boat and a tow net that has remote opening and closing capabilities. To determine the volume of water sampled by nets towed obliquely or horizontally, a device that measures flow through the net is mounted in the net mouth. To calculate the density of animals sampled, the volume of water filtered must be known. The sampling method chosen would be dictated by the study objectives (e.g. baseline data collection, seasonal changes in taxonomy or biomass).

Figure 2.4-1 Plankton Tow Net



Source: Cavanagh *et al.* 1994

VI. References

- MEND 4.5.2 1992. Field Quality Assurance/Quality Control (QA/QC) Protocols for Monitoring and Predicting Impacts of Acid Rock Drainage. BC AMD Task Force Report. March.
- MEND 4.5.4 1997. Guideline Document for Monitoring Acid Mine Drainage. Appendix A – Technical Summary Notes. October.
- MEND 4.7.6 1992. Use of Paleolimnological Techniques to Assess the Effects of Acid Rock Drainage. BC AMD Task Force Report. March.
- AETE 2.3.2 1997. Technical Evaluation of Monitoring Methods Using Macrophytes, Phytoplankton and Periphyton to Assess the Impacts of Mine Effluents on the Aquatic Environment. November.
- Cavanagh, N., Nordin, R.N. and Warrington, P.D. 1994. Biological Sampling Manual. British Columbia Ministry of Environment, Lands, and Parks, Victoria, B.C.

2.4.3 BENTHIC INVERTEBRATES

I. Discussion of Theory

Benthic invertebrates (animals living in or on bottom sediments) are commonly sampled as part of baseline characterization. Changes in benthic invertebrate community structure (species composition and abundance) can be used to evaluate impacts during the operational or closure phase of a mine. Because of their sessile nature, benthic invertebrates are directly influenced by mine-related discharges, thus monitoring of changes in benthic invertebrate community structure over time provides a good means of detecting effects.

The study area chosen for monitoring usually encompasses the region between the origin of a point source discharge and the boundary where ambient water chemistry conditions exist (i.e. where mine-related chemistry can no longer be reliably detected). Typically, changes to benthos in the area being monitored are compared to baseline data or to a reference area where similar physical and chemical conditions exist (e.g. an area upstream of a discharge source). The numbers of sampling stations monitored are a function of the size of the affected area and the amount of variability in benthic community structure (i.e. due to differences in depth, sediment type, and species diversity).

Benthic invertebrates are often key components of investigative monitoring programs and are likely to be an important component of Environmental Effects Monitoring (EEM) studies.

II. Discussion of MEND Research

Several MEND documents discuss sampling methods. MEND 4.5.4 includes chapters on benthic invertebrate sampling methods. MEND 4.5.2 includes QA/QC protocols for benthic invertebrate sampling and a summary of biases associated with different sampling devices. MEND also sponsored a study that used benthic invertebrates in artificial stream channels (troughs) to assess toxicity of ARD (MEND 4.7.2).

III. Applications and Limitations

Benthic invertebrate sampling methodologies are specific to particular types of substrates and environmental conditions. Different methods commonly apply to streams (rock/cobble substrate) and lakes/estuaries/marine habitats (usually sand or mud substrates). Large, fast-flowing rivers with coarse substrate are the most difficult habitats to sample, and no completely satisfactory method of sampling has been established. A comparison of the applications and limitations of different benthic invertebrate sampling devices is contained in Table 2.4-1. As with plankton, seasonal differences in the distribution, abundance, and species composition of benthic invertebrates exists and care must be taken to sample different areas at similar times. Benthic invertebrate populations are usually less variable in fall than other times of the year.

Table 2.4-1
Recommended Samplers for Collecting Benthic Invertebrates

Sampler	Hess	Box	Surber
Size	0.1 m ²	0.1 m ²	0.1 m ²
Habitat	Shallow, flowing streams, less than 32 cm in depth with good current; rubble substrate, mud, sand and gravel	Same as for Hess	Same as for Hess
Effectiveness	Relatively quantitative when used by experienced biologist; performance depends on current, substrate and mesh size	Same as for Hess	Same as for Hess
Advantages	Completely encloses area for sampling; prevents escape of organisms; stable platform; samples a unit area; can be used in weed beds.	Same as for Hess	Encloses area for sampling; easily transported or constructed; samples a unit area
Limitations	Difficult to set in some substrate types such as large rubble; cannot be used efficiently in still or slow moving waters.	Same as for Hess	Same as for Hess

Note: Stream-net samplers vary in size depending on the manufacturer, therefore it is important to always confirm the dimensions of the sampler used.

Source: MEND 4.5.3 (Adapted from Environment Canada 1993)

IV. Base Methods

1. Stream Sampling

Generally, the preferred method for small stream sampling is to use a net sampler. There are several varieties of net samplers, of which Hess and Surber samplers are the most common (Figure 2.4-2). A common feature of net samplers is a device that encloses or delineates a fixed area of substrate upstream of the net. This net is supported by a frame that directs the bag in the direction of the flow, such that invertebrates dislodged from the substrate are collected in the net. The recommended mesh size for the collection net ranges from 180 to 250 μm . Mesh size will vary according to study objectives and is a balance between study detail, expense, and abundance of organisms. To operate, the samplers require enough current to inflate the net. They generally cannot be reliably operated in depths much over 30 cm.

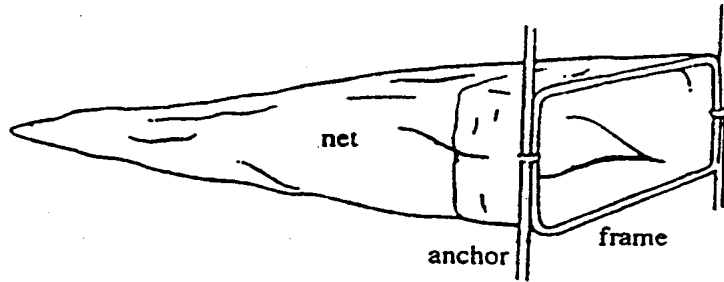
A net sampler is operated by placing it in a randomly-selected location within the stream, with the net oriented downstream. If rocks are present, they are lifted and brushed to dislodge organisms and then removed from the sampling area. The substrate within the enclosed area is hand-stirred for a fixed length of time (usually one to two minutes) to dislodge invertebrates from the substrate where they are captured by the net. The organisms are washed and/or picked from the collection net and placed in sampling jars and preserved. The next sample is collected from similar habitat at a randomly-selected location upstream of any area previously sampled.

In large, fast flowing streams or rivers, collection of benthos can be very difficult. Large artificial substrate traps filled with clean, native substrate (rocks and stones) can be set by divers and left to be colonized by invertebrates. Retrieval of the nets requires that divers place mesh bags over the traps to prevent the loss of organisms before the traps are raised to the surface. This is a logistically difficult, costly and risky means of monitoring benthos in large rivers. Despite this, few other quantitative measures exist for large rivers.

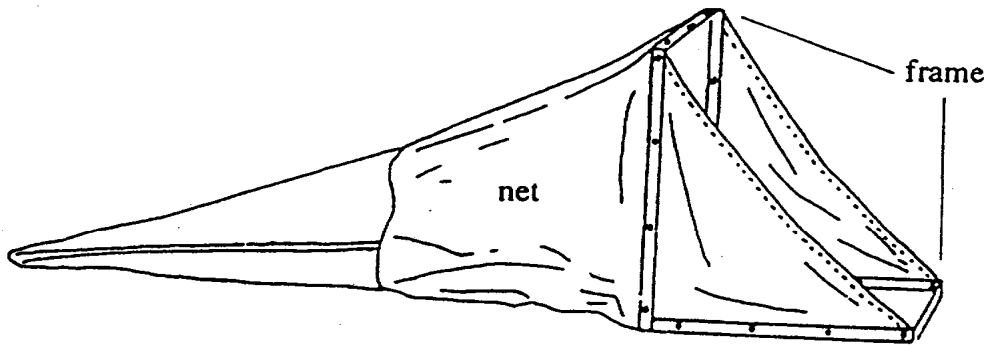
2. Lake and Estuary Sampling

The base method for collecting samples from lake and estuarine habitats is to use a grab sampler. There are several different designs of grab samplers, of which the most common are Ponar (standard or petite), Petersen, van Veen and Ekman (Figure 2.4-3). All of these grab samplers operate in a similar manner by capturing a known dimension of substrate. Typically a grab sampler is operated from a boat, usually by hand, but sometimes with a winch when using large grabs. The sampler is lowered to the bottom at a speed not exceeding 0.5 m/sec and allowed to penetrate the bottom substrate. It is important that the grab not be lowered too quickly, such that organisms below the sampler cannot detect the bow wave and possibly avoid capture. The grab is then triggered (upon contact with the bottom or with a messenger delivered from the surface) and then is slowly pulled or winched back to the surface.

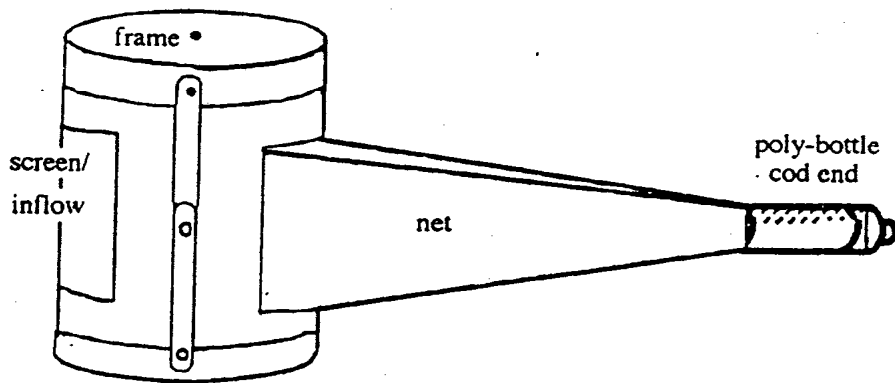
Figure 2.4-2 Common Benthic Macro-Invertebrate Samplers



Drift net sampler



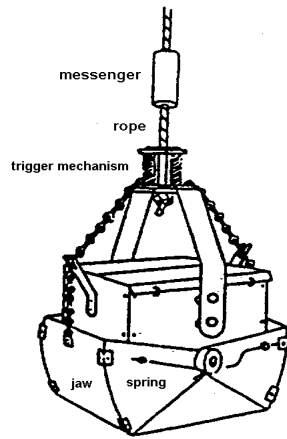
Surber sampler



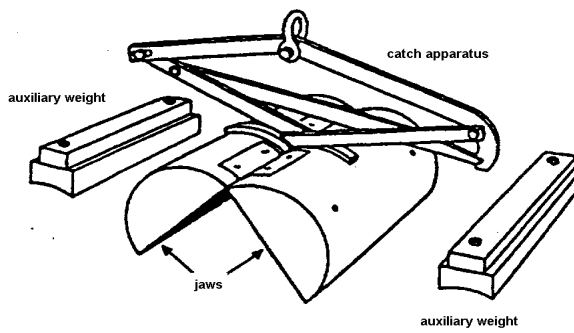
Hess sampler

Source: Cavanagh *et al.* 1994

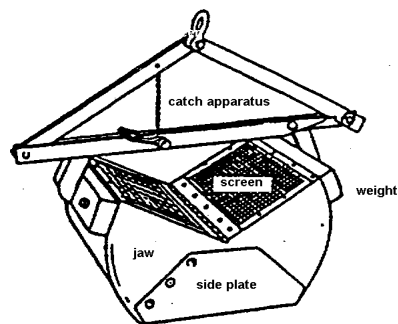
Figure 2.4-3 Common Sediment Grab Samplers



Ekman grab



Petersen Grab



Ponar grab

Source: Cavanagh *et al.* 1994

The type of grab sampler used will depend upon sediment type. Very soft sediments in small lakes or ponds are most easily collected by hand with an Ekman sampler. Coarser sediments may require larger, heavier devices such as a Ponar or van Veen sampler. In deeper lakes and estuarine environments where large, heavy samplers are required, use of a winch is necessary.

It is important that an intact, undisturbed sample is collected. Since rocks and twigs can prevent the jaws from closing completely, leakage from grab samplers can occur. Leakage can significantly bias sampling results, as different samples will be different sizes. These samples should be discarded. Therefore, it is important to set criteria for acceptable grab samples. EVS Environment Consultants (1993) recommend the following criteria for all grab samples:

- Overlying water should be present (indicates minimal leakage);
- Overlying water should be clear and not murky;
- The sediment surface should be relatively flat (indicates minimal disturbance or winnowing);
- The entire surface of the sample must be included in the sampler; and
- The sampler must have penetrated to a pre-established depth (acceptable depths will vary with substrate type).

3. Preservation

Benthic invertebrate samples should be preserved in the field using 10% formalin buffered with Borax to a pH of at least 8.2. Prior to preservation, grab samples should be sieved using a 180 to 250 μm screen to remove fine sediment particles and very small organisms. If a large amount of organic material still remains after sieving (or is present in a net sample), 20% formalin should be used. Again, the size of mesh used depends upon the level of detail required. Estuarine/marine samples are usually sieved with a 500 μm mesh screen.

Sampling jars should be properly labelled with indelible ink and include the following information: date of sample collection; location; and a unique sample station identifier. A label with the same information should be placed inside each jar. Jars should have secure lids to prevent leakage of preservative during transportation. Air transport of samples preserved in formalin may require hazardous goods transportation forms. If properly preserved and sealed, samples can be stored indefinitely.

IV. Variations

Artificial substrate samplers can be used instead of natural substrate samplers. They are particularly useful in large, fast-flowing rivers with large substrate where natural substrate samplers are ineffective or difficult to operate. There are two types of artificial substrate samplers, multiplate (Hester Dendy) and basket samplers. Multiplate samplers have standardized, reproducible surfaces, with uniform shape and known surface area. Basket

samplers may vary in size and shape. They are designed to be filled with natural rock that varies from 2.5 to 7.5 cm in diameter. Trays and bags can be used instead of baskets. The choice of sampling device will depend on the size of the river (depth, width), flow, and season.

Artificial substrate samplers have the advantages of reducing variability between samples and permitting greater flexibility in sampling programs. However, both types of artificial samplers have disadvantages. Artificial substrates obtained via artificial substrate samplers may not fully represent the natural community as some types of organisms prefer them, while others avoid them (this is particularly true for Hester Dendy samplers). Also, the use of artificial samplers does not account for long-term changes in benthic community structure and only measures differences for as long as the samplers are left in place. There are also other variables that can affect colonization of traps that may not be mine-related, such as depth, flow, season, food availability and so on. The use of artificial substrate samplers can be time consuming and labour intensive requiring two sampling trips, one to set the samplers and another to retrieve them. Animals are often lost as the sampler is brought to the surface. There is a potential for the entire sampler to be lost in the interim. In general, sampling of natural substrates is preferable to artificial substrate samplers.

