



MEND MANUAL
VOLUME 3 – PREDICTION
MEND 5.4.2c

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Sponsored by:

Natural Resources Canada
Northern Ontario Development Agreement (NODA- MEND Ontario)
Québec Mineral Development Agreement (NEDEM-Québec)
Organizing Committee for the 4th International Conference on Acid Rock Drainage

December, 2000

MEND MANUAL



VOLUME 3

PREDICTION

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
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Section 4.8	SENES Consultants Limited URS Norecol Dames & Moore
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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

ACKNOWLEDGEMENTS

VOLUME 3 – PREDICTION

The MEND Manual was created with assistance from members of the various technical committees of MEND and the MEND 2000 Steering Committee. The work on this Manual commenced in 1995 under the leadership of Grant Feasby. The project was sponsored through the Canada/Northern Ontario Development Agreement (NODA – MEND Ontario), the Canada/Québec Mineral Development Agreement (NEDEM – Québec) and the Organizing Committee for the 4th International Conference on Acid Rock Drainage.

In addition to the large number of volunteers who were responsible for the original MEND research, the MEND Secretariat gratefully acknowledges the many people who have contributed to the production of this Manual. In particular we wish to highlight the contribution of Stephen Day of SRK Consulting and Rikkert (Rik) Vos of BC Research Inc. (Laboratory Methods and Field Methods) and Randy Knapp and Carol Pettit of SENES Consultants Limited (Modelling) in the preparation of Volume 3 of the Manual.

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

Benoit Godin	Environment Canada
John Kwong	Natural Resources Canada (CANMET)
Bill Price	BC Ministry of Energy and Mines
Carl Weatherell	Carleton University.

Finally we offer a special thank you to Charlene Hogan of the MEND Secretariat for editing and preparation of the final document and to colleagues in Natural Resources Canada for proof reading the document prior to its publication.

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.

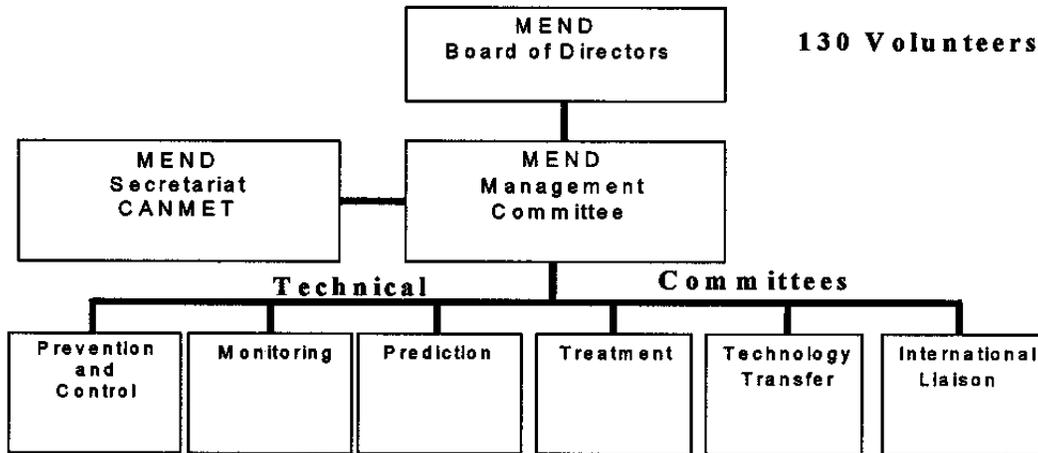
To ensure transparency of the program, it was also recommended that all research reports produced be made available to the partners and the public. Prior to their release the reports were critically reviewed and edited to enhance credibility and provide quality.

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

MEND Reports are cited in Appendix C.

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3.0 PREDICTION

3.1 INTRODUCTION

Prediction in the context of acidic drainage refers to a suite of integrated approaches used to determine in advance the geochemical behaviour of a rock or mineral waste. Specific questions commonly posed for mining projects depend on whether the mine is new, operating or closed. For new mines, it may be necessary to determine whether wastes are potentially acid generating or metal leaching, when acid and metal release may start and what impacts may be expected as a result of acid and metal leaching. Prediction studies at an early stage can be very beneficial in reducing long term site management costs by identifying wastes that should be managed to prevent acid generation. The objective for new mines is often to prevent acid generation and metal leaching from occurring. At operating and closed mines, prediction studies may be needed to address existing drainage quality problems, and determine how acid and metal loadings can be expected to vary in the long term. These studies can be used to identify and classify problematic sources for remedial actions.

This Volume is intended to give the reader an overview of available prediction techniques. Major contributions by the MEND program to this field have included development of procedural manuals, compilation of databases to evaluate the success rate of prediction methods, and development of several models to predict the geochemical behaviour of wastes.

MEND reports on predictive techniques and related projects are listed in Table 3.1-1.

**Table 3.1-1
Prediction Projects**

MEND Project	Title
1.11.1	Critical Literature Review of Acid Drainage from Waste Rock
1.12.1b	DBARD for Paradox: Developments in DBARD, the Database for Acid Rock Drainage
1.14.2b	Sampling and Monitoring Data from the Mine Doyon South Waste Rock Dump (1990 to 1995)
1.14.2c	Heat Transfer during Acid Mine Drainage Production in a Waste Rock Dump, La Mine Doyon (Québec)
1.14.2d	Water Budget for the Waste Rock Dump at La Mine Doyon, (Québec)
1.14.2e	Diversité microbologique dans la production de drainage minier acide à la halde sud de la Mine Doyon
1.14.3e	Peer Review of MEND Studies Conducted from 1990 to 1994 on Acid Mine Drainage at Mine Doyon South Waste Rock Dump
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
1.15.2a	MINEWALL 2.0 Users Manual
1.15.2b	MINEWALL 2.0 - Literature Review and Conceptual Models
1.15.2c	Application of MINEWALL 2.0 to Three Minesites
1.16.1a	Investigation of Prediction Techniques for Acid Mine Drainage
1.16.1b	Acid Rock Drainage Prediction Manual
1.16.1c	New Methods for Determination of Key Mineral Species in Acid Generation Prediction by Acid-Base Accounting

1.16.2a	Interlaboratory Measurement Program for the Standard ARD Material NBM-1
1.16.3	Determination of Neutralization Potential for Acid Rock Drainage Prediction
1.16.4	Evaluation of Static and Kinetic Prediction Test Data and Comparison with Field Monitoring Data
1.17.1a	Hydrogeochemical Investigation of Reactive Tailings at the Waite Amulet Tailings Site, Noranda, Québec 1985 Program
1.17.1b	Hydrogeochemical Investigation of Reactive Tailings at the Waite Amulet Tailings Site, Noranda, Québec, Phase 2 – 1986 Program
1.17.1c V.1	Hydrogeochemical Investigation of Reactive Tailings at the Waite Amulet Tailings Site, Noranda, Québec, Phase 3 - 1987 Program, Volume I – Report
1.17.1c V.2	Hydrogeochemical Investigation of Reactive Tailings at the Waite Amulet Tailings Site, Noranda, Québec, Phase 3 - 1987 Program, Volume II – Appendices
1.17.1c Sup	Hydrogeochemical Investigation of Reactive Tailings at the Waite Amulet Tailings Site, Noranda, Québec, Phase 3 - 1987 Program, Supplementary Report
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"
1.19.1	Long Term Acid Generation Studies: Cinola Project British Columbia
1.19.2	Scaling Analysis of Acid Rock Drainage
1.21.1a	Critical Review of the Reactive Acid Tailings Assessment Program (RATAP.BMT2),
1.21.1b	Workshop on Modelling of Reactive Tailings Sponsored by the MEND Prediction Committee, Final Report
1.21.2	Laboratory Studies of Pyrrhotite Oxidation
1.22.1a	Field Procedures Manual: Gas Transfer Measurements Waste Rock Piles Heath Steele Mines New Brunswick
1.22.1b	Assessment of Gas Transfer-Ansto Model at Heath Steele Mines
1.25.1	Soilcover Users Manual, Version 2
1.26.1**	Rock Pile Water Quality Modelling. Phase 1 – Final Draft
1.27.1a	Guide for Predicting Water Chemistry from Waste Rock Piles
1.32.1	Prediction and Prevention of Acid Rock Drainage from a Geological and Mineralogical Perspective
1.41.4	Whistle Mine Waste Rock Study
1.42.1	Critical Review of Geochemical Processes and Geochemical Models Adaptable for Prediction of Acidic Drainage from Waste Rock
1.44.1	History of Eskay Creek Mine's Waste-Rock Dump from Placement to Disassembly
1.51.1	Quantitative Analysis of Chemical and Biological Kinetics for the Acid Mine Drainage Problem,
1.51.2	Nonlinear Modelling of Chemical Kinetics for the Acid Mine Drainage Problem and Related Physical Topics,
1.61.3	Column Leaching Characteristics of Cullaton Lake B and Shear (S) - Zones Tailings Phase 2: Cold Temperature Leaching
2.12.1	Louvicourt Man-Made Lakes Disposal
2.13.1a*	Wet Barriers on Pyritic Uranium Tailings
2.13.3*	WATAIL 1.0 User's Manual. A Tailings Basin Model to Evaluate Transient Water Quality of Acid Mine Drainage
2.22.2a	Évaluation en laboratoire de barrières sèches construites à partir de résidus miniers
2.23.2d	A Geochemical, Hydrogeological and Hydrological Study of the Tailings Impoundment at the Falconbridge Limited, Kidd Creek Division Metallurgical Site, Timmins, Ontario
2.31.1a	Heath Steele Waste Rock Study, Phases I to III
2.31.1b	Engineering Design and Construction Phase IV: Composite Soil Cover Acid Waste Rock Study Heath Steele Mines
2.31.1b	Monitoring Report Phase IV: Composite Soil Cover Acid Waste Rock Study Heath Steele Mines
2.31.1c	Monitoring Program 1995-96 Phase V: Composite Soil Cover on Waste Rock Pile 7/12 at Heath Steele, New Brunswick
2.32.1**	Kutcho Creek Project: Blending and Segregation, Acid Generation Testwork
2.36.3	Assessing the Subaqueous Stability of Oxidized Waste Rock
PA-1***	Hydrogeology of Waste Rock Dumps
PA-2***	Metal Transport at Immobilization of Mine Tailings Impoundments

* Open file report

** BC AMD Task Force

*** MEND Associate Project

3.2 LABORATORY METHODS

3.2.1 STATIC GEOCHEMICAL TESTS

Static geochemical tests provide information on bulk geochemical characteristics of materials, for example, the total concentration of copper in a tailings sample. By definition, these tests do not provide any direct information on rates of processes or rates of release of weathering products. The results may be used in conjunction with other tests to evaluate kinetic processes.

MEND projects specifically carried out in the area of static geochemical tests are listed in Table 3.2-1.

Table 3.2-1
Projects in Static Geochemical Testing

MEND Project	Title
1.16.1a	Investigation of Prediction Techniques for Acid Mine Drainage
1.16.1b	Acid Rock Drainage Prediction Manual
1.16.1c	New Methods for Determination of Key Mineral Species in Acid Generation Prediction by Acid-Base Accounting
1.16.2a	Interlaboratory Measurement Program for the Standard ARD Material NBM-1
1.16.3	Determination of Neutralization Potential for Acid Rock Drainage Prediction
1.16.4	Evaluation of Static and Kinetic Prediction Test Data and Comparison with Field Monitoring Data
1.19.2	Scaling Analysis of Acid Rock Drainage
1.32.1	Prediction and Prevention of Acid Rock Drainage from a Geological and Mineralogical Perspective
2.36.3	Assessing the Subaqueous Stability of Oxidized Waste Rock.

A comprehensive description of all relevant methodologies for static geochemical tests is included in MEND 1.16.1.

Most research has been conducted on waste rock-type materials but the methods are equally applicable to tailings. In the following sections, the term “waste” applies to all types of mining mineral products, including waste rock, tailings, ore and concentrate.