V. MEND and Relevant Publications

- MEND 4.5.2 1992. Field Quality Assurance/Quality Control (QA/QC) Protocols for Monitoring and Predicting Impacts of Acid Rock Drainage. BC AMD Task Force Report. March.
- MEND 4.5.3 1994. ARD Technical Monitoring Manual. Open file report. February.
- MEND 4.5.4 1997. Guideline Document for Monitoring Acid Mine Drainage. Appendix A – Technical Summary Notes. October.
- MEND 4.7.2 1990. Literature Review for Biological Monitoring of Heavy Metals in Aquatic Environments. BC AMD Task Force Report. September.
- AETE 2.1.2 1997. Optimization of Field and Laboratory Methods for Benthic Invertebrate Biomonitoring. January.
- EVS Consultants. 1993. Guidelines for Monitoring Benthos in Freshwater Environments. Prepared for Environment Canada

2.4.4 FISH

I. Discussion of Theory

Fish are important monitoring organisms for several reasons. Fish have high economic value, are highly visible, and impacts to fish and fish populations are easily understood by the public. Also, fish are at the top of the food web and tend to integrate effects observed in lower trophic levels and thus are excellent indicator species. Effects on fish can be measured at the cellular level, individual level (i.e. tissue metals concentrations, health and condition), population level (e.g. changes in growth, fecundity), and the community level (e.g. ecological effects such as changes in species composition, relative abundance and distribution). The decision to measure effects at the individual, population, or community level will depend upon study objectives, affected environment (lake, stream, estuary), mechanism of effects, baseline conditions, availability of a reference area, and others.

Fish are sampled during baseline monitoring programs to document species composition, population size, and document population characteristics (e.g. length-weight relationships, age-structure, sex ratio, fecundity, growth). Sampling fish tissue to determine metals concentrations is also common. Fish population characteristics and tissue metal concentrations are commonly part of investigative monitoring programs implemented during the operation or closure phase of a mine. Some type of fish sampling is expected to be included in Environmental Effects Monitoring studies.

II. Discussion of MEND Research

Several MEND documents summarise sampling techniques. MEND 4.5.4 contains descriptions of fish sampling methods. MEND 4.5.2 includes a review of QA/QC procedures related to fish sampling.

III. Applications and Limitations

Fish capture techniques will vary according to the type of habitat that is sampled (stream, river, lake, estuarine environment), species, purpose of the study, weather conditions and others. Fish sampling methods will also vary according to whether monitoring of effects is being conducted at the individual, population or community level.

There is no defined base method for fish sampling and there are many applications and limitations of fish sampling gear. For example, electro-fishers and beach seines do not work effectively in water depths greater than 2-3 m. However, electro-fishers are very effective at sampling small streams where beach seines are completely ineffective. Minnow traps can be used in lakes and stream inlets or outlets, but do not provide quantitative data. The capture of fish by angling can be greatly affected by the skill and experience of the angler and it is difficult to account for this effect. Gill nets can be very effective at capturing fish of many species over a

wide size range. However, many factors can affect capture efficiency, such as season, water clarity and temperature, depth, mesh size, and experience of the fisher. Unlike benthos, fish are also very mobile and are able to move large distances over brief time intervals. Therefore, measuring tissue metals concentrations in fish that are migratory may not provide meaningful data. To summarize this, Table 2.4-2 lists the applications and limitations of different types of gear for collecting fish.

To detect effects on fish, quantitative comparisons should be made and compared to baseline conditions, if such data exist. If not, sampling of an appropriate reference area (such as a nearby lake, or upstream from a discharge site) should be conducted coincidentally. Because of the difficulty in separating mine-related effects from natural variability, good quantitative data and a good ecological understanding of the area(s) potentially affected are required.

IV. Methods

Fish capture methods and type of data requirements (e.g. tissue samples, abundance and growth data, etc.) will vary depending upon the study objectives and site specific conditions. A good understanding of the environment being sampled is a pre-requisite to ensure that meaningful, representative data are collected. For example, being prepared to use more than one capture technique may be important if the study objective requires that a specific number or species of fish are required for tissue analyses. Sampling of a reference area or a comparison to good baseline data is usually required.

The kinds of fisheries data normally collected include date, location, time, and method of capture, species, length (mm), and weight (g). If possible, sex and state of maturity should be recorded. If destructive sampling is required, sex, maturity, age structure, stomach contents, presence of parasites or other deformities should be noted and a tissue sample should be collected. Tissue samples should be placed in properly labelled sealed plastic bags and frozen until analysed, or for archival purposes.

1. Streams

Measuring fish population abundance in streams is usually accomplished by removal methods that involve temporarily removing the majority of fish in a small reach. The most common sampling methods are beach seining (where possible) and electro-fishing. This is accomplished by setting nets in a reach (e.g. 100 m) to prevent immigration and emigration of fish and conducting repeated sweeps of the reach to enumerate all fish. Fish are returned to the stream once sampling has been completed and changes in abundance over time are monitored. Large streams can be sampled with boat-mounted electro-fishers in a similar fashion. In addition, the use of hoop-nets or fyke-nets to monitor fish movements and migrations (for example, by mark-recapture studies) to enumerate fish populations and monitor abundance and utilization is also common. Comparisons of these data over time or with similar data in unaffected reaches will

Table 2.4-2
Recommended Fish Collection Gear

Sampler	Habitat	Effectiveness	Advantages	Limitations
Electroshocker	Flowing waters, such as rivers/streams, fresh and saltwater channels.	Useful for collections in relatively shallow, clear, flowing waters; most effective for collecting larger fish.	Portable (backpack) and boat-mounted types used; access to difficult locations, narrow streams/rivers.	Relatively ineffective for collections of small benthic fishes; poor results in hard and/or turbid waters.
Gill Net	All habitats.	Useful for size-selective collections; can be used in shallow and deep waters.	Can be deployed with (deeper waters) or without (shallow waters) a boat; low effort; variable mesh size for size selection	Fish may not remain viable for long; net can trap non-target organisms, such as fish-eating birds.
Seine Net	All habitats.	Useful in shallow water; most useful for collecting smaller fish	Easily deployed by two people in shallow waters.	Easily fouled on rocks or other debris.
Purse Seine	All habitats except fast-flowing rivers and small rivers/streams.	Used to encircle pelagic fish in deep waters; useful for collecting larger fish.	Relatively large areas can be encircled; large sample sizes can be obtained.	Boat is needed to deploy.
Otter Trawl	Lakes, estuaries, ocean.	Used mainly to collect benthic fish.	Useful in shallow and deep waters.	Boat is needed to deploy.
Angling	All habitats.	Useful in sites difficult to access with gear (e.g., under ice).	Useful in shallow and deep waters.	Small sample sizes are collected; biased in terms of species caught, age, size and condition of fish.
Trap Nets, Hoop Nets, Fyke Nets	All habitats but open ocean.	Generally not size selective; best suited to shallow water.	Useful for catching fish in difficult to sample locations and at awkward times (e.g., night); low effort.	Catch may be biased by the bait used.
Pesticide	All habitats but open ocean.	Useful only in backwaters, of limited use.	Effective in killing broad range of fish	Fish are killed; may not kill all fish, especially benthic species.

Source: MEND 4.5.3 (Adapted from Environment Canada 1992)

provide a quantitative means by which to determine the magnitude of possible effects. Individual fish can be acquired from each of these capture methods to measure tissue metals concentrations.

The British Columbia Ministry of Environment, Lands, and Parks' Biological Sampling Manual (Cavanagh *et al.* 1994) describes protocols for beach seining, electro-fishing and setting lines (a form of angling). It also details methods of processing fish tissues.

2. Lakes and Estuaries

The abundance and condition of fish populations in lakes and estuaries are usually measured using nets (e.g. gill nets and trap nets) and by angling. In very large lakes or estuaries, trawling or purse-seining is sometimes used. Studies conducted in large waterbodies are normally focussed at the population or community level, and not at the individual level. To determine possible effects on fish populations or communities, information on species composition, abundance, and distribution of fish is required. This requires that many fish must be captured from a relatively large area using quantitative, non-destructive techniques. For example, changes in relative abundance of lake, estuarine and marine fish populations are generally estimated using catch-per-unit-effort (CPUE) statistics (e.g. number of fish captured per 100 m of net per hour). Regions of lakes are fished repeatedly over time using gill nets (net sets are short to minimize mortality of fish) or trap nets to determine changes in the number of fish captured per unit time, in comparison with a reference area. Changes in CPUE are indicative of changes in fish species composition and relative abundance at the community level. In addition, changes at the population level such as growth, fecundity, condition factor and age-frequency distribution can be used to determine effects. Such studies are normally conducted over long time periods and require specialized knowledge.

Fish for tissue analyses can be collected using any of the methods used for population sampling. Minnow traps target smaller fish that are not easily sampled with nets and may be appropriate for use in some lakes. The British Columbia Ministry of Environment, Lands, and Parks' Biological Sampling Manual (Cavanagh *et al.* 1994) describes protocols for setting gill nets.

V. **MEND and Relevant Publications**

- MEND 4.5.2 1992. Field Quality Assurance/Quality Control (QA/AC) Protocols for Monitoring and Predicting Impacts of Acid Rock Drainage. BC AMD Task Force Report. March.
- MEND 4.5.3 1994. ARD Technical Monitoring Manual. Open file report. February.
- MEND 4.5.4 1997. Guideline Document for Monitoring Acid Mine Drainage. Appendix A – Technical Summary Notes. October.

AETE 2.2.3 1999. Technical Evaluation of Fish Methods in Environmental Monitoring for the Mining Industry in Canada. February.

Cavanagh, N., Nordin, R.N. and Warrington, P.D. 1994. Biological Sampling Manual. British Columbia Ministry of Environment, Lands, and Parks, Victoria, B.C.

Environment Canada. 1992. Aquatic Environmental Effects Monitoring Requirements.

2.5 GEOPHYSICS AND REMOTE SENSING

I. Discussion of Theory

The main applications for geophysical techniques in environmental monitoring for AMD are to:

- Locate, define and monitor conductive AMD groundwater plumes emanating from waste rock piles, tailings areas, or other minesite contaminant sources; and
- Characterize sulphide content of *in situ* rock destined to become waste rock.

Because geophysical surveys are not routine, they are most commonly contracted out to specialized contractors. Some surveys require special expertise and equipment, but it is possible to conduct some surveys using in-house staff without prior geophysical experience. Many mining companies will have staff experienced with geophysical surveys within their exploration departments, and they may be able to provide advice, equipment or even conduct the required surveys.

Geophysical surveys can be used as part of a larger study that includes borehole investigations and monitoring. Geophysical surveys are not a substitute for boreholes because no direct sample is obtained, but they can be used to minimize the number of boreholes required. This is done by using the geophysics data to precisely locate boreholes in specific areas of interest, and to correlate between boreholes. For these purposes, geophysical techniques are faster and cheaper than the additional drilling that would have otherwise been required.

For any geophysical technique to work, there must be a contrast between the material of interest and the background material. This should be evaluated on a case by case basis.

Electromagnetic (EM) surveys are most commonly used for measuring conductivity in the subsurface. Historically this is a well-proven technique used to find conductive massive sulphide ore deposits. It is now being adapted to detect and characterize conductive groundwater plumes containing conductive AMD products such as sulphate and metal ions. EM surveys can be conducted from the air, on the ground, or down boreholes.

EM surveys utilize a transmitter coil and a receiver coil. An alternating electromagnetic field generated by the source coil induces alternating secondary currents in the ground, which vary depending on the presence of any conductors. The resulting ground current is then detected at the receiving coil. No physical contact with the ground is required for EM surveys, which allows them to be conducted from the air as well as from the ground. EM survey results can be complicated by the presence of naturally conductive groundwater, conductive bedrock or clay soils.

Induced Polarization (IP) surveys are most useful for detecting disseminated sulphides. This is a proven technique for finding and characterizing ore deposits comprised of disseminated sulphides, such as porphyry copper deposits. IP is also being used experimentally to characterize disseminated sulphides within tailings areas.

IP surveys measure the time decay of a voltage applied to the earth after a pulse of current has been turned off. Two electrodes are placed into the soil, one transmitting the current, and the other receiving. The receiving electrode provides a measure of electrical polarization or chargeability of the subsurface. The strongest source of the IP effect is polarization at the boundary between electrolytic conduction in groundwater and metallic conduction in sulphide grains. The two electrodes are moved along a line to measure the chargeability at different locations to generate a profile. Different electrode spacings are used to determine changes in electrical polarization with depth.

II. Discussion of MEND Research

MEND has sponsored several studies in this area. MEND 4.6.1, *Applications of Geophysical Methods for Monitoring Acid Mine Drainage*, demonstrates and describes the use of electrical conductivity, induced polarization, self potential, and electromagnetic methods for monitoring acidic drainage. Examples of the use of these techniques at mine sites in the Sudbury area are provided. This report should be referred to if detail is required on geophysical methods as they relate to acidic drainage. The report contains appendices of technical notes on the various techniques, as well as numerous case studies.

MEND 4.6.3, *Application of Remote Sensing and Geophysics to the Detection and Monitoring of Acid Mine Drainage*, provides a compendium of information on methods presently in use, organizations active in the field, equipment and service suppliers, and lists of available products and equipment. Tabular form guides assist users to assess the applicability and effectiveness of techniques to detect and monitor acidic drainage.

III. Base Methods / Applications and Limitations

1. Airborne EM

Description: Airborne EM surveys are usually performed by helicopter and are commonly used in the exploration industry. A boom is towed underneath the helicopter which contains multiple coil configurations which can operate at multiple frequencies. This allows multiple data sets to be collected with one pass. The different frequencies and coil orientations provide information about conductive materials surveyed. Lower frequencies penetrate further into the earth. Coil configurations need to suit the geometry of the conductors. These differing responses provide information on the type of conductor being detected. Horizontal coplanar coils respond best to flat lying conductors such as contaminated water-saturated overburden, while vertical coaxial

pairs have a maximum response typical of subvertical sulphide or graphitic conductors in Canadian Shield bedrock.

Application: Detection and definition of conductive groundwater plumes. Detection and definition of conductive rock, either *in situ* or in a waste rock dump.

Limitations and Advantages: Airborne surveys are best suited to providing data over large areas at a relatively low cost. Apparent conductivity maps are valuable tools for reconnaissance mapping of groundwater quality. They are very useful in focusing follow-up investigations into well-defined areas. Airborne geophysical data has been used in the Sudbury area to quickly locate AMD groundwater plumes for follow-up using ground-based methods.

For any EM technique to be effective, there must be a contrast between background and target materials. The presence of conductive clay deposits could reduce the usefulness of airborne EM surveys. Man-made structures such as rail lines, buildings, power lines also can create local areas of anomalous conductivity which can obscure areas of interest.

Airborne EM data may already be available for a minimal reprocessing cost if the area has been flown for exploration applications, either by government or privately. Historic airborne data can be compared to recent data to determine any changes over time.

Recommendations: Excellent technique for reconnaissance investigations. Useful in defining specific areas where follow-up ground surveys are required, and therefore minimizing the cost of ground surveys.

2. Ground EM - Frequency

Description: Frequency domain EM surveys are the most common EM surveys. There are a variety of systems in use for environmental applications with various coil orientations and spacings which allow for depth penetration up to 48 m. All systems use circular transmitting and receiving coils, which may be held in a vertical or horizontal orientation. The smallest systems are operated by one person and utilize coplanar transmitting and receiving coils linked with a rigid boom.

An example is the EM31, which is one of a series of EM units that Geonics has developed specifically for environmental applications. This unit gives a depth penetration of up to 4 m. Two person units consist of a transmitting and receiving coil linked by a cable, such as the EM34 which can be used with separation lengths of 10, 20 or 40 m and can give information on depths up to 48 m.

Application: Used as a follow-up to airborne EM anomalies. Useful for defining locations for boreholes/monitoring wells.

Limitations and Advantages:

- Fast, easy to operate and relatively inexpensive;
- Does not necessarily require geophysical specialists to operate;
- Not suitable for environments with high background conductivity (transient EM is preferred); and
- Limited to maximum detection depth of 48 m.

Recommendation: This is the preferred ground geophysics-based method for detection of contaminated groundwater, unless the background environment is very conductive, or the target is deep.

IV. Variations / Applications and Limitations

1. Ground EM - Transient

Description: In transient EM discrete current pulses are transmitted, unlike frequency EM where a continuous current is transmitted. The decay with time of induced secondary currents is measured. Later signal values correspond to deeper zones. The measured voltages are converted to apparent resistivity for the various depths. The equipment differs from frequency EM systems. A large transmitter loop is laid out on the ground (minimum diameter of 20 m). The smaller receiver can be put anywhere, except near the transmitter. For large transmitter loops, the receiver is put in the centre of the transmitter loop. For smaller transmitter loops, the receiver can be put outside the transmitter loop.

Application: For use in high conductivity environments or for deep targets.

Limitations and Advantages:

- Deeper depth penetration than frequency EM;
- More costly and slower than frequency EM; and
- A conductivity target at depth may be masked by surface conductive material, such as clay deposits.

Recommendation: Due to higher cost, only use for targets where frequency EM systems are not suitable.

2. Induced Polarization (IP)

Description: Induced Polarization (IP) surveys measure the time decay of a voltage applied to the earth after a pulse of current has been turned off. A DC electrical current is passed between two current electrodes set on a survey line. Two potential electrodes are set up, typically inside the two current electrodes. The DC current is shut off and the time decay of the voltage in the ground is measured. This provides a measure of the electrical polarization or chargeability of the subsurface. The strongest source of the IP effect is polarization at the boundary between metallic conduction in disseminated sulphide grains and electrolytic conduction in groundwater.

The electrodes are moved along a line to measure the chargeability at different locations to generate a profile. Different electrode spacings are used to determine changes in electrical polarization with depth. Typically numerous readings from various electrode configurations are collected at each station to collect depth specific information which is plotted as a pseudosection that can be correlated to sulphide content.

Measurements of resistivity (and conductivity) can be made using the same electrode set up, with the current left on. Frequency domain IP systems are also used, in low signal, high background noise environments.

Limitations and Advantages: The advantage of geophysical methods such as IP 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. Geophysical methods must be used in combination with borehole investigations to correlate geophysical responses with measured parameters such as sulphide content.

IP does not work well in areas with resistive dry surface layers which limit the current that can be put into the ground. Also, IP does not work well in very conductive environments or where high voltage power lines cause interference.

Recommendations: Use existing exploration surveys of rock expected to become waste rock, to assist in characterizing sulphide content of a waste rock pile. IP can be used to characterize the sulphide content of tailings areas if no better information is available from other sources such as mill records.

3. Other Geophysical Methods

Other geophysical techniques, that may be applicable to AMD for special situations, or are useful indirectly, are described briefly below:

Seismic Refraction: Surveys can be used to map bedrock contours when bedrock is covered by overburden or tailings. This is indirectly useful for prediction of groundwater flowpaths when the underlying bedrock topography controls groundwater flow.

Radiometric: Surveys measure the total natural gamma radiation, emitted by uranium, thorium and potassium, and can be used to estimate the radioactive content of tailings/waste rock, which is relevant to AMD monitoring of uranium mines or mines that contain high levels of uranium associated with other metals. Down-hole gamma surveys are also used to log soil types; as finer-grained soils usually contain more gamma emitters.

Resistivity: Resistivity is another method of measuring conductivity and uses the IP set up. If an IP survey is being conducted, resistivity information should also be obtained. In a case where only conductivity is required, EM techniques are preferred over resistivity due to the ease and speed of EM surveys, which do not require electrodes to be placed in the earth.

Self Potential (SP): Surveys measure voltages present within the earth. A tailings area undergoing oxidation is a large electrochemical cell with a SP difference between the oxidizing top and the reduced bottom. Although this technique is experimental with respect to AMD monitoring, there may be some application in the future for providing data for predictive modelling of tailings. Self potential measurements can be made with minimal extra work while an IP/resistivity survey is being conducted.

VLF (Very Low Frequency): VLF surveys are another type of EM survey. For these surveys, distant US navy radio signals are utilized as the transmitter, and one person operates the receiver. These surveys are commonly used in exploration, however for environmental applications, EM surveys are more common.

4. Electrical Conductance Bottom-Contacting Probe

Application: The probe is an experimental reconnaissance technique used for locating groundwater contaminated by AMD where it discharges to surface waters, and estimating the impact of the contaminated groundwater (MEND 4.8.2). It is used to detect areas of discharge and to quantify the discharge.

Description: The sediment probe consists of a bottom-contacting tube towed from a small boat. The tube contains instruments to measure conductivity, pH, and radiation. The probe is dragged along the bottom in areas where groundwater discharge is suspected. Continuous data from the probe is transmitted via the cable to a data acquisition system aboard the boat. A shore-based laser positioning system can be used to determine the boat location.

Limitations and Advantages: The main advantage of the probe is that it is the only practical reconnaissance method for locating contaminated groundwater discharges to surface water. The alternatives, such as piezometer installations or seepage meters are not suited for reconnaissance investigations.

For the survey to be useful, there must be a good contrast between the contaminated groundwater and the surface water. Also, follow-up sampling using piezometers is necessary to identify chemical characteristics of any pH/conductivity anomalies identified by the probe. Ice cover in winter is another limitation.

Recommendations: This is a technique that should be considered for the early stage of any investigation where there is a concern regarding contaminated groundwater seepages discharging to surface waters, especially when the potential discharge area is large.

VI. Cost

Geophysical methods can reduce costs by reducing the number of samples and boreholes required, while providing the same information. Each case is site and method-specific.

VII. MEND and Relevant Publications

- | | |
|------------|---|
| MEND 4.6.1 | 1994. Applications of Geophysical Methods for Monitoring Acid Mine Drainage. December. |
| MEND 4.6.3 | 1994. Application of Remote Sensing and Geophysics to the Detection and Monitoring of Acid Mine Drainage. September. |
| MEND 4.6.4 | 1994. Piezocone Technology – Demonstration Project. Open file report. |
| MEND 4.8.2 | 1994. Evaluation of an Underwater Monitoring Probe for Locating and Estimating the Impact of Groundwater Discharges to Surface Waters Adjacent to Potential Sources of Acid Mine Drainage. March. |

2.6 CHEMICAL ANALYSIS

Chemical analysis of individual elements and compounds is an essential part of kinetic and static test programs to interpret the weathering process. Many labour intensive analysis have been advanced to rapid instrument determinations which have lowered cost and improved accuracy. MEND projects were conducted using well-established standard chemical analytical methods but were not involved in the development of any analytical procedures.

2.6.1 WATER

2.6.1.1 pH

I. Discussion of Theory

pH is the most frequently used water chemistry test. Practically every phase of water chemistry, including, acid-base neutralization, metal ion solubility, wastewater treatment and corrosivity is pH dependent. pH is defined as the $-\log_{10} [H^+]$, a measure of the degree of hydrogen ionization. The ionization of pure water is very low and results in equal concentrations of H^+ and OH^- ions. The resulting neutral pH is 7.0 at 25°C. Water with a pH <7.0 is said to be acidic, whereas water with a pH >7.0 is said to be alkali. The basic principle of pH measurement is the determination of the activity of the hydrogen ions by potentiometric measurement using a standard hydrogen electrode and a reference electrode. Due to the difficulty in the use of the hydrogen electrode, the glass electrode is commonly used. The electromotive force produced in the glass electrode system varies linearly with pH. Modern glass electrodes combine the reference and standard electrode in one unit which can be purchased in a number of different shapes, sizes and protective coatings. The electrode is calibrated over the measuring range using certified standard buffers standardized at a specified temperature prior to measuring the sample. The temperature of the sample should be the same as the buffers; otherwise the temperature of the sample should be recorded. Many pH meters have a temperature dial to adjust the potentiometric slope to compensate for temperature.

II. Applications and Limitations

pH is used for a variety of applications for mines, including:

- Paste pH of finely ground solids;
- Static and kinetic mine waste testing;
- Mine runoff and receiving water; and
- AMD treatment control systems.

pH can be used to estimate other parameters if a good relationship has been developed. For example, pH can sometimes be related directly to the amount of acidity and sulphate in AMD.

For mine application, the glass pH electrode is relatively free from the interference of colour, turbidity, suspended or colloidal solids, reductants, oxidants or high salinity. Temperature effects must be taken into consideration. Temperature has mechanical effects that are caused by the changes in the properties of the electrode when immersed in a sample at a different temperature than the electrode. As the temperature of the electrode changes to equilibrate with the sample temperature the pH value will drift until equilibrium has been obtained. Another effect is the change in the hydrogen ion activity with temperature. For example, the pH of pure water is 7.0 at 25°C and 7.5 at 0°C. Mechanical effects can be eliminated by allowing the temperature of the electrode and sample to equilibrate before measurement. The variation of hydrogen ion activity with temperature can be eliminated by recording the temperature at which the measurement was taken and making the necessary corrections.

A common problem with pH electrodes is fouling. The pH electrode is a potentiometric electrode which requires that an electrical circuit be completed to obtain a reading. Most electrodes are sealed combination electrodes with a ceramic wick which can become coated with scaling material associated with neutralizing products of AMD. Scaling is commonly caused by calcium carbonate which occurs when carbon dioxide reacts with excess lime (calcium hydroxide) and/or by gypsum (calcium sulphate), the product of acid neutralization with lime. When scaling occurs the pH electrode responds slowly and will soon become inaccurate. Both forms of scale can be easily removed by immersing the electrode in weak hydrochloric acid for a few minutes followed by thorough rinsing with tap water.

III. Base Method

The suggested base method is described in Standard Methods (1992).

Electrode Storage: The manufacturer's recommended procedure for pH electrode preparation and storage should be followed. The use of distilled water for electrode storage should be avoided since it causes excess leakage of ions through the ceramic wick. Tap water, or preferably pH 4 buffer or 2M KCl, are better for short-term storage.

pH Calibration and Measurement: During calibration or measurement the solution should be gently stirred. The electrode must be thoroughly rinsed and blotted with soft tissue to remove excess water before immersing in a different solution whether buffer or sample. The pH electrode is first calibrated with pH 7.0 buffer, which represents its isopotential point (0 mV). The electrode is then placed in an appropriate buffer that brackets the sample pH. For example, a sample with a pH of approximately 5 would require a buffer of 4.0. With the second buffer the "slope" dial is adjusted. The sample is now ready to read. pH measurements should be

conducted soon after the sample is taken. The sample temperature should also be recorded if different from the buffer temperature. The temperature compensation dial should be adjusted to reduce the effects of temperature.

IV. Variations

There are numerous colour indicators for pH which are useful when accuracy requirements of 0.5 pH units are acceptable (Kirk-Othmer 1995). The most common is litmus paper which turns red in acidic solutions and blue in alkali solutions. Litmus paper also comes in a double band which increases the accuracy of the reading. Colour indicators are a rapid trouble free method to obtain an approximate pH value.

V. Cost

Cost for measuring pH of liquid samples range from approximately \$5 to \$10 per sample while solid samples are \$7.50 to \$15 per sample. pH meters and electrodes can be purchased through various suppliers for laboratory or field use.

VI. MEND and Relevant Publications

Kirk-Othmer. Encyclopedia of Chemical Technology, Fourth Edition Volume 13. John Wiley & Sons, Toronto Canada, 1995.

Standard Methods for the Examination of Water and Wastewater. 1992. 18th Edition, APHA, AWWA and WEF, Washington DC.

2.6.1.2 Acidity

I. Discussion of Theory

Acidity of water is its quantitative capacity to react with a strong base to a designated pH. The major source of acidity in unpolluted waters is usually carbon dioxide. Titration to pH 8.3 at 25°C corresponds to stoichiometric neutralization of carbonic acid and bicarbonate in pure water. Titration using colour indicators such as phenolphthalein or metacresol purple, both of which undergo a colour change at pH 8.3, are suitable to obtain accurate results. In more complex mixtures such as acidic drainage, hydrolyzable metal constituents such as iron and manganese are treated with hydrogen peroxide at elevated temperature to ensure oxidation and rapid hydrolysis prior to titration for acidity. Highly variable results will be obtained if this procedure is not followed. Colour indicators should be avoided for coloured or turbid samples to avoid the difficulty in visually detecting the endpoint. Acidity for these samples should be determined potentiometrically to the desired pH.

II. Applications and Limitations

Acidity can be used for a variety of applications at mine sites, including:

- Determination of water quality from kinetic testing of mine waste;
- Determination of water quality for mine runoff and receiving water; and
- Estimation of lime requirements for AMD treatment.

Since most acidity determinations will be conducted with a pH meter, the limitations that apply to pH measurement (Section 2.6.1.1) are applicable to the accuracy of acidity determinations. For AMD treatment a direct correlation between acidity and lime addition cannot be made due to coating of unreacted lime which occurs during addition. Acidity measurements for kinetic testing do not correlate well with acidity release rates. These should be calculated from the concentration of sulphate in the leachate.