3.2.1.1 Acid-Base Accounting

I. Discussion of Theory

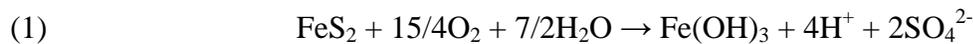
Acid-Base Accounting (ABA) is a two-part analytical procedure for determining both the Acid Potential (AP) and Neutralizing Potential (NP) of mine wastes. Other terms used in the literature include:

- Acid Production Potential (APP), which is sometimes used as equivalent to AP; and

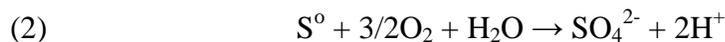
- Maximum Potential Acidity (MPA). Historically, MPA is determined from the total sulphur concentration which may over-estimate true acid potential because not all forms of sulphur generate acid.

AP should be reserved for acid potential based on sulphur concentration in the form of sulphide since in most situations sulphide is the main source of acid. NP is sometimes referred to as Acid Consumption Potential (ACP). The accurate determination of the acid generation and acid neutralization potential is the first step in assessing ARD potential.

AP is typically caused by sulphide oxidation in the presence of oxygen and water. For example, the complete oxidation of iron disulphide is:



Elemental sulphur when oxidized also generates acid:



However, non-ferrous sulphide minerals, such as sphalerite, in which the mole ratio of metal to sulphur is equal to or greater than 1:1 do not generate acid:



The sulphuric acid shown in Equation 1 above, if not neutralized, can contribute to the dissolution of heavy metals and toxicity to the environment. Acid neutralizing compounds consist of a wide variety of minerals including carbonates, silicates, aluminum silicate as well as some oxides and hydroxides. However, the most effective neutralizing minerals occurring in mine wastes are commonly the carbonates. The simplified reaction of calcite with sulphuric acid under low pH conditions is:



and under non-acidic conditions is:



AP is calculated from the quantity of unoxidized sulphur in the waste material. In the reaction equations (1) coupled with (4) above, 1 mole of sulphur produces 2 moles of H^+ which can be neutralized by 1 mole of CaCO_3 . Therefore, neutralization of the acid generated from 1 mole of S requires 1 mole of CaCO_3 . Based on a weight equivalency, 1 g of S is neutralized by 3.125 g of CaCO_3 ¹. Since sulphur assay results are usually expressed in percent, 1% sulphur requires 3.125 kg

¹ Molecular weight of CaCO_3 divided by the atomic weight of sulphur ($100/32 = 3.125$)

CaCO₃ per 100 kg and when expressed in the standard parts per thousand units the multiplier is 31.25 kg CaCO₃/tonne of waste material. These results can also be expressed in kg H₂SO₄/tonne by multiplying the CaCO₃/tonne value by the molecular weight factor of H₂SO₄/CaCO₃ (0.98). The conventional usage in Canada is in equivalents of calcium carbonate rather than sulphuric acid.

In summary, AP (in kg CaCO₃/t) is calculated by:

$$(6) \quad AP = S(\%) \times 31.25$$

where S(%) is the amount of sulphur capable of generating acid.

Neutralization Potential (NP) is determined by reacting a known weight of finely ground sample with a mineral acid. The amount of mineral acid that is consumed is expressed in equivalent kilograms of calcium carbonate or sulphuric acid per tonne of waste.

The results of ABA analysis are expressed in the same units so that an "account" can be made to assess the net potential for acid generation. These units are expressed in parts per thousand of either sulphuric acid or calcium carbonate. The net potential of the waste material to generate acid is determined from the difference between AP and NP. The calculation assumes that all of the available acid generating material and acid neutralizing material is available to react. Theoretically, waste material that has excess acid neutralizing minerals will have a lower probability to generate acidity than those that are deficient in neutralizing minerals. This concept may be expressed as net neutralization potential (NNP):

$$(7) \quad NNP = NP - AP$$

or the neutralization potential ratio (NPR):

$$(8) \quad NPR = NP/AP$$

Both presentations have value, however, NP/AP is preferred because it allows comparison of a wide range of NP and AP on the same basis which is not the case for NNP, for example:

Case	NP kg CaCO ₃ /t	AP kg CaCO ₃ /t	NNP kg CaCO ₃ /t	NPR Ratio
1	210	200	10	1.1
2	20	10	10	2.0

Both cases indicate the same NP excess (10 kg CaCO₃/t), yet compared to Case 1, Case 2 has twice as much NP as AP, which is clearly shown by the NPR.

II. Discussion of MEND Research

MEND 1.16.1a Investigation of Prediction Techniques for Acid Mine Drainage

This study investigated the prediction techniques on the basis of simplicity, resources required, ease of interpretation, value of data, cost and time required. Prediction tests, which included both kinetic and static tests, were also compared with field data. The static test procedures showed the importance of determining sulphate sulphur content. This oversight was responsible for an erroneous prediction by most procedures. Discounting this error, only the BC Research procedure accurately predicted all samples.

MEND 1.16.1b Acid Rock Drainage Prediction Manual

This manual provides detailed methodology for field and laboratory static and kinetic tests. The manual was produced to provide industry and consultants with the methodology for assessing the potential for acid rock drainage from mining wastes.

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

This study investigated the deficiencies of ABA procedures. Deficiencies included the quantity of acid from pyrrhotite sulphur compared to pyrite sulphur, overestimation of potential acidity due to oxidized sulphur, and overestimation of neutralization by calcium carbonate, siderite (FeCO_3) and silicate minerals. Methods were tested to eliminate or reduce these deficiencies. A method was tested which was able to distinguish between pyrrhotite sulphur and pyrite sulphur. Also, overestimation of NP from siderite was corrected by treating the neutralization leach with peroxide prior to back titration. The report recommended additional work to refine some of the test procedures.

MEND 1.16.2a Interlaboratory Measurement Program for the Standard ARD Material NBM-1

This report describes development of the NBM-1 certified acid-base accounting control reference material. An important finding of the validation study was that neutralization potential results reported by different laboratories for the standard showed a bimodal distribution. This is probably attributable to the complex carbonate mineralogy of the sample which included both calcium- and iron-based carbonates.

MEND 1.16.3 Determination of Neutralization Potential for Acid Rock Drainage Prediction

This study investigated the problems associated with the Sobek "fizz" test (Sobek *et al.* 1978). The study compared the modified acid-base accounting procedure (MEND 1.16.1a) with the Sobek procedure and carbonate-NP. The study showed that if the fizz test was erroneously interpreted and more acid was added than required, NP values were much higher than if the correct amount of acid was used. Back titration curves of the acid leach solutions produced inflection points which showed

qualitative evidence of elements that were associated with various minerals. For example, an inflection point at pH 4 to 4.5 was probably associated with aluminum precipitation suggesting silicate mineral dissolution (i.e. aluminum silicates). Also investigated was the use of whole rock analysis and carbonate values as inputs to a CIPW¹ normative composition procedure (Kelsey 1965) to calculate the quantitative mineralogical assemblage of neutralizing minerals. This procedure should be used with caution because it does not always produce a mineralogical composition that is the same as the actual mineral assemblage. From the CIPW calculation, the neutralizing minerals were then given a relative reactivity value to arrive at a quantitative NP value. These values were then compared to the Sobek modified NP and carbonate NP values. Good correlation was observed between the calculated NP and the modified and carbonate-NP.

MEND 1.16.4 Evaluation of Static and Kinetic Prediction Test Data and Comparison with Field Monitoring Data

This study involved extensive testing of tailings samples using standard and modified acid-base accounting methods. Difference in neutralization potential results for different procedures was documented. The study recommended using the NP method described in MEND 1.16.1a due to over-estimation of NP using the Sobek procedure (Sobek *et al.* 1978).

MEND 1.32.1 Prediction and Prevention of Acid Rock Drainage from a Geological and Mineralogical Perspective

This report provides a method for calculating NP based on mineralogical composition. Each mineral is assigned an equivalent calcium carbonate neutralization potential, and the neutralization potential for the total sample is estimated by summing the contributions of individual minerals.

The Draft Acid Rock Drainage Technical Guide (British Columbia Acid Mine Drainage Task Force Report 1989)

This manual for industry and consultants outlines the process of acid rock drainage and provides guidance and recommendations in the application of prediction, control and monitoring techniques.

Guidelines for ARD Prediction in the North (Steffen, Robertson and Kirsten 1992)

This document prepared for Indian and Northern Affairs Canada (also known by the acronym “DIAND”) provides a set of guidelines for prediction of acid rock drainage in northern Canada. The report compared cost, test duration, data obtained, and advantages and disadvantages of various ABA procedures. The report concluded that there is no difference in the methodology or interpretation for ABA for northern climates.

¹ An acronym for the 1902 authors

Draft Guidelines and Methods for the Prediction of Metal Leaching and Acid Rock Drainage at Minesites in British Columbia (Price 1997)

This document, issued by the British Columbia Ministry of Energy and Mines (Reclamation Section), provides a comprehensive description of methods suggested for characterizing mine wastes in western Canada. Some new methods are presented, for example, to estimate leachable metal concentrations and paste pH. Examples of data interpretation for all procedures are provided.

III. Applications and Limitations

ABA may be used to evaluate the following typical data requirements:

- The extent of the potential ARD problem. The ABA data provides regulators and mine operators with an overall estimate of the net acidity that could occur from weathering of wastes;
- The quantity of kinetic testing required. Evaluation of ABA data is used to make decisions on which wastes will be tested kinetically. Samples with a high NP compared to AP are often not tested since these are considered to be benign; and
- Preliminary mine site planning and disposal options. ABA data can quickly show problem wastes, which affect the mine site plan and disposal options.

The main limitations associated with acid-base accounting procedures are that the data does not distinguish between the types of minerals that are responsible for NP and AP and the inability to correlate ABA data with kinetic weathering characteristics for the majority of data. NP is difficult to accurately determine and should not be directly compared to field neutralization potential for a number of factors:

- The neutralization potential determination is conducted at an acidic pH < 6.0 where all of the carbonate is expelled as CO₂ gas. Under field conditions calcite weathering may take place at neutral to alkali pH levels and incomplete neutralization to bicarbonate (HCO₃⁻) occurs;
- Another source of over-estimation is from the test conditions. The Sobek ABA procedure (Sobek *et al.* 1978) uses hydrochloric acid at near 100°C temperatures and at a pH which is often < 2.0. At this pH and at the aggressive heating conditions, minerals which do not contribute neutralization potential at a pH > 5.0 are being included in the NP value. These include silicate minerals such as kaolinite, montmorillinite and albite (MEND Report 1.16.4);
- NP can be over-estimated by the dissolution of reduced iron compounds such as siderite. These compounds initially contribute to neutralization but hydrolyze to form hydroxides and release their acidity back into the environment; and
- False neutralization potential can be derived from pyrrhotite if the iron does not oxidize fully during the test (MEND Report 1.16.1c).



The AP can be over-estimated if sulphide, in forms other than acid-generating, is included in the calculation. Possible interferences requiring resolution by different analytical methods include:

- Monosulphides with metal:sulphur ratios ≤ 1 (e.g. S as sphalerite, galena);
- Weakly soluble sulphates (e.g. barite, anglesite); and
- Weak acid soluble sulphates (e.g. gypsum, anhydrite, zinc sulphate, copper sulphate)

IV. Base Method

ABA is a two part analytical procedure consisting of AP and NP determinations. The sample is prepared by drying at no more than 60°C.

The base method for AP is typically calculated from the difference in total sulphur and sulphate-sulphur soluble in hydrochloric acid. Total sulphur can be used for the calculation only after it can be shown that the quantity of sulphate-sulphur present in the waste is negligible.

Total sulphur is determined by direct combustion in a furnace. The evolved SO₂ gas is either determined by an infrared detector which gives a direct reading that is compared to sulphur standards or by absorption and iodometric titration of the solution.