III. Base Method

The applicable methods are described in Standard Methods (1992) Section 2310. The sample must not be filtered, diluted, concentrated or altered in any way prior to analysis. For unpolluted samples a known volume of sample is titrated with standardized 0.1 N sodium hydroxide after adding a colour indicator for the desired pH endpoint. The titration should be carried out against a white background so that the colour change can be more easily observed. Residual chlorine, if present, must be destroyed by the addition of 0.1 N sodium thiosulphate solution. Samples containing hydrolyzable metals must be pretreated with hot peroxide prior to potentiometric titration to a designated pH. The final endpoint pH is reported with the acidity result, expressed in mg CaCO₃/L. The detection limit is dependent on the sample volume titrated and the concentration of the sodium hydroxide used. Generally, for unpolluted samples, a detection limit of 2 mg CaCO₃/L is obtained when using a 50 mL sample.

IV. Variations

A variation of the procedure applicable for acidic drainage samples is the construction of a titration curve. The initial sample pH is recorded, along with subsequent pH increases in 0.2 pH increments obtained from the step-wise addition of standard sodium hydroxide until pH 9 is reached. The inflection points of the titration curve will show the buffering effects at various pH levels. The acidity can be recorded for one or more of the inflection points.

V. Costs

Costs for acidity measurements by the base method range from \$8 to \$25 per sample, depending on source and complexity of sample.

VI. MEND and Relevant Publications

Standard Methods for the Examination of Water and Wastewater, Section 2310. 1992. 18th Edition, APHA, AWWA and WEF, Washington DC.

British Columbia Environmental Laboratory Manual for the Analysis of Water, Wastewater, Sediment and Biological Materials. 1994.

2.6.1.3 Alkalinity

I. Discussion of Theory

Alkalinity of water is its acid neutralizing capacity. Commonly occurring materials which can elevate the pH of water are carbonate, bicarbonate, hydroxide and other titratable bases such as phosphates, borates and silicates. Alkalinity is expressed as the equivalent amount of calcium carbonate in milligrams per litre, rather than as specific substance(s) present in the water sample. The principle of alkalinity measurement is the titration of hydroxyl ions in the sample, resulting from the dissociation or hydrolysis of solutes, with standard acid. Thus the alkalinity depends on the pH endpoint used. Depending on sample appearance - clear, coloured or turbid - colour indicators or potentiometric titrations can be employed for analysis. Alkalinity is determined by titrating to 8.3 initially and finally to 4.5. Titration to 8.3 is referred to as the phenolphthalein endpoint since this colour indicator can be used for the endpoint. Total alkalinity is represented by titration to 4.5. From these two endpoints the hydroxide, carbonate, and bicarbonate alkalinities can be calculated (Standard Methods 1992). Alkalinity relationships may also be calculated from nomographs.

II. Applications and Limitations

Alkalinity can be used for a variety of applications for mines:

- Determination of water quality from kinetic testing of mine waste;
- Determination of water quality for mine runoff and receiving water;
- Estimation of the neutralizing potential of the water for AMD treatment. For example, a high alkaline water could be mixed with acidic water to improve the water quality of the acidic water; and
- Calculation of the alkalinity forms (carbonate, bicarbonate and hydroxide) for modeling.

Since most alkalinity determinations are conducted with a pH meter the limitations that apply to pH measurements (Section 2.6.1.1) are applicable to the accuracy of alkalinity determinations. Alkalinity measurements for kinetic testing do not correlate well with alkali release rates. These should be calculated from the concentration of calcium and magnesium in the leachate.

III. Base Method

The base method for alkalinity is the potentiometric titration technique. Samples with high pH are titrated potentiometrically to pH 8.3 and finally to 4.5. The amount of mineral acid added is converted to equivalent mg CaCO₃/L and reported along with the titrated pH endpoint. Titration to pH 4.5 is a measure of total alkalinity. The detection limit is dependent on the sample volume titrated and the concentration of the mineral acid used. Generally for unpolluted samples a detection limit of 2 mg CaCO₃/L is obtained using a 50 mL sample. The suggested base method is detailed in Standard Methods 1992, Section 2320.

IV. Variations

Phenolphthalein colour indicator can be used for titration to pH 8.3 for samples that are relatively unpolluted (non-turbid and colourless). For samples with low alkalinity (<20 mg/L), an extrapolation technique can be used to obtain greater accuracy. Alkalinity measurements by automated systems which use a colourimetric endpoint can be used only if the samples are free of turbidity and colour. Free carbon dioxide, carbonate, hydroxide, and bicarbonate can be calculated nomographically if the pH, total alkalinity, temperature and total dissolved solids are known. This procedure should only be used when salts of weak acids other than carbonic are absent, or present in extremely small amounts (Standard Methods 1992).

V. Costs

Costs for alkalinity analysis range from \$10 to \$20 per sample.

VI. MEND and Relevant Publications

Standard Methods for the Examination of Water and Wastewater, Section 2320. 1992. 18th Edition, APHA, AWWA and WEF, Washington DC.

2.6.1.4 Sulphate

I. Discussion of Theory

Sulphate is a naturally occurring ion and may be present in waters over a wide concentration range. Acidic drainage may contribute large amounts of sulphate from oxidation of pyrite and other sulphide minerals. Increased levels of sulphate are usually the first indication of acid generation. Sulphate concentrations can be measured by ion chromatography, colourimetry, gravimetrically or turbidimetrically using either manual and/or automated procedures.

II. Applications and Limitations

Sulphate can be used for a variety of applications at mine sites:

- Determination of water quality from kinetic testing of mine waste;

- Determination of water quality for mine runoff and receiving water;
- Determination of acidity depletion for kinetic tests;
- Estimation of the lime requirements for treatment of acidic drainage; and
- Early indicator of acidic drainage.

The main limitation of sulphate occurs in the interpretation of data. The source of the sulphate ion can be incorrectly attributed to acidic drainage, when in fact it may be from solubilization of salts such as gypsum.

III. Base Method

The base method for sulphate analysis is the turbidimetric procedure, whereby sulphate ion in acidic medium is precipitated with barium chloride to form barium sulphate. The resulting suspension is measured by a photometer at 420 nanometers or with a turbidity meter. The instrument of use is calibrated with sulphate standards of known concentrations. Initial turbidity in the samples must be removed by filtration prior to analysis. The minimum detectable sulphate concentration by this method is 1 mg/L. The procedure is outlined in Standard Methods, Section 4500 E (1992).

IV. Variations

Sulphate concentrations that are <1 mg/L can be determined by ion chromatography. In this procedure the sample anions of interest are separated on the basis of their relative affinities for a low capacity, strongly basic anion exchanger. The advantage of this method is that other anions can be determined at the same time. The gravimetric procedure is a classical method based on the low solubility of barium chloride. The procedure is time consuming and is only used when sulphate levels are very high. Sulphate analysis has been automated by the methylthymol blue method. This colourimetric procedure can only be conducted on samples that are free of colour and turbidity. Sulphate can also be determined by ICP-AES (Section 2.6.1.8) provided sulphide sulphur is not present. The results are expressed as sulphur and must be converted to sulphate.

V. Costs

Cost for the base method ranges from \$10 to \$20 per sample, depending on the number of samples and pretreatment required.

VI. MEND and Relevant Publications

Standard Methods for the Examination of Water and Wastewater, Section 4500 E. 1992. 18th Edition, APHA, AWWA and WEF, Washington DC.

2.6.1.5 Redox Potential

I. Discussion of Theory

Redox (oxidation and reduction) reactions dictate the behavior of many chemical constituents found in potable, process and wastewaters and are of equal importance in biological systems where redox conditions control the mobility and reactivity of elements such as iron, sulfur, nitrogen, carbon and many metallic elements (Standard Methods 1992). Oxidation reduction potential (ORP) is determined potentiometrically using an inert indicator electrode, usually made from gold or platinum, and a reference electrode (calomel or silver/silver chloride). Combination electrodes are also available for ORP analysis. The potential measured with the ORP electrode system is proportional to the ratio of the concentration of reduced and oxidized constituents contained in the sample.

II. Applications and Limitations

Redox potential can be used for a variety of applications for mine sites:

- Estimation of the relative amounts of ferrous and ferric iron in acidic drainage water (Pourbaix 1966). For example, at pH 2.5 an Eh value of 450 mV using a silver/silver chloride reference electrode would indicate that the total iron is approximately equally divided between the ferrous and ferric states;
- Determination of the degree of oxidation of the iron in AMD. The Eh data can be used to determine the quantity of oxidizing agent that is required to oxidize all ferrous iron to the ferric form; and
- Determination of the general water chemistry data for mine runoff and kinetic testing.

While measurement of ORP is relatively straightforward, limitations are imposed on the interpretation of the results by factors such as electrode poisoning, irreversible reactions, inert or multiple redox couples. However, properly executed analysis and interpretation is useful in developing a more complete understanding of water chemistry.

III. Base Method

Since it is not feasible to calibrate Eh electrodes over a range of redox potentials, standard solutions of known redox potential are used to check for electrode response at the temperature of measurement. The manufacturer's instructions should be followed for the preparation of electrodes and standard solutions and the application with the pH/millivolt meter. The calibration solution and the sample to be tested should be at the same temperature. The readings are stabilized by gentle magnetic stirring. The millivolt reading obtained and the sample temperature are recorded if different from the standard solution. If the millivolt readings for the standard is outside ± 10 mV of the theoretical value, the calibration should be repeated after

cleaning the electrodes according to the manufacturer's instructions. The type of reference electrode used for measurement must also be reported with the results. The suggested base method is outlined in Standard Methods, Section 2580 (1992).

IV. Variations

There are no recommended variations for redox potential.

V. Costs

Cost for analysis is \$5 to \$10 per sample.

VI. MEND and Relevant Publications

Standard Methods for the Examination of Water and Wastewater, Section 2580. 1992. 18th Edition, APHA, AWWA and WEF, Washington DC.

Pourbaix, M. 1966. Atlas of Electrochemical Equilibria in Aqueous Solutions. (Translated by J.A. Franklin). Pergamon Press, New York.

2.6.1.6 Total Dissolved Solids

I. Discussion of Theory

Total dissolved solids, also referred to as filterable residue, represents the portion of the sample (water, wastewater, effluent) that passes through a filter of a particular size. Generally, a pore size of 0.45 μm is considered to be adequate to differentiate between microscopic particulate and dissolved material. The final result, after evaporation and drying to constant weight at 180°C, represents the total dissolved solids.

II. Applications and Limitations

Total dissolved solids (TDS) can be used for a variety of applications at mine sites:

- Determination of water quality from kinetic testing of mine waste;
- Determination of mine runoff and receiving water quality;
- General check of other water quality parameters. For example, total dissolved solids should approximate the sum of all dissolved cations and anions analyzed in a water sample. Any suspect samples can be reanalyzed; and
- Calibration of another parameter. For example, sulphate concentration can be calibrated to TDS allowing reduction in frequency of analysis of either parameter.

Total dissolved solids results are limited to providing a measure of the total water soluble fraction and do not reveal the quantity or type of individual contaminants in the sample.

III. Base Method

The suggested base method is outlined in Standard Methods (1992) Section 2540C. In preparation for the analysis, a clean evaporating dish is heated in an oven at 180°C for one hour. After cooling in a desiccator, the dish is weighed on a four or five decimal balance immediately before use. The filter paper to be used is prepared by washing with several portions of distilled or deionized water on a vacuum filtration unit. Most commonly, glass fibre filter discs, such as Whatman 934 AH, Gelman type A/E, Millipore AP 40 and others are used for the filtration of the sample. A known volume of sample is filtered through the prepared filter. The filtrate is collected in a clean flask and the filter is washed with three successive 10 mL portions of reagent grade water which are added to the filtrate. The total volume of filtrate and washings is transferred into the preweighed evaporation dish and placed on a steam bath for evaporation. Ideally, sufficient sample is processed to obtain 10 to 200 mg of residue. Analysis is completed by heating the evaporating dish for at least one hour in an oven at 180°C. The dish is then cooled in a desiccator and weighed. The cycle of drying, cooling and desiccating is repeated until a constant weight is obtained. The total dissolved solids are reported as the increase in weight of the dish per unit volume of sample, mg/L.

IV. Variations

A combination TDS/conductivity meter is applicable for field use which can provide an estimate of TDS concentration.

V. Cost

Cost for total dissolved solids analysis ranges from \$8 to \$15 per sample. The field unit costs approximately \$400 (Cdn).

VI. MEND and Relevant Publications

Standard Methods for the Examination of Water and Wastewater, Section 2540C. 1992. 18th Edition, APHA, AWWA and WEF, Washington DC.

2.6.1.7 Conductivity

I. Discussion of Theory

Conductivity is a numerical expression indicative of the ability of an aqueous solution to carry an electric current. This ability depends on the presence of ions, their mobility, valence, total concentration and the temperature of measurement. Conductivity is defined as the reciprocal of resistance. The conductivity of a solution is measured between two spatially fixed inert electrodes of known surface area. Conductance is directly proportional to the electrode surface area and inversely proportional to the distance between the electrodes. The constant of

proportionality, k , is called conductivity or specific conductance. In the international system of units, conductivity is reported as millisiemens per metre (mS/m); $1 \text{ mS/m} = 10 \text{ } \mu\text{mhos/cm}$ and $1 \text{ } \mu\text{S/cm} = 1 \text{ } \mu\text{mho/cm}$.

II. Applications and Limitations

Conductivity can be used for a variety of applications at mine sites, such as to:

- Compare with other water quality parameters to show potential gross errors in analysis. For example, an increase or decrease in conductance of a particular water source will result in a similar increase or decrease in other water quality parameters such as total dissolved solids, sulphate and metals. If this is not observed, analysis should be considered suspect and repeated;
- Establish degree of mineralization to assess the effect of total concentration of ions on chemical equilibria; and
- Estimate the total dissolved solids in a sample by multiplying conductivity by an empirical factor determined from analysis.

Conductivity results given alone are very limiting as they do not measure individual contaminants nor the overall state of the water.

III. Base Method

The base method is described in Standard Methods, Section 2510 (1992). The conductivity of a sample is measured with a self-contained conductivity meter (Wheatstone bridge or equivalent). The instrument must be standardized with KCl solutions of known conductance before use. The cell is washed with 0.01 M KCl followed by one to two rinses with the sample prior to measurement. Temperature corrections are made if the sample is not analyzed at 25°C.

IV. Variations

The conductivity can be calculated from measured ionic concentrations as outlined in Standard Methods 1992.

V. Costs

Analytical costs for instrumental measurement of conductivity range from \$4 to \$10 per sample.

VI. MEND and Relevant Publications

Standard Methods for the Examination of Water and Wastewater, Section 2510. 1992. 18th Edition, APHA, AWWA and WEF, Washington DC.

2.6.1.8 Metals

I. Discussion of Theory

A wide range of analytical techniques are available for the detection and quantification of metal analytes. These techniques can be classified into two main groups, namely spectroscopic and non-spectroscopic techniques. Spectroscopic techniques include the following:

- Atomic Absorption Spectroscopy (AA)
- Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES)
- X-Ray Fluorescence Spectroscopy (XRF)
- Inductively Coupled Plasma Mass Spectroscopy (ICP-MS)
- Neutron Activation Analysis (NAA)

Non-Spectroscopic methods include, but are not limited to, the following:

- Ion Chromatography
- Titrimetric and Volumetric Methods
- Colourimetric Analysis
- Gravimetric Methods
- Specific Ion Electrode Methods
- Polarographic techniques

Spectroscopic techniques are based on the premise that all elements absorb and emit radiation at specific and characteristic wavelengths, and the ability of a spectrometer to measure the absorption/emission produced. Therefore, elements can be identified by their characteristic radiation and quantified by the spectroscopic technique.

The analysis of metals by non-spectroscopic methods usually involves the separation of the analyte of interest from its matrix by basic chemical procedures and final quantification by gravimetric, colourimetric, conductivity, volumetric or other means.

II. Applications and Limitations

Metal leaching into the environment is the principal concern of acidic drainage. Metal analysis is one of the key parameters in assessing the weathering characteristics of mining waste. Metal analysis are applicable to determine:

- Water quality for kinetic testing of mine waste; and

- Water quality of mine runoff and receiving water.

Metal analysis is only limited by selection of the appropriate analytical method and proper sampling and preparation.

III. Base Method

The base method for determining metals in solution is plasma emission spectroscopy. This method is described in Standard Methods 1992, Section 3120. To obtain precise and accurate analytical results, environmental and process sample integrity must be maintained by following sample collection and preservation protocols that will ensure elimination of potential contamination sources and loss of analytes. Samples destined for total metal analysis must be digested prior to analysis to ensure extraction of the elements of interest from non-filterable constituents and destruction of organics contained in the sample. Digestion procedure blanks should be prepared concurrent with the samples.

For dissolved metal analysis the sample is filtered through a 0.45 μm polycarbonate membrane or fluorocarbon filter. The filtrate is acidified with purified nitric acid to a pH of <2 for preservation of the metal species. If precipitates develop after filtration and addition of acid, the filtered sample must be digested as for total metals.

Inductively coupled plasma atomic emission spectroscopy analysis (ICP-AES) is particularly useful when the concentration of a large number of metals is required in samples. In ICP-AES, atomic spectra is measured in the ultraviolet, visible, and near infrared region of the electromagnetic spectrum. Prior to excitation and measurement, the sample must be atomized. In AES, the ICP provides the energy for atomization and excitation. ICP-AES is a rapid multi-element technique capable of simultaneous analysis of major, minor and trace elements in solution, including digests of sediment, soils and biota. No specific operating instructions are feasible due to the diversity of makes and models available. The manufacturer's instructions should be followed for operating conditions, instrument calibration, quality control, analysis of samples, interference checks and inter-element correction procedures.

IV. Variations

Due to the differences between the various makes and models of AA spectrophotometers, detailed instructions applicable to every instrument cannot be given. The manufacturer's operating instructions for the particular instrument must be followed. In general, the sample is aspirated and vapourized into a flame produced by air-acetylene or, for refractory elements, an acetylene-nitrous oxide flame, to produce ground state atoms. The reference beam is produced by a hollow cathode lamp of the element of interest. The reduction of light intensity caused by the light absorbed by the atomized element is measured and correlated directly with the concentration of the elemental atomic species. For the determination of parts per billion

concentrations, the atomic absorption spectrophotometer can be fitted with a graphite furnace for flameless atomic absorption analysis.

Plasma mass spectrometry (ICP-MS) provides greater sensitivity for most elements compared to ICP-AES; however, the cost is substantially higher and total dissolved solids content must be kept low to avoid adverse instrument performance. Dilution of samples, therefore, can result in substantially decreased detection limits. In contrast to plasma emission spectroscopy, the plasma generated ions in ICP-MS are introduced to the mass spectrometer, where they are separated according to their mass to charge ratio. In this manner the constituents of an unknown sample can be identified and quantified.

V. Costs

Costs for ICP-AES multi-element scans, depending on the number of analytes and detection limits required, range from \$30 to \$80 per sample. Single element analysis by flame AA range from \$5 to \$15 per sample while flameless atomic absorption analysis costs range from \$10 to \$25 per sample.

VI. MEND and Relevant Publications

Standard Methods for the Examination of Water and Wastewater, Section 3120. 1992. 18th Edition, APHA, AWWA and WEF, Washington DC.

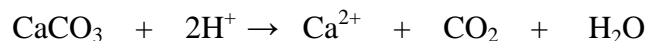
British Columbia Environmental Laboratory Manual. 1994. Laboratory Services Environmental Protection. Department Ministry of Environment, Lands and Parks Province of British Columbia.

2.6.2 SOLIDS

2.6.2.1 Carbonate

I. Discussion of Theory

Carbonate minerals, such as calcite and aragonite, are considered to be the main sources of neutralizing potential (NP). Carbonate content is determined indirectly by reacting a finely ground sample with a mineral acid to liberate CO₂:



The CO₂ is then measured and expressed in equivalent kg CaCO₃/tonne of waste material. This value can be compared with NP values obtained from ABA analysis. Correlation between ABA-NP and carbonate-NP shows what portion of the ABA-NP is associated with carbonate minerals

and what portion is associated with non-carbonate minerals. Since most carbonate minerals react quickly to neutralize acid their contribution to the ABA-NP is of major significance.

II. Discussion of MEND Research

MEND 1.16.1c discusses determination of carbonate forms by HCl digestion and atomic absorption measurement of calcium and magnesium. It was assumed that calcium and magnesium released due to HCl digestion could be directly correlated to calcite in the sample. However, the presence of calcium and magnesium silicate minerals in basic rocks (e.g. granodiorite) could also lead to the release of Ca and Mg, which resulted in poor correlation.

III. Application and Limitations

Carbonate analysis may be used to evaluate the following typical data requirements at mine sites:

- Carbonate analysis can quickly show what portion of the NP is associated with reactive carbonate minerals;
- Possible correlation of carbonate-NP with ABA-NP to support the ABA data;
- Correlation of carbonate-NP and ABA-NP may allow investigators to substitute ABA-NP determinations for less expensive carbonate analysis; and
- Carbonate determination can be used to confirm the presence of carbonate by petrographic examination.

The main limitation of carbonate analysis is in the correlation to ABA-NP. Carbonate-NP excludes NP associated with other neutralizing minerals such as silicate minerals, natural oxides and hydroxides and phosphates. The presence of these minerals will result in a poor carbonate-NP/ABA-NP correlation. In addition, carbonate minerals such as siderite (FeCO_3) and malachite ($\text{Cu}_2\text{CO}_3(\text{OH})_2$) will give erroneously higher carbonate-NP values. For example, the NP associated with siderite is questionable since neutralization of siderite and subsequent oxidation of ferrous to ferric iron will generate the same amount of acid upon hydrolysis of the ferric iron as was consumed during siderite dissolution (MEND 1.16.1c).

IV. Base Method

The base method for carbonate determination is direct measurement of CO_2 evolved from an acid digestion. The evolved CO_2 can be determined by either volumetric, gravimetric or titrimetric methods. The volumetric method described by Jeffery (1981) is the preferred method. In this procedure 0.20 g of pulverized sample is leached with dilute hydrochloric acid. Evolved carbon dioxide is carried into a measuring burette by a stream of oxygen. The gases are then passed through a potassium hydroxide solution that dissolves carbon dioxide. The oxygen is returned to the burette and the volume is again measured. The difference in volume, corrected for

temperature and atmospheric pressure, is proportional to the percentage of inorganic carbon in the sample. The detection limit is 0.2% carbonate. The evolution of H₂S from pyrrhotite breakdown or H₂ from metal contamination can give erroneously higher results. If these are known to be present analysis should be carried out by another method, such as the coulometric described below.

V. Variations

In the coulometric procedure the CO₂ is absorbed quantitatively into a cell containing a solution of ethanolamine. The CO₂ produces a colour change in the pH indicator and a corresponding increase in the light transmittance. Hydroxyl ions are electrically generated to restore the colour and the original transmittance value. The total current consumption is automatically integrated and the result expressed in micrograms of carbon absorbed. This value is then expressed in equivalent kg CaCO₃/tonne. The method has a detection limit of 0.01% carbonate. The procedure is described by Morrison *et al.* (1990) and Sviridenko *et al.* (1983).

Another procedure is ignition of the sample with a LECO furnace. Two carbon analysis are required. Part of the sample is analyzed for total carbon through ignition and measurement of the CO₂ released. Another portion of sample is treated with 15% HCl to remove carbonate-carbon and re-analyzed for carbon. The carbonate-carbon is calculated from the difference between total carbon and non-carbonate carbon (HCl treated). The detection limit is 0.01% CO₂.

VI. Cost

Cost for carbonate analysis is dependent on the procedure used and the accuracy required. Cost for the base method ranges from \$10 to \$15 per sample. The Leco procedure costs \$12 to \$18 per sample and the coulometric procedure \$25 to \$35 per sample.

VII. MEND and Relevant Publications

MEND 1.16.1c 1991. New Methods for Determination of Key Mineral Species in Acid Generation Prediction by Acid Base Accounting. April.

Jeffery, P.G. 1981. Chemical Methods of Rock Analysis. Pergamon Press.

Morrison, J.L., Atkinson S.D., Davis A. and Scetz B.E. 1990. *The Use of CO₂ Coulometry in Differentiating and Quantifying the Carbonate Phases in the Coal-Bearing Strata of Western Pennsylvania: Its Applicability in Interpreting and Modifying Neutralization Potential (NP) Measurements*. In: Proceedings of the 1990 Mining and Reclamation Conference and Exhibition. Charleston, WV. 23 to 26 April. pp. 243-248.

Sviridendo, Zh. V., Orzhekhovskaya A.I., Sidendo E.A., Shegeda V.B. and Kharchenko L.A. 1983. *Rapid Determination of CO₂ in Carbonate Rocks and Minerals by a Coulometric Method* Abstract. *Zavod. Lab.* Vol 49, pp.16-17.

2.6.3 QUALITY ASSURANCE AND QUALITY CONTROL

I. Discussion of Theory

Quality assurance (QA) is a set of operating principles that are designed to produce data of known and defensible quality. The accuracy of the analytical results can thus be stated with a high level of confidence. A QA program includes the organization and procedures such as staff organization and responsibilities, sample control and documentation procedures, training requirements, equipment maintenance procedures, calibration procedures, internal quality control activities, validating and reporting. Quality control (QC) may be either internal and/or external. QC programs should include, certification of operator competence, recovery of known additions, analysis of externally supplied standards, analysis of reagent blanks, calibration with standards, analysis of duplicates and maintenance of control charts (Standard Methods 1992).

Laboratories may have their QA programs certified through a third party such as the Standards Council of Canada (SCC) which is the accreditation body for quality systems registrar in Canada. A company that is ISO 9000 series registered provides a level of assurance to its customers that is recognised world-wide.

II. Applications and Limitations

QA/QC can be used for a variety of applications for mine sites. Programs are applicable for:

- All kinetic and static test programs for new and existing mines; and
- Samples collected to monitor acidic drainage sites (Volume 6). A good QA/QC program will ensure defensible results for meeting permit requirements.

QC data requires proper interpretation. For example, accuracy of analysis is reduced as the lower limit of detection (LLD) is approached. This will result in poor QC, such as duplicates and spike recoveries, and may lead the reviewer to suspect all results. With any QC program guidelines are required that define accuracy. These guidelines can then be used to determine when analysis are inaccurate so that they can be repeated if possible. In addition to laboratory errors, contamination of samples can also occur from other samples or sample preparation equipment. These errors can be difficult to identify since they will not be discovered as an inaccurate analysis.

Another limitation of a QA/QC program is the increase in cost of testing and analysis. A good QA/QC program which will include proper sample tracking, 10% duplication, known addition spiking, and analysis of certified standards can add 15% to 20% to the cost of analysis. Some analysis do not have certified standards and rely on standards prepared in the lab.

III. Base Method

The base QA/QC method will vary with each analyte or test being conducted since QC standards may not be available. The following guidelines are recommended:

Samples on arrival at the analytical laboratory should be checked by an analyst who:

- Ensures that all samples are present and labeled with name and site;
- Checks to see a complete request for analysis accompanies the samples; and
- Enters the following information in a computerized and/or hard copy log-in system
 - Sample description
 - Sample type
 - Date received
 - Analyses requested.

QC protocol includes:

- Analysis as soon as possible or check to ensure that samples have been properly preserved;
- Blank analysis along with the samples to determine if interferences are present because of glassware, reagents or equipment;
- Blank samples should be prepared from a "blank" kinetic test (does not contain waste material) for use in laboratory kinetic testing;
- Ten percent replicate analyses for reproducibility of the analytical procedure;
- Known additions are recommended for each batch of samples or every 25th sample for large batches; and
- Performance evaluation materials (reference materials) such as the NBM-1 where available for every batch of samples.

The performance evaluation materials (e.g. NBM-1 reference material developed by MEND) may be prepared by the quality control section or purchased from institutes such as NIST, EPA or NRCan. Data derived from the analysis of performance evaluation materials should be monitored using control charts to give an indication of long term trends. Samples can be also be split and analyzed by another laboratory as a means of evaluating results.

Recommended QC is shown in the following table for typical acidic drainage analysis.

Table 2.6-1
Quality Assurance and Control Criteria for Various Analytes

Analysis	Recovery of Known Additions*	Precision of Low-Level Duplicates*⁺	Precision of High-Level Duplicates*⁺	Accuracy on Reference Materials or Standard
Acidity/Alkalinity	n/a	60-140	80-120	n/a
Sulphate (water)	80-120	75-125	90-110	10
Metals (water)	80-120	75-125	90-110	10
NP-ABA	80-120	75-125	80-120	15
Sulphate (solids)	80-120	60-140	80-120	15
Total sulphur	80-120	60-140	80-120	15
Metals (solid)	n/a	60-140	80-120	15

*Additions calculated as % of the known addition recovered, duplicates calculated as the difference as a percentage of the mean $[100(x_1-x_2)/x_{\text{mean}}]$.

⁺Low-level refers to the concentration less than 20 times the method detection limit (MDL) where MDL is defined as that concentration which produces a signal with a 99% probability that it is different from the blank (for seven replicates of the sample the mean must have a standard deviation of 3.14 above the blank). High-level refers to concentrations greater than 20 times the MDL.

QC information should be reported with the results with the respective accuracy noted for spiked samples and reference samples.