Sulphate-sulphur is determined by dissolution in HCl. In this procedure 5 g of pulverized sample is treated with 20 mL of 3N HCl. The sample is heated to boiling, allowed to cool, filtered and washed with distilled or deionized water and brought to a final volume of 100 mL. The sulphate is then determined by either ion chromatography, gravimetrically or by the turbidimetric method (Standard Methods 1992). The quantity of sulphide-sulphur is then calculated from the difference between total sulphur and sulphate-sulphur. The sulphide-sulphur is expressed as a percentage (w/w) of the original sample and multiplied by the conversion factor of 31.25 to express the results in kg CaCO₃/tonne.

For NP determination, the Sobek procedure (Sobek *et al.* 1978) is the recommended base procedure. This method has been widely used by the mining industry for 20 years, and therefore many practitioners can interpret the data. This procedure requires little equipment and can be completed in a relatively short time-frame for large quantities of samples. In this procedure hydrochloric acid is used as the neutralizing acid. The quantity of acid added is determined by a fizz test. The fizz test consists of adding 1:3 HCl to a small quantity of pulverized sample and rating the reaction according to the amount of bubbling or "fizz". After adding the appropriate amount of HCl the sample is heated to near boiling. Water is then added to a volume of approximately 125 mL and the sample is boiled to expel any dissolved carbon dioxide. The sample is then cooled and back-titrated with standard

sodium hydroxide to determine the quantity of acid consumed. This value is converted to kg CaCO₃/tonne of waste.

Paste pH is a measure of the natural pH of the waste material and the Sobek procedure (Sobek *et al.* 1978) is the recommended base procedure. In this procedure approximately 10 g of pulverized sample (specified as finer than 60 mesh) is weighed into a small beaker. Five millilitres of distilled water are added and allowed to wet the sample by capillary action without stirring. The sample is then stirred with a glass rod or spatula until a thin paste is formed. More water or solids may be added to keep the sample at the saturation point. The pH of the paste is then measured with a calibrated pH meter. Price (1997) provides a discussion of the interpretation of paste pH.

For ABA quality control the NBM-1 standard reference material was developed and can be purchased from CANMET (MEND 1.16.2a). This standard contains recommended values for total sulphur, NP and paste pH. The reference material should be analysed for each batch of samples.

The results should be presented in a table format. An example is shown below. Due to the number of different methods available for acid-base accounting, the results should be clearly annotated to indicate units, analytical methods and a description of abbreviations used.

Sample ID	Paste pH	S _{Total} (wt %)	S _{Sulphate} (wt %)	S _{Sulphide} (wt %)	TIC (wt %C)	AP (kg CaCO ₃ /t)	NP _{Sobek} (kg CaCO ₃ /t)	NP _{CO3} (kg CaCO ₃ /t)	NNP (kg CaCO ₃ /t)	NPR
Sample-1	8.6	0.32	0.03	0.29	0.48	9.1	50	50	41	5.5

Paste pH: Sobek Method

S_{Total} by Leco Furnace

S_{Sulphate}: HCl Soluble (Sobek Method)

S_{Sulphide}: By difference (S_{Total} – S_{Sulphate})

TIC – Total inorganic carbon

AP = 31.25xS_{Sulphide}

NP_{Sobek} by Sobek Method

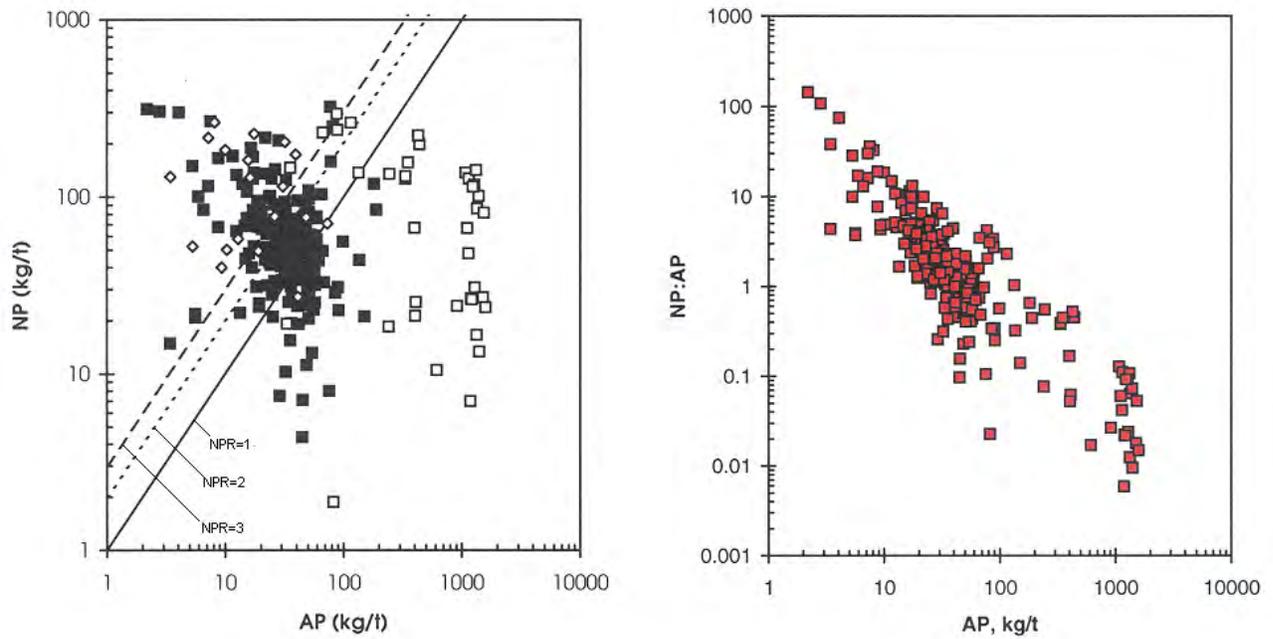
NP_{CO3} = TIC*(1000/12)

NNP = NP-AP

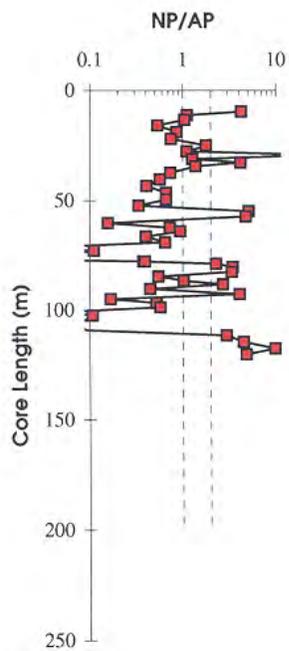
NPR = NP/AP

Results are commonly plotted as NP vs. AP scatter plots, AP vs. NP/AP, NP vs. pH (Figure 3.2-1), or as individual parameters compared to rock types, mineralogical descriptors or spatial coordinates.