IV. Variations

There are no variations for QA/QC although the level of QA/QC will vary for a particular analytical program.

V. Costs

QA/QC costs approximately 10% to 20% of the cost of analysis.

VI. MEND and Relevant Publications

Standard Methods for the Examination of Water and Wastewater, 1992. 18th Edition, APHA, AWWA and WEF, Washington DC.

APPENDIX A – MEND CONTRACTORS

MEND CONTRACTORS

PREDICTION/PRÉVISION

- 1.11.1 Critical Literature Review of Acid Drainage from Waste Rock, April 1991.
Contractors: *Northwest Geochem, Vancouver, BC*
Morwijk Enterprises Ltd, Vancouver BC
- 1.12.1b DBARD for Paradox: Developments in DBARD, the Database for Acid Rock Drainage, March 1996.
Contractor: *University of British Columbia, Vancouver BC*
- 1.14.2b Sampling and Monitoring Data from the Mine Doyon South Waste Rock Dump (1990 to 1995), March 1994 (revised September 1997).
Contractor: *Laval University, Sainte-Foy QC*
- 1.14.2c Heat Transfer during Acid Mine Drainage Production in a Waste Rock Dump, La Mine Doyon (Québec), March 1994 (revised August 1997).
Contractor: *Laval University, Sainte-Foy QC*
- 1.14.2d Water Budget for the Waste Rock Dump at La Mine Doyon (Québec) March 1994 (revised August 1997).
Contractor: *Laval University, Sainte-Foy QC*
- 1.14.2e Diversité microbiologique dans la production de drainage minier acide à la halde sud de la Mine Doyon, March 1994 (revised August 1997).
Contractor: *Laval University, Sainte-Foy QC*
- 1.14.3E Peer Review of MEND Studies Conducted from 1990 to 1994 on Acid Mine Drainage at Mine Doyon South Waste Rock Dump, November 1996.
- 1.14.3F Revue technique des études réalisées par NEDEM de 1990 à 1994 sur le drainage minier acide de la halde sud de la mine Doyon, novembre 1996.
Contractors: *Geocon, SNC-Lavalin Environment Inc., Montréal QC*
Unité de recherche et de service en technologie minérale, Rouyn-Noranda QC
Noranda Technology Centre, Pointe-Claire QC
SENES Consultants Limited, Richmond Hill ON
- 1.15.2a MINEWALL 2.0 Users Manual, September 1995.
- 1.15.2b MINEWALL 2.0 - Literature Review and Conceptual Models, September 1995.
- 1.15.2c Application of MINEWALL 2.0 to three Minesites, September 1995.
Contractor: *Morwijk Enterprises Ltd., Vancouver BC*
- 1.16.1a Investigation of Prediction Techniques for Acid Mine Drainage, November 1989.
Contractor: *Coastech Research Inc., North Vancouver, BC*
- 1.16.1b Acid Rock Drainage Prediction Manual, March 1991.
Contractor: *Coastech Research Inc., North Vancouver, BC*
- 1.16.1c New Methods for Determination of Key Mineral Species in Acid Generation Prediction by Acid-Base Accounting, April 1991.
Contractor: *Norecol Environmental Consultants Ltd., Vancouver BC*

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- 1.16.3 Determination of Neutralization Potential for Acid Rock Drainage Prediction, July 1996.
Contractor: University of British Columbia, Vancouver BC
- 1.16.4 Evaluation of Static and Kinetic Prediction Test Data and Comparison with Field Monitoring Data, December 1995.
Contractor: University of British Columbia, Vancouver BC
- 1.16.5 Interprétation minéralogique d'essais statiques et cinétiques
Contractor: COREM, Sainte-Foy PQ
- 1.17.1 Hydrogeochemical Investigation of Reactive Tailings at the Waite Amulet Tailings Site, Noranda, Québec 1985 Program, July 1986; Phase 2 - 1986 Program, July 1987; Phase 3 - 1987 Program, Volume I Report, May 1988; Phase 3 - 1987 Program, Volume II - Appendices, March 1988; Phase 3 - 1987 Program, Supplementary Report, March 1989; Generation and Evolution of Acidic Pore Waters at the Waite Amulet Tailings - Final Report", April 1990.
*Contractors: Noranda Technology Centre, Pointe-Claire QC
Natural Resources Canada, Elliot Lake ON
University of Waterloo, Waterloo ON*
- 1.19.1 Long Term Acid Generation Studies: Cinola Project British Columbia, March 1994.
Contractor: Norecol, Dames and Moore, Vancouver BC
- 1.19.2 Scaling Analysis of Acid Rock Drainage, December 1995.
Contractor: Synergetic Technology, Calgary AB
- 1.21.1a Critical Review of the Reactive Acid Tailings Assessment Program (RATAP.BMT2), April 1990.
*Contractors: SENES Consultants Limited, Richmond Hill ON
Beak Consultants Limited, Brampton ON*
- 1.21.1b Workshop on Modelling of Reactive Tailings Sponsored by the MEND Prediction Committee, Final Report, August 1990.
Contractor: Kilborn Engineering (BC) Ltd., Vancouver BC
- 1.21.2 Laboratory Studies of Pyrrhotite Oxidation, March 1998.
Contractor: University of Waterloo, Waterloo ON
- 1.22.1a Field Procedures Manual: Gas Transfer Measurements, Waste Rock Piles, Heath Steele Mines, New Brunswick, March 1994.
*Contractors: Nolan, Davis and Associates (N.B.) Limited, Fredericton NB
Australian Nuclear Science and Technology Organization (ANSTO), Australia*
- 1.22.1b Assessment of Gas Transfer-ANSTO Model at Heath Steele Mines, July 1997.
*Contractors: ADI Nolan Davis Inc., Fredericton NB
Australian Nuclear Science and Technology Organization (ANSTO), Australia*
- 1.25.1 Soilcover Users Manual Version 2.0, December 1996.
Contractor: University of Saskatchewan, Saskatoon SK

- 1.27.1a Guide for Predicting Water Chemistry from Waste Rock Piles, July 1996.
Contractor: *Norecol, Dames & Moore, Vancouver BC*
- 1.32.1 Prediction and Prevention of Acid Rock Drainage from a Geological and Mineralogical Perspective, October 1993.
Contractor: *National Hydrology Research Institute (Environment Canada), Saskatoon SK*
- 1.41.4 Whistle Mine Waste Rock Study, December 1997.
Contractors: *Golder Associates, Sudbury ON*
SENES Consultants Limited, Richmond Hill ON
- 1.42.1 Critical Review of Geochemical Processes and Geochemical Models Adaptable for Prediction of Acidic Drainage from Waste Rock, April 1995.
Contractors: *Noranda Technology Centre, Pointe-Claire QC*
Alberta Research Council, Edmonton AB
University of Western Ontario, London ON
- 1.44.1 History of Eskay Creek Mine's Waste-Rock Dump from Placement to Disassembly, May 1997.
Contractor: *Minesite Drainage Assessment Group, Vancouver BC*
- 1.51.1 Quantitative Analysis of Chemical and Biological Kinetics for the Acid Mine Drainage Problem, June 1994.
Contractor: *Synergetic Technology, Calgary AB*
- 1.51.2 Nonlinear Modelling of Chemical Kinetics for the Acid Mine Drainage Problem and Related Physical Topics, October 1993.
Contractor: *University of Alberta, Edmonton AB*
- 1.61.1 Roles of Ice, in the Water Cover Option, and Permafrost in Controlling Acid Generation from Sulphide Tailings, November 1996 (revised October 1997).
Contractor: *Natural Resources Canada, Ottawa ON*
- 1.61.2 Acid Mine Drainage in Permafrost Regions: Issues, Control Strategies and Research Requirements, July 1996.
Contractors: *AGRA Earth & Environmental Limited, Calgary AB*
Morwijk Enterprises Ltd., Vancouver BC
- 1.61.3 Column Leaching Characteristics of Cullaton Lake B and Shear (S) - Zones Tailings Phase 2: Cold Temperature Leaching, June 1997.
Contractors: *Natural Resources Canada, Elliot Lake ON*
Laurentian University, Sudbury ON
- 1.62.2 Acid Mine Drainage Behaviour in Low Temperature Regimes-Thermal Properties of Tailings, July 1998.
Contractor: *Norwest Mine Services Ltd., Vancouver BC*

PREVENTION AND CONTROL/PRÉVENTION ET CONTRÔLE

- 2.11.1a Subaqueous Disposal of Reactive Mine Wastes: An Overview, June 1989.
Contractor: *Rescan Environmental Services Ltd., Vancouver BC*

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- 2.11.1a A Preliminary Assessment of Subaqueous Tailings Disposal in Benson Lake, British Columbia, March 1990.
Contractor: Rescan Environmental Services Ltd., Vancouver BC
- 2.11.1a A Preliminary Assessment of Subaqueous Tailings Disposal in Anderson Lake, Manitoba, March 1990.
Contractor: Rescan Environmental Services Ltd., Vancouver BC
- 2.11.1a A Preliminary Assessment of Subaqueous Tailings Disposal in Mandy Lake, Manitoba, March 1990.
Contractor: Rescan Environmental Services Ltd., Vancouver BC
- 2.11.1b Geochemical Assessment of Subaqueous Tailings Disposal in Buttle Lake, British Columbia, March 1990.
Contractor: Rescan Environmental Services Ltd., Vancouver BC
- 2.11.1b Geochemical Assessment of Subaqueous Tailings Disposal in Anderson Lake, Snow Lake Area, Manitoba, September 1990.
Contractor: Rescan Environmental Services Ltd., Vancouver BC
- 2.11.1b Geochemical Assessment of Subaqueous Tailings Disposal in Mandy Lake, Flin Flon Area, Manitoba, September 1990.
Contractor: Rescan Environmental Services Ltd., Vancouver BC
- 2.11.1c A Preliminary Biological and Geological Assessment of Subaqueous Tailings Disposal in Benson Lake, British Columbia, March 1991.
Contractor: Rescan Environmental Services Ltd., Vancouver BC
- 2.11.1c Chemical Diagenesis of Submerged Mine Tailings in Benson Lake and Natural Sediments in Keogh Lake, Vancouver Island, British Columbia, June 1992.
Contractor: Rescan Environmental Services Ltd., Vancouver BC
- 2.11.1d A Critical Review of MEND Studies Conducted to 1991 on Subaqueous Disposal of Tailings, July 1992.
Contractor: The Rawson Academy of Aquatic Science, Ottawa ON
- 2.11.1e Review of MEND Studies on the Subaqueous Disposal of Tailings (1993-95), May 1996.
Contractor: P.G. Sly, Picton ON
- 2.11.2a Literature Review Report: Possible Means of Evaluating the Biological Effects of Subaqueous Disposal of Mine Tailings, March 1993.
Contractor: INRS-Eau, Sainte-Foy QC
- 2.11.3abc Geochemical Assessment of Subaqueous Tailings Disposal in Anderson Lake, Manitoba. 1993-1995 Study Program, August 1996.
*Contractors: Rescan Environmental Services Ltd., Vancouver BC
Analytical Service Laboratories Limited, Vancouver BC
University of British Columbia, Vancouver BC*

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- 2.11.4a Geochemical Assessment of Subaqueous Tailings Disposal in Buttle Lake, British Columbia. 1993 Study Program. May 1995.
Contractors: Rescan Environmental Services Ltd., Vancouver BC
Analytical Service Laboratories Limited, Vancouver BC
University of British Columbia, Vancouver BC
- 2.11.5ab Shallow Water Covers - Equity Silver Base Information on Physical Variables, May 1996.
Contractor: Hay & Company Consultants Inc., Vancouver BC
- 2.11.5c Geochemical Assessment of the Equity Silver Tailings Pond, August 1996.
Contractor: Rescan Environmental Services Ltd., Vancouver BC
- 2.11.9 Design Guide for the Subaqueous Disposal of Reactive Tailings in Constructed Impoundments, March 1998.
Contractors: Lorax Environmental Services Ltd., Vancouver BC
University of British Columbia, Vancouver BC
Hay & Company Consultants Inc., Vancouver BC
Bruce Geotechnical Services, Vancouver BC
Mehling Environmental Services, Vancouver BC
- 2.12.1a Evaluation of Man-Made Subaqueous Disposal Option as a Method of Controlling Oxidation of Sulphide Minerals – Synopsis Report
Contractor: SENES Consultants, Richmond Hill ON
University of British Columbia, Vancouver BC
- 2.12.1b Evaluation of Man-Made Subaqueous Disposal Option as a Method of Controlling Oxidation of Sulphide Minerals – Background and General Description
Contractor: Golder Associés Ltée, Pointe-Claire PQ
- 2.12.1c Subaqueous Disposal of Reactive Mine Tailings – Louvicourt Mine Test Cells – Geochemical Sampling and Analysis – Final Report
Contractor: INRS – Eau, Sainte-Foy PQ
- 2.12.1d Reactivity Assessment and Subaqueous Oxidation Rate Modelling for Louvicourt Tailings
Contractor: Noranda Technology Centre, Pointe-Claire QC
- 2.12.1e Evaluation of Man-Made Subaqueous Disposal Option as a Method of Controlling Oxidation of Sulphide Minerals: Column Studies – Final Report
Contractor: Natural Resources Canada, Ottawa ON
- 2.13.1a Wet Barriers on Pyritic Uranium Tailings - Part I and II - Laboratory Lysimeter Studies of Oxidation and Limestone Neutralization Characteristics of Uranium Tailings and Waste Rock, January 1998
Contractor: Natural Resources Canada, Elliot Lake ON
- 2.13.1b Wet Barriers on Pyritic Uranium Tailings - Part III - Laboratory Diffusion Lysimeter Studies of Uranium Tailings Deposited under a Shallow Water Cover, January 1998
Contractor: Natural Resources Canada, Elliot Lake ON
- 2.13.2a Expérimentation de l'inondation du parc à résidus miniers – Solbec-Cupra (Phase IV). Rapport sommaire, Décembre 1993.
Contractor: Roche Ltée, Groupe-conseil, Sainte-Foy QC

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- 2.13.2b Flooding of a Mine Tailings Site – Solbec-Cupra. Suspension of Solids: Impact and Prevention, March 1994.
Contractor: McGill University, Montréal QC
- 2.13.2c Inondation artificielle du parc à résidus miniers Solbec-Cupra: Études microbiologique et chimique - Rapport final, Mars 1994.
Contractor: Laval University, Sainte-Foy QC
- 2.13.2d Suivi environnemental du parc à résidus minier Solbec - 1994-1997
*Contractors: Les Consultants S.M. inc., Sherbrooke PQ
University of Western Ontario, London ON*
- 2.15.1a Flooding of Pre-Oxidized Mine Tailings: Mattabi Case Study, June 2000.
Contractor: Noranda Technology Centre, Pointe-Claire QC
- 2.15.1b Laboratory Studies of Shallow Water Cover on Reactive Tailings and Waste Rock: Part 1- Oxidation and Leaching Characteristics
Contractor: Natural Resources Canada, Ottawa ON
- Laboratory Studies of Shallow Water Cover on Reactive Tailings and Waste Rock: Part 2 - Roles of Oxygen Limiting Barriers and Water Flows
Contractor: Natural Resources Canada, Ottawa ON
- Laboratory Studies of Shallow Water Cover on Reactive Tailings and Waste Rock: Part 3 - Mobility of Mine Tailings under Wave Action
*Contractors: National Research Council, Ottawa ON
Natural Resources Canada, Ottawa ON*
- 2.15.3 Laboratory Study of Particle Resuspension, Oxidation and Metal Release in Flooded Mine Tailings, November 1998.
Contractor: University of Western Ontario, London ON
- 2.17.1 Review of use of an Elevated Water Table as a Method to Control and Reduce Acidic Drainage from Tailings, March 1996.
Contractor: SENES Consultants Limited, Richmond Hill ON
- 2.18.1 Review of Water Cover Sites and Research Projects, September 1997.
Contractor: University of Western Ontario, London ON
- 2.20.1 Evaluation of Alternate Dry Covers for the Inhibition of Acid Mine Drainage from Tailings, March 1994.
Contractor: SENES Consultants Limited, Richmond Hill ON
- 2.21.1 Development of Laboratory Methodologies for Evaluating the Effectiveness of Reactive Tailings Covers, March 1992.
*Contractors: University of Waterloo, Waterloo ON
Noranda Technology Centre, Pointe-Claire QC*

- 2.21.2 Field Evaluation of the Effectiveness of Engineered Soil Covers for Reactive Tailings: Volume 1- Laboratory and Field Tests, October 1993.
Contractor: *Noranda Technology Centre, Pointe-Claire QC*
- Field Evaluation of the Effectiveness of Engineered Soil Covers for Reactive Tailings: Volume 2 - University Contracts, October 1993.
Contractors: *École Polytechnique, Montréal QC*
McGill University, Montréal QC
- 2.21.3 Review of Soil Cover Technologies for Acid Mine Drainage - A Peer Review of the Waite Amulet and Heath Steele Soil Covers, July 1997.
Contractor: *University of Saskatchewan, Saskatoon, SK*
- 2.21.3b A Review of Non-traditional Cover Materials
Contractor: *University of Saskatchewan, Saskatoon, SK*
- 2.21.4 Design, Construction and Monitoring of Earthen Covers for Waste Rock and Tailings
Contractors: *University of Saskatchewan, Saskatoon, SK*
École Polytechnique, Montréal QC
University of Western Ontario, London ON
- 2.22.2a Évaluation en laboratoire de barrières sèches construites à partir de résidus miniers, mars 1996.
Contractor: *École Polytechnique, Montréal QC*
- 2.22.2b Études de laboratoire sur l'efficacité de recouvrement construites à partir de résidus miniers, avril 1999.
Contractor: *École Polytechnique, Montréal QC*
- 2.22.2c Études sur les barrières sèches construites à partir de résidus miniers, Phase II - Essais en place, novembre 1999.
Contractors: *École Polytechnique, Montréal QC*
Unité de recherche et de service en technologie minérale (URSTM), Rouyn-Noranda QC
- 2.22.3 Valorisation des résidus miniers : une approche intégrée - Phase II. Rapport final, mars 1998. Valorisation des résidus miniers : une approche intégrée - Phase II. Annexes, avril 1998.
Contractor: *Unité de recherche et de service en technologie minérale (URSTM), Rouyn-Noranda PQ*
- 2.22.4aE Construction and Instrumentation of a Multi-Layer Cover, Les Terrains Aurifères, February 1999.
- 2.22.4aF Construction et instrumentation d'une couverture multicouche au site Les Terrains Aurifères Québec, Canada, février 1999.
Contractors: *Golder Associés Ltée, Montréal QC*
École Polytechnique, Montréal QC
Unité de recherche et de service en technologie minérale (URSTM), Rouyn-Noranda QC

- 2.22.4bE Field Performance of the Les Terrains Aurifères Composite Dry Covers, March 2000.
2.22.4bF Suivi du comportement du recouvrement multicouche Les Terrains Aurifères, mars 2000.
*Contractors: Golder Associés Ltée, Montréal QC
École Polytechnique, Montréal QC
Unité de recherche et de service en technologie minérale (URSTM),
Rouyn-Noranda QC*
- 2.22.5 Évaluation des processus de dégradation dans la barrière de résidus forestiers à la Mine East Sullivan, mars 2000.
Contractor: INRS - Géoressources, Sainte-Foy QC
- 2.23.2ab Hydrologic and Hydrogeologic Evaluation of the Thickened Tailings Disposal System at Kidd Creek Division, Falconbridge Limited, October 1993.
Contractor: Noranda Technology Centre, Pointe-Claire QC
- 2.23.2c The Verification of Modelled Pore Water Movement within Thickened Tailings using Tracers at the Falconbridge Limited Kidd Metallurgical Division Timmins, Ontario. May 2000.
*Contractors: Falconbridge Limited, Timmins ON
SENES Consultants Limited, Richmond Hill ON*
- 2.23.2d A Geochemical, Hydrogeological and Hydrological Study of the Tailings Impoundment at the Falconbridge Limited, Kidd Creek Division Metallurgical Site, Timmins, Ontario, October 1995.
Contractor: University of Waterloo, Waterloo ON
- 2.23.3 Investigation of the Porous Envelope Effect at the Fault Lake Tailings Site, May 1995.
Contractor: Noranda Technology Centre, Pointe-Claire QC
- 2.24.1 Manual of Methods Used in the Revegetation of Reactive Sulphide Tailings Basins, November 1989.
Contractor: The Proctor & Redfern Group, North Bay ON
- 2.25.1a Reclamation of Sulphide Tailings using Municipal Solid Waste Compost: Literature Review and Recommendations, July 1992.
Contractor: Laurentian University, Sudbury ON
- 2.25.1b Reclamation of Sulphide Tailings using Municipal Solid Waste Compost: Laboratory Studies, June 1995.
Contractor: Laurentian University, Sudbury ON
- 2.25.2 Parcelles expérimentales au parc East Sullivan - Rapport d'étape 1994 et rapport final, décembre 1994.
Contractor: Roche Ltée - Groupe-conseil, Sainte-Foy PQ
- 2.25.3 Evaluation of the Use of Covers for Reducing Acid Generation from Strathcona Tailings, September 1997.
Contractor: Lakefield Research Limited, Lakefield ON
- 2.31.1a Heath Steele Waste Rock Study, Phases I to III, March 1992.
*Contractors: Nolan, Davis & Associates Limited, Halifax NS
Noranda Technology Centre, Pointe-Claire QC*

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- 2.31.1b Engineering Design and Construction Phase IV - Composite Soil Cover - Acid Waste Rock Study - Heath Steele Mines, November 1994.
Contractor: ADI Nolan Davis, Fredericton NB
- 2.31.1b Monitoring Report Phase IV - Composite Soil Cover - Acid Waste Rock Study - Heath Steele Mines, March 1996.
Contractor: ADI Nolan Davis, Fredericton NB
- 2.31.1c Monitoring Program 1995-96 Phase V - Composite Soil Cover on Waste Rock Pile 7/12 at Heath Steele, New Brunswick, February 1998.
Contractor: Noranda Technology Centre, Pointe-Claire QC
- 2.32.3a Injection de résidus miniers dans des stériles miniers comme moyen de réduction des effluents acides, janvier 1994.
Contractor: Laval University, Sainte-Foy QC
- 2.34.1 Evaluation of Field-scale Application of a Shotcrete Cover on Acid Generating Rock, September 1996.
*Contractors: C.E. Jones & Associates Ltd., Victoria BC
Powertech Labs Inc., Surrey BC*
- 2.35.2b Evaluation of Techniques for Preventing Acidic Rock Drainage: Final Report, January 1997.
*Contractors: Noranda Technology Centre, Pointe-Claire QC
University of Western Ontario, London ON*
- 2.36.1 Review of In-Pit Disposal Practices for the Prevention of Acid Drainage - Case Studies, September 1995.
Contractor: SENES Consultants Limited, Richmond Hill ON
- 2.36.2a Hydrogeochemistry of Oxidised Waste Rock from Stratmat Site, N.B., March 1999.
Contractor: Noranda Inc., Technology Centre, Pointe-Claire QC
- 2.36.2b Hydrology and Solute Transport of Oxidised Waste Rock from Stratmat Site, N.B. March 1999.
Contractor: Noranda Inc., Technology Centre, Pointe-Claire QC
- 2.36.3 Assessing the Subaqueous Stability of Oxidized Waste Rock, April 1999.
*Contractors: Lorax Environmental Services Ltd., Vancouver BC
Norecol Dames & Moore, Vancouver BC*
- 2.37.1 Blending and Layering Waste Rock to Delay, Mitigate or Prevent Acid Rock Drainage and Metal Leaching: A Case Study Review, April 1998.
Contractor: Mehling Environmental Management Inc., Vancouver BC
- 2.37.3 Control of Acidic Drainage in Layered Waste Rock: Laboratory Studies and Field Monitoring, September 1997.
Contractor: Minesite Drainage Assessment Group, Vancouver BC
- 2.44.1 Microbial Plugging of Uranium Mine Tailings to Prevent Acid Mine Drainage - Final Report, December 1992.
Contractor: Natural Resources Canada, Ottawa ON

- 2.45.1a Separation of Sulphides from Mill Tailings - Phase I, June 1994.
Contractor: Cominco Engineering Services Ltd., Vancouver BC
- 2.45.2 Separation of Sulphides from Mill Tailings - Field, September 1997.
*Contractors: University of Waterloo, Waterloo ON
INCO Limited, Sudbury ON*

TREATMENT/TRAIITEMENT

- 3.11.1 Treatment of Acidic Seepages using Wetland Ecology and Microbiology: Overall Program Assessment, July 1993.
Contractor: Boojum Research Limited, Toronto ON
- 3.12.1a Assessment of Existing Natural Wetlands Affected by low pH, Metal Contaminated Seepages (Acid Mine Drainage), May 1990.
Contractor: P. Lane and Associates Limited, Halifax NS
- 3.12.2 Panel Wetlands - A Case History of Partially Submerged Pyritic Uranium Tailings under Water, February 1993.
Contractor: Natural Resources Canada, Elliot Lake ON
- 3.14.1 Review of Passive Systems for Treatment of Acid Mine Drainage, May 1996 (revised 1999).
Contractor: Kilborn Inc., Toronto ON
- 3.21.1a Study on Metals Recovery/Recycling from Acid Mine Drainage, July 1991.
Contractor: Natural Resources Canada, Ottawa ON
- 3.21.1b Metals Removal from Acid Mine Drainage by Ion Exchange, June 1995.
Contractor: Natural Resources Canada, Ottawa ON
- 3.21.2a Metals Removal from Acidic Drainage - Chemical Method, March 1996.
*Contractors: McGill University, Montréal QC
Noranda Technology Centre, Pointe-Claire QC*
- 3.22.1 Canada-Wide Survey of Acid Mine Drainage Characteristics, December 1994.
Contractor: Natural Resources Canada, Ottawa ON
- 3.32.1 Acid Mine Drainage - Status of Chemical Treatment and Sludge Management Practices, June 1994.
Contractor: SENES Consultants Limited, Richmond Hill ON
- 3.42.2a Characterization and Stability of Acid Mine Drainage Treatment Sludges, May 1997.
Contractor: Natural Resources Canada, Ottawa ON
- 3.42.2b The Effect of Process Parameters and Aging on Lime Sludge Density and Stability, February 1999.
Contractor: Natural Resources Canada, Ottawa ON

MONITORING/SURVEILLANCE

- 4.1.1 Field Sampling Manual for Reactive Sulphide Tailings, November 1989.
Contractor: Canect Environmental Control Technologies Limited, Vancouver BC
- 4.2.1 Review of Canadian and United States Legislation Relevant to Decommissioning Acid Mine Drainage Sites, September 1993.
Contractor: Jacques Whitford Environmental Limited, Ottawa ON
- 4.3.1 RTS-1, RTS-2, RTS-3 and RTS-4: Sulphide Ore Mill Tailings Reference Materials, April 1990
Contractor: Natural Resources Canada, Ottawa ON
- 4.5.1-1 Review of Waste Rock Sampling Techniques, June 1994.
*Contractors: SENES Consultants Limited, Richmond Hill ON
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APPENDIX C – MEND REPORTS