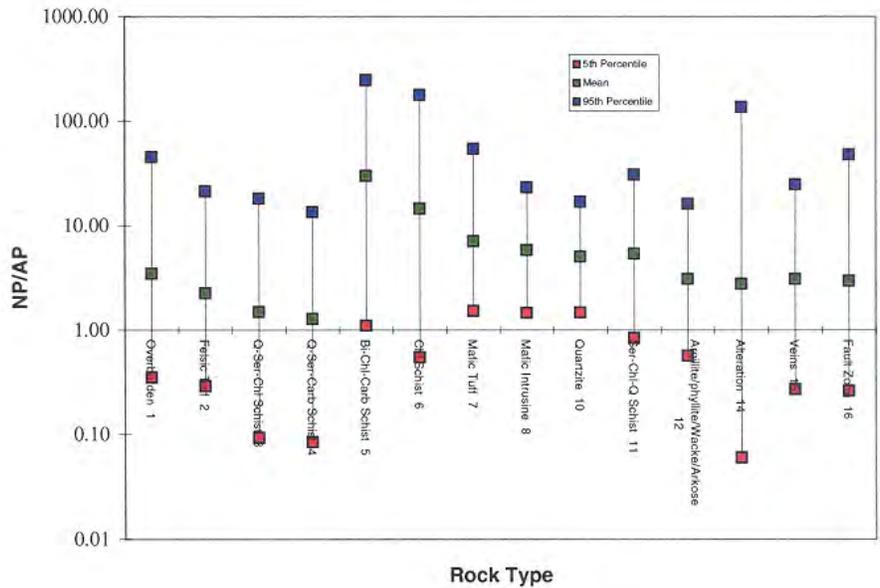
Figure 3.2-1 Examples of Graphical Illustrations of ABA Data



DDH 94-46



NP/AP by Rock Type



V. Variations

Variations to the procedure address both the chemical form of sulphur and neutralization potential, and direct determination of acid generation potential.

Form of Sulphur

Total sulphur can be determined by ICP or XRF. These methods provide a low cost means of determining total sulphur on samples when metal analysis is also required. The samples are prepared as for metals, and sulphur is included as part of the suite of elements to be measured.

Sulphur in various mineralogical forms can be estimated by a variety of methods, including:

- Direct determination of total sulphide (commonly an oxidizing acid digestion, for example nitric acid and bromine);
- Estimation of sulphur as barite using barium determined by XRF (Section 3.2.1.4.2). This determination may over-estimate baritic sulphur if barium occurs in other forms such as carbonates and silicates;
- Estimation of sulphur as zinc, copper and lead sulphides using zinc, copper and lead concentrations determined by *aqua regia* digestions (Section 3.2.1.4.2); and
- Estimation of sulphur as water-soluble sulphate using a deionized water digestion.

Form of Neutralization Potential

A number of variations on the Sobek procedure (Sobek *et al.* 1978) have been recommended primarily to address the concern that the Sobek procedure accounts for mineral forms that may not be natural acid consumers.

The ABA procedure developed at BC Research by Bruynesteyn and Duncan (1979) has gained wide acceptance; however, the BC Research method requires more equipment and a longer turn-around time for large numbers of sample. In the BC Research procedure a 10 g portion of pulverized sample is suspended in 100 mL of distilled or deionized water and stirred with a magnetic stirrer for 15 minutes before the natural pH of the sample is recorded. The sample is then titrated to pH 3.5 with 1.0 N sulphuric acid using an automatic titrator. The test is continued until less than 0.1 mL of acid is added over a 4 hour period to maintain the target pH end-point. The total volume of acid added is recorded and multiplied by the conversion factor 5.00 to express the results in kg CaCO₃/tonne.

A modification of the Sobek procedure was introduced by Morrison *et al.* (1990) to account for NP from siderite. Under normal weathering conditions ferrous iron will oxidize and hydrolyze to produce ferric hydroxide which would release the acidity back into the environment. The modification consists of filtration of the leach solution and treatment with peroxide which converts

the ferrous iron to ferric iron. The sample is then back titrated as per the Sobek procedure. Another modification to the Sobek procedure described in MEND 1.16.1a was developed to address concerns that the Sobek procedures could over-estimate the NP due to the elevated temperature that the test is conducted and misinterpretation of the fizz test. In this procedure the acid leach is allowed to occur at ambient (30°C) temperature for 24 hours on a mixing device such as a gyratory shaker. The leach solution is then back titrated to pH 8.3 rather than 7.0 as with the Sobek procedure.

Two recent modifications to neutralization potential methods have been used to better understand the minerals contributing to the neutralization potential. MEND 1.16.3 monitored the NP titration curve and interpreted inflection points to clarify various types of alkalinity in solution. Day *et al.* (1997) analyzed the leachate from acid digestions used in NP determinations to reveal the minerals that have undergone dissolution.

Determination of total carbonate (total inorganic carbon, TIC) (Section 3.2.1.2) and total carbon (C_{Total}) is useful to evaluate the amount of carbonate compared to the neutralization potential. Both methods are relatively straightforward and not prone to significant analytical errors. Total carbonate cannot be converted to neutralization potential because heavy metal carbonates, particularly those enriched in iron, are not necessarily acid consumers. TIC is useful in inferring the presence of other neutralization potential measures if carbonate NP cannot account for all the available NP in a sample. In non-carbonaceous materials, C_{Total} may be a surrogate for carbonate, and therefore may represent a rapid method for neutralization potential estimation.

Direct Estimation of Acid Generation Potential

Another variation of the ABA procedure is the net acid production test (MEND 1.16.1a) or net acid generation pH test (NAG pH) (Miller *et al.* 1997). This procedure does not differentiate between AP and NP, but instead attempts to arrive at a net value for potential acid generation. This procedure involves the addition of hydrogen peroxide to a known weight of sample. The reaction of the hydrogen peroxide oxidizes sulphide to sulphuric acid which in turn is neutralized by neutralizing agents present in the sample. The remaining acid is titrated with standardized base to pH 7.0 to give the net acid produced by the reaction which is expressed in kg CaCO₃ equivalent per tonne. The procedure is widely used, particularly in southeast Asia and Australia as a management tool at operating mines. It is also a useful field screening tool for site investigations. However, it cannot be used in carbonaceous rocks because oxidation of carbon during the procedure produces acid, which does not occur naturally. The procedure should be used with caution and results compared to other procedures such as acid-base accounting.

Procedures for Tailings and Waste Rock

The analytical procedures are comparable for tailings and waste rock. Sample preparation will vary.

Generally, waste rock samples must be dried, then crushed and pulverized to provide suitable material for analysis. Tailings samples usually need to be dried and broken up to reduce aggregation. Some tailings can be analyzed directly while others must be pulverized depending on the particle size distribution.

V. Cost

Costs for ABA are dependent on a number of factors. The AP portion of the test for the base method includes total sulphur and sulphate sulphur. Cost for the base method and the most frequently used variation (BC Research Method) are similar and range from \$50 to \$120 (1996 Canadian dollars) depending on the laboratory used, sample preparation requirements and the number of samples.

VI. MEND and Relevant Publications

- MEND 1.16.1a 1989. Investigation of Prediction Techniques for Acid Mine Drainage. November.
- MEND 1.16.1b 1991. Acid Rock Drainage Prediction Manual. March.
- MEND 1.16.1c 1991. New Methods for Determination of Key Mineral Species in Acid Generation Prediction by Acid-Base Accounting. April.
- MEND 1.16.3 1996. Determination of Neutralization Potential for Acid Rock Drainage Prediction. July.
- MEND 1.16.4 1995. Evaluation of Static and Kinetic Prediction Test Data and Comparison with Field Monitoring Data. December.
- MEND 1.32.1 1993. Prediction and Prevention of Acid Rock Drainage from a Geological and Mineralogical Perspective. October.

British Columbia Acid Mine Drainage Task Force Report. 1989. Draft Acid Rock Drainage Technical Guide. Volume 1, August.

Bruynesteyn, A. and Duncan D.W. 1979. *Determination of Acid Production Potential of Waste Materials*. In: AIME Annual Meeting, New Orleans, LA. 19 to 21 February. Paper A-79-29.

Day, S., Hope, G. and Kuit, W. 1997. *Waste Rock Management Planning for the Kudz Ze Kayah Project, Yukon Territory: 1. Predictive Static and Kinetic Test Work*. In: Proceedings of the 4th

International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June, Vol 1, pp. 81-98.

Kelsey, C.H. 1965. *Calculation of the C.I.P.W. Norm*. Mineralogical Magazine, Vol 34, pp. 276-282.

Miller, S., Robertson, A. and Donohue, T. 1997. *Advances in Acid Drainage Prediction Using the Net Acid Generation (NAG) Test*. In: Proceedings of the 4th International Conference on Acid Rock Drainage, Vancouver, British Columbia. 31 May to 6 June. Vol 2, pp. 533-549.

Morrison, J.L., Atkinson, S.D., Davis, A. and Sceetz, 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.

Price, W.A. 1997. Draft Guidelines and Methods for the Prediction of Metal Leaching and Acid Rock Drainage at Minesites in British Columbia.

Sobek A.A, Schuller W.A., Freeman J.R. and Smith R.M. 1978. Field and Laboratory Methods Applicable to Overburden and Minesoils. USEPA Report No. 600/2-78-054, 203 pp.

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

Steffen, Robertson and Kirsten (B.C.) INC. 1992. Guidelines for ARD Prediction in the North. Report 102902. Prepared for Indian and Northern Affairs Canada.

3.2.1.2 Total Inorganic Carbon (TIC)

I. Discussion of Theory

Carbonate analysis measures the quantity of carbon dioxide that is released from a pulverized sample when reacted with hydrochloric acid. Minerals such as calcite, dolomite and siderite release carbon dioxide under these reaction conditions. The quantity of carbon dioxide released is converted, by calculation, to neutralization potential and compared with NP obtained from standard ABA determination.

II. Applications and Limitations

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

- To measure the neutralization potential associated with carbonates;
- To complement mineralogy data (e.g. XRD) for presence of carbonate bearing minerals such as calcite and dolomite; and
- As a field method for determining presence of carbonate minerals.

The main limitation of the procedure is that it provides only the carbonate fraction of the total NP. Also, by itself it can give a misleadingly high NP when siderite is the main carbonate mineral. Although the procedure is less costly than NP it can only be used to complement the NP results.

III. Base Method

The most common method used by geochemical laboratories for carbonate analysis is carbon analysis by Leco furnace. In this procedure the sample is fired in a carbon/sulphur analyzer to release CO₂ and SO₂. The CO₂ is measured by an infrared detector which gives a direct reading of the carbon content. A split portion of the sample is treated with 15% hydrochloric acid to remove inorganic carbon in the form of carbon dioxide. The treated sample is then analyzed on the carbon/sulphur analyzer to determine the carbon content. The difference in the carbon content of the sample is assumed to be carbonate carbon and is expressed as either percent total inorganic carbon (TIC) or CO₂. The detection limit is 0.1% CO₂.

This procedure is adequate for hard rock samples or soils with low organic carbon content. However, for samples with high organic carbon content, such as coal, the difference in carbon content before and after removal of the inorganic carbon may be minimal due to the high background carbon from coal. In this case, another procedure involving direct measurement of the carbon dioxide evolved, should be used.