PREDICTION/PRÉVISION

- 1.11.1 Critical Literature Review of Acid Drainage from Waste Rock, April 1991. \$25
- 1.12.1b DBARD for Paradox: Developments in DBARD, the Database for Acid Rock Drainage, (6 diskettes included) March 1996. \$25
- 1.14.2b Sampling and Monitoring Data from the Mine Doyon South Waste Rock Dump (1990 to 1995)(diskette included), March 1994 (revised September 1997). \$35
- 1.14.2c Heat Transfer during Acid Mine Drainage Production in a Waste Rock Dump, La Mine Doyon (Quebec), March 1994 (revised August 1997). \$15
- 1.14.2d Water Budget for the Waste Rock Dump at La Mine Doyon, (Quebec), March 1994 (revised August 1997). \$20
- 1.14.2e Diversité microbiologique dans la production de drainage minier acide à la halde sud de la Mine Doyon, March 1994 (revised August 1997). \$25
- 1.14.3E Peer Review of MEND Studies Conducted from 1990 to 1994 on Acid Mine Drainage at Mine Doyon South Waste Rock Dump, November 1996. \$35
- 1.14.3F Revue technique des études réalisées par NEDEM de 1990 à 1994 sur le drainage minier acide de la halde sud de la mine Doyon, novembre 1996. \$35
- 1.15.2a MINEWALL 2.0 Users Manual (diskette included), September 1995. \$30
- 1.15.2b MINEWALL 2.0 - Literature Review and Conceptual Models, September 1995. \$25
- 1.15.2c Application of MINEWALL 2.0 to Three Minesites, September 1995. \$25
- 1.16.1a Investigation of Prediction Techniques for Acid Mine Drainage, November 1989. \$25
- 1.16.1b Acid Rock Drainage Prediction Manual, March 1991. \$40
- 1.16.1c New Methods for Determination of Key Mineral Species in Acid Generation Prediction by Acid-Base Accounting, April 1991. \$25
- 1.16.2a Interlaboratory Measurement Program for the Standard ARD Material NBM-1, July 1994 (Report only). Reference material (\$95 CDN for 100g) available from the Canadian Certified Reference Material Program - tel: 613-995-4738 fax: 613-943-0573 (Copy of the report also comes with purchase of reference materials).
- 1.16.3 Determination of Neutralization Potential for Acid Rock Drainage Prediction, July 1996. \$40
- 1.16.4 Evaluation of Static and Kinetic Prediction Test Data and Comparison with Field Monitoring Data, December 1995. \$25
- 1.17.1a Hydrogeochemical Investigation of Reactive Tailings at the Waite Amulet Tailings Site, Noranda, Québec 1985 Program, July 1986. \$25
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- 1.17.1d Hydrogeochemical Investigation of Reactive Tailings at the Waite Amulet Tailings Site, Noranda, Québec, "Generation and Evolution of Acidic Pore Waters at the Waite Amulet Tailings - Final Report", April 1990. \$60
- 1.19.1 Long Term Acid Generation Studies: Cinola Project British Columbia (includes diskette), March 1994. \$35
- 1.19.2 Scaling Analysis of Acid Rock Drainage, December 1995. \$25
- 1.21.1a Critical Review of the Reactive Acid Tailings Assessment Program (RATAP.BMT2), April 1990. \$30
- 1.21.1b Workshop on Modelling of Reactive Tailings Sponsored by the MEND Prediction Committee, Final Report, August 1990. \$40
- 1.21.2 Laboratory Studies of Pyrrhotite Oxidation, March 1998. \$35
- 1.22.1a Field Procedures Manual: Gas Transfer Measurements Waste Rock Piles Heath Steele Mines New Brunswick, March 1994. \$30
- 1.22.1b Assessment of Gas Transfer-Ansto Model at Heath Steele Mines, July 1997. \$40
- 1.25.1 Soilcover Users Manual Version 2.0 (includes diskettes), December 1996. \$40 (Version 1.0 also available). Version 4.0 (Windows) is available from: Greg Newman, Geo-Analysis 2000 Ltd., 202 Kerr Rd., Saskatoon, Canada, S7N 3L9, E-Mail: GEO2000@the.link.ca
- 1.27.1a Guide for Predicting Water Chemistry from Waste Rock Piles, July 1996. \$35
- 1.32.1 Prediction and Prevention of Acid Rock Drainage from a Geological and Mineralogical Perspective, October 1993. \$35
- 1.41.4 Whistle Mine Waste Rock Study (2 volumes), December 1997. \$50
- 1.42.1 Critical Review of Geochemical Processes and Geochemical Models Adaptable for Prediction of Acidic Drainage from Waste Rock, April 1995. \$30
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- 1.61.3 Column Leaching Characteristics of Cullaton Lake B and Shear (S) - Zones Tailings Phase 2: Cold Temperature Leaching, (diskette included) June 1997. \$35
- 1.62.2 Acid Mine Drainage Behaviour in Low Temperature Regimes-Thermal Properties of Tailings, July 1998. \$30

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- PA-1 Hydrogeology of Waste Rock Dumps, July 1995. \$20
- PA-2 Metal Transport and Immobilization at Mine Tailings Impoundments, March 1997. \$30

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- 2.11.1b Geochemical Assessment of Subaqueous Tailings Disposal in Buttle Lake, British Columbia, March 1990. \$25
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- 2.11.1c A Preliminary Biological and Geological Assessment of Subaqueous Tailings Disposal in Benson Lake, British Columbia, March 1991. \$25
- 2.11.1c Keo Chemical Diagenesis of Submerged Mine Tailings in Benson Lake and Natural Sediments in Keogh Lake, Vancouver Island, British Columbia, June 1992. \$25
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- 2.11.3abc Geochemical Assessment of Subaqueous Tailings Disposal in Anderson Lake, Manitoba. 1993-1995 Study Program, August 1996. \$50
- 2.11.4a Geochemical Assessment of Subaqueous Tailings Disposal in Buttle Lake, British Columbia. 1993 Study Program. May 1995. \$40
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- 2.12.1c Subaqueous Disposal of Reactive Mine Tailings Louvicourt Mine Test Cells Geochemical Sampling and Analysis, February 2001. \$40.
- 2.12.1d Reactivity Assessment and Subaqueous Oxidation Rate Modelling for Louvicourt Tailings, March 2001. \$40
- 2.12.1e Evaluation of Man-Made Subaqueous Disposal Option as a Method of Controlling Oxidation of Sulfide Minerals: Column Studies (CD included), March 2001. \$40
- 2.13.2a Expérimentation de l'inondation du parc des résidus miniers - Solbec Cupra (Phase IV). Rapport Sommaire, Décembre 1993. \$35
- 2.13.2b Flooding of a Mine Tailings Site - Solbec Cupra. Suspension of Solids: Impact and Prevention, March 1994. \$25
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- 2.22.2a Évaluation en laboratoire de barrières sèches construites à partir de résidus miniers, mars 1996. \$30
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- 2.22.2c Études sur les barrières sèches construites à partir de résidus miniers, Phase II - Essais en place (inclus disquettes) novembre 1999. \$40
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- 2.23.2ab Hydrologic and Hydrogeologic Evaluation of the Thickened Tailings Disposal System at Kidd Creek Division, Falconbridge Limited, October 1993. \$35

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- 2.23.2c The Verification of Modelled Pore Water Movement Within Thickened Tailings Using Tracers at the Falconbridge Limited Kidd Metallurgical Division Timmins, Ontario. May 2000. \$35
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- 2.31.1b Engineering Design and Construction Phase IV - Composite Soil Cover Acid Waste Rock Study Heath Steele Mines, November 1994. \$30
- 2.31.1bMon Monitoring Report Phase IV - Composite Soil Cover Acid Waste Rock Study Heath Steele Mines, March 1996. \$35
- 2.31.1c Monitoring Program 1995-96 Phase V - Composite Soil Cover on Waste Rock Pile 7/12 at Heath Steele, New Brunswick, February 1998. \$25
- 2.32.3a Injection de résidus miniers dans des stériles miniers comme moyen de réduction des effluents acides, janvier 1994. \$20
- 2.34.1 Evaluation of Field-scale Application of a Shotcrete Cover on Acid Generating Rock, September 1996. \$30
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- 2.37.3 Control of Acidic Drainage in Layered Waste Rock: Laboratory Studies and Field Monitoring, September 1997. \$40

- 2.44.1 Microbial Plugging of Uranium Mine Tailings to Prevent Acid Mine Drainage - Final Report, December 1992. \$25
- 2.45.1a Separation of Sulphides from Mill Tailings - Phase I, June 1994. \$30.
- 2.45.2 Separation of Sulphides from Mill Tailings - Field, September 1997. \$30.

Associate Projects/Projets associés

- APC -1 Subaqueous Deposition of Tailings in the Strathcona Tailings Treatment System, September 1996. \$40

TREATMENT/TRAITEMENT

- 3.11.1 Treatment of Acidic Seepages Using Wetland Ecology and Microbiology: Overall Program Assessment, July 1993. \$35
- 3.12.1a Assessment of Existing Natural Wetlands Affected by low pH, Metal Contaminated Seepages (Acid Mine Drainage), May 1990. \$25
- 3.12.2 Panel Wetlands - A Case History of Partially Submerged Pyritic Uranium Tailings Under Water, February 1993. \$35
- 3.14.1 Review of Passive Systems for Treatment of Acid Mine Drainage, May 1996 (revised 1999). \$30
- 3.21.1a Study on Metals Recovery/Recycling from Acid Mine Drainage, July 1991. \$25
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- 3.22.1 Canada-Wide Survey of Acid Mine Drainage Characteristics, December 1994, (includes diskette). \$40
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- 3.42.2b The Effect of Process Parameters and Aging on Lime Sludge Density and Stability, February 1999. \$40

MONITORING/SURVEILLANCE

- 4.1.1 Field Sampling Manual for Reactive Sulphide Tailings, November 1989. \$15
- 4.2.1 Review of Canadian and United States Legislation Relevant to Decommissioning Acid Mine Drainage Sites, September 1993. \$25
- 4.3.1 RTS-1, RTS-2, RTS-3 and RTS-4: Sulphide Ore Tailings Certified Reference Materials, April 1990. Report only. Reference materials (\$75.00 each) available from the Canadian Certified Reference Material Program - tel: 613-995-4738 fax: 613-943-0573 (Free copy of the report comes with purchase of reference materials)
- 4.5.1-1 Review of Waste Rock Sampling Techniques, June 1994. \$25
- 4.5.1-2 Handbook for Waste Rock Sampling Techniques, June 1994. \$20
- 4.5.4 Guideline Document for Monitoring Acid Mine Drainage, October 1997. \$40

- 4.5.4 App Appendix A - Technical Summary Note: Guideline Document for Monitoring Acid Mine Drainage, October 1997. \$20 (both for \$50).
- 4.6.1 Applications of Geophysical Methods for Monitoring Acid Mine Drainage, December 1994. \$50
- 4.6.3 Application of Remote Sensing and Geophysics to the Detection and Monitoring of Acid Mine Drainage, September 1994. \$30
- 4.6.5ac A Survey of *In Situ* Oxygen Consumption Rates on Sulphide Tailings: Investigations on Exposed and Covered Tailings, November 1997. \$35
- 4.6.5b A Rapid Kinetic Technique for Measuring Reactivity of Sulphide Waste Rock: The Oxygen Consumption Method, December 1997. \$35
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- MA-1 Environmental Monitoring of Uranium Mining Wastes Using Geophysical Techniques Phase 1 - A Comparison and Evaluation of Conductivity and Resistivity Methods to Monitor Acid Mine Drainage from Uranium Waste Rock Piles and Tailings Areas, February 1996. \$50

TECHNOLOGY TRANSFER/TRANSFERT DE LA TECHNOLOGIE

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| 5.4.2a | MEND Manual. Volume 1 – Summary. March 2001. \$25 |
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- 5.5.1 Reactive Acid Tailings Stabilization (RATS) Research Plan, July 1988. \$15
- 5.6.1 Proceedings - Second International Conference on the Abatement of Acidic Drainage, Montréal, September 16, 17 and 18, 1991 (4 Volumes). \$150
- 5.7.1 1992 Revised Research Plan/Plan de recherche révisé 1992, August 1992. Complimentary
- 5.8 E Report of Results of a Workshop on Mine Reclamation. Toronto, Ontario, March 10-11, 1994. \$20
- 5.8 F Résultats de l'atelier sur la réhabilitation des sites miniers. Toronto, Ontario, les 10 et 11 mars, 1994. \$20
- 5.8.1 Economic Evaluation of Acid Mine Drainage Technologies (includes diskette), January 1995. \$20

- 5.9 Evaluation Study of the Mine Environmental Neutral Drainage Program (MEND), October 1996. \$25
AR -95 1995 Annual Report, June 1996. Complimentary (1991 to 1994 annual reports available on request)

NEW IDEAS/NOUVELLES IDÉES

- 6.1 Preventing AMD by Disposing of Reactive Tailings in Permafrost, December 1993. \$25
6.2 Polymer-Modified Clay as Impermeable Barriers for Acid Mining Tailings, April 1994. \$25
6.3 A Critique of Japanese Acid Mine Drainage Technology. April 1994. \$35

INTERNATIONAL/E

- 7.1 Proceedings of the Third International Conference on the Abatement of Acidic Drainage, Pittsburgh 1994. \$15
7.2 Proceedings of the Fourth International Conference on Acid Rock Drainage, ICARD, Vancouver 1997. \$150
7.2b CD ROM: Proceedings of the Fourth International Conference on Acid Rock Drainage, ICARD, Vancouver 1997. (Includes Plenary Session) \$75

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- W.001 Traitement chimique du drainage minier acide, Val d'Or, septembre 1994
W.002 Chemical Treatment of Acid Mine Drainage, Val d'Or, September 1994
W.003 Economic Evaluation of AMD, Sudbury, November 1994
W.004 Évaluation économique des techniques de traitement du drainage minier acide (DMA), Sudbury, novembre 1994
W.005 Economic Evaluation, "Implications of Long-Term Treatment" and Chemical Treatment of AMD", Vancouver, February 1995
W.006 Acid Mine Drainage Control in the Coal and Metal Mining Industries, Sydney, June 1995
W.007 In-Pit Disposal Practices for AMD Control/Lime Treatment of Acid Mine Drainage, Sudbury, October 1995
W.008 Selection and Interpretation of Chemical Prediction Methods and Mathematical Prediction Methods, Pointe-Claire, December 1995
W.009 Acid Mine Drainage Technology Transfer Workshop, Winnipeg, March 1996
W.010 Dry Covers Technologies Workshop, Sudbury, April 1996
W.011 Monitoring and Waste Management for Acid Mine Drainage, Saskatoon, June 1996
W.012 Water Covers to Prevent Acid Mine Drainage Workshop, Vancouver, September 1996
W.013 The Prediction of Acid Rock Drainage Workshop, Vancouver, November 1996.
W.014 Managing Mine Wastes in Permafrost Zone, Edmonton, May 1997.

- W.015 Prevention Technologies for Acid Mine Drainage, Fredericton, November 1997
- W.016 Acidic Drainage Workshops, Fredericton, Moncton , March 1998

MEND 2000 WORKSHOP NOTES/NOTES DES ATELIERS NEDEM 2000

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- BC.02 6th Annual BC MEM - MEND 2000 Metal Leaching/ARD Workshop. *Case Studies, Research Studies and Effects of Mining on Natural Water Bodies* Vancouver, December 1999. \$50
- BC.03 7th Annual BC MEM – MEND 2000 Metal Leaching/ARD Workshop. *Dry Covers, Predicting Solubility Constraints, Research and New Developments*. Vancouver, November 2000. Available from BC MEM. \$80.
- ME.01 Assessment and Management of Risks Associated with Metal Leaching and Acid Rock Drainage at Mine Sites. Sudbury, September 1999. \$25
- ME.02 Case Studies on Wet and Dry Covers for Tailings and Waste Rock. Sudbury, September 1999. \$25

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- IW.01 Water Covers and Underwater Disposal.
- IW.02 Chemical Prediction Techniques for Acid Rock Drainage.
- IW.03 Predictive Models for Acid Rock Drainage.
- IW.04 Dry Covers for Mine Tailings and Waste Rock.
- IW.05 Treatment of Acid Mine Drainage.
- IW.06 Bonding and Security.
- IW.07 Waste Rock and Tailings Disposal Technologies.

The Acid Mine Drainage Prevention/Treatment in Coal Mining Workshop notes are not available through MEND. Please contact Kelly Wolfe to purchase the document entitled: Acid Mine Drainage Control & Treatment, 2nd edition at: National Mine Land Reclamation Center, West Virginia University, Box 6064, Morgantown WV, 26506-6064 USA.