IV. Variation

A variation of the procedure also converts the carbonates to carbon dioxide using hydrochloric acid. Two methods are commonly used. One method involves leaching 0.20 g of pulverized sample with dilute hydrochloric acid (Hillebrand *et al.* 1953). Carbon dioxide is released and carried into a measuring burette by a stream of oxygen. The gases are then passed through a potassium hydroxide solution that absorbs carbon dioxide. The oxygen is returned into 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% CO₂. In a similar gravimetric procedure, the carbon dioxide is evolved with sulphuric acid and absorbed onto Ascarite after passing through a number of gas scrubbing tubes (Snell and Biffen 1944). The weight increase of the Ascarite is attributed to the carbon dioxide evolved and converted to percent carbonate content.

V. Cost

Cost for the base method ranges from \$10 to \$20.

VI. MEND and Relevant Publications

Hillebrand, W.F., Lundell, G.E.F., Bright, H.A. and Hoffman, J.I. 1953. Applied Inorganic Analysis, 2nd Edition. John Wiley & Sons, Inc., New York.

Snell, D.F. and Biffen, F.M. 1944. Commercial Methods of Analysis, 1st Edition. McGraw-Hill Book Company, Inc., New York.

3.2.1.3 Mineralogy

I. Discussion of Theory

The type and quantity of minerals present in wastes influence their weathering characteristics. Although ABA and chemical analyses provide considerable information on the potential weathering characteristics, these analyses provide only the gross quantities of the characteristics and elements present. Empirical calculation of mineral types is not practical due to the complexity of most host rock. The use of petrographic instruments can provide substantial information on mineral identification, grain size, grain boundaries and an estimate of their quantities. These data can be used to support the chemical analysis.

II. Discussion of MEND Research

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

This study discusses the methods used for petrographic examination as it relates to NP.

MEND 1.16.3 Determination of Neutralization Potential for Acid Rock Drainage Prediction

This report describes use of whole rock analysis results and carbonate values as inputs to a CIPW normative composition procedure to calculate the quantitative mineralogical assemblage of samples (Kelsey 1965). The neutralizing minerals were then given a relative reactivity value to arrive at a quantitative NP value. These values were then compared to the Sobek modified NP and carbonate NP values (Sobek *et al.* 1978).

III. Applications and Limitations

Mineralogy may be used to evaluate the following typical data requirements:

- Mineralogy can be used to support ABA and chemical analysis data;

- Knowledge of the types of minerals present can be used to estimate the weathering characteristics;
- Information on the grain size and spatial distribution of the minerals can be used to support weathering characteristics. For example, whether acid consuming constituents are in direct contact with sulphides; and
- Examination of rinds on weathered wastes can aid in confirming the amount of oxidation that has taken place and how the oxidation products are coating the minerals.

The main limitation of the procedures used in providing mineralogical data is the detection limits and the overall accuracy of the examination due to the small sample size examined for the procedures. The accuracy of the data are largely dependent on the experience and skill of the examiner. Most procedures are qualitative and provide only semi-quantitative results. The use of petrography has only recently been included in ARD prediction and a database to compare results is very limited.

IV. Base Method

Mineral speciation is a stepwise process which begins in the field by a trained geologist. Optical microscopy is the first method used for mineral identification. In the field the instruments are generally limited to hand lens and binocular microscope.

X-ray powder diffraction is generally the most useful tool to determine major minerals. Bulk samples are ground to a powder and positioned at the centre of an X-ray goniometer. To collect a diffraction spectrum, the detector is moved in an arc around the sample, through a range of incident angles. Episodes of constructive interference is a function of the crystal structure of the sample and are seen as peaks in the spectrum. The position and intensity of the peaks are used to identify the minerals in the sample, and to obtain a semi-quantitative (at best) estimate of their relative abundances.

Preparation of clay-bearing samples requires disaggregation in water and three different treatments on slides. The X-ray spectra collected from the slides show differences, which may be used to identify the clay minerals present in the sample.

X-ray powder diffraction does not provide information on the grain size or spatial distribution and because bulk samples are used, diffractometry is less useful for identifying secondary minerals. As a general rule, the presence of all minerals identified by X-ray diffractometry should be confirmed by other means such as optical microscopy and microprobe analysis.

In the laboratory, mineralogy details are obtained by preparing polished thin sections for examination using a petrographic microscope. The examination and interpretation are based on the examiner's

knowledge and experience. The microscope allows measurement of the grains and boundaries with a detection limit of 5 μm . Point counting may also be conducted to quantitatively determine the abundance of different minerals.

Further verification is conducted by scanning electron microscopy (SEM) on the same polished thin sections which are mounted on a stub and coated with a thin layer of carbon or gold to prevent charging. An electron beam is scanned across the sample, and secondary electrons are collected by a detector and used to create a magnified image (up to 100,000 times) on a TV screen. Back-scattered electrons are collected by a different detector to give compositional information. Image analysis techniques can be used to determine the amount of a particular mineral in a sample. Some SEMs are equipped with Energy Dispersive Spectrometers (EDS) which are used to analyze X-rays given off by the sample in response to the electron beam. Because different elements produce X-rays with distinctive energies, the spectrum provides a semi-quantitative chemical analyses.

A description of mineralogical techniques can be found in Jambor and Blowes (1994).

V. Variations

The electron microprobe is similar to the SEM but is optimized for chemical analysis rather than imaging. Wavelength Dispersive Spectrometers (WDS) are used to analyze X-rays given off from a very small area of the sample in response to the electron beam. The intensities of the X-ray peaks are compared to those of standards of known composition for quantitative analysis.

VI. Cost

X-ray powder diffraction costs approximately \$100 per sample and somewhat more for clays. Optical microscopy costs \$60 to \$150 depending on sample volume, mineral diversity and thin and/or polished section preparation. SEM work generally costs \$100 to \$150 per hour. Electron microprobe studies generally cost about \$200 per hour (or about \$20 per analysis). Because new electron microprobes cost about \$1.5 million they are generally only found at universities and other research institutions.

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. |
| MEND 1.16.3 | 1996. Determination of Neutralization Potential for Acid Rock Drainage Prediction. July. |

Jambor J.L. and Blowes, D.W. 1994. Short Course Handbook on Environmental Geochemistry of Sulphide Mine Wastes. Mineralogical Association of Canada. Waterloo, Ontario, May.

Kelsey, C.H. 1965. *Calculation of the C.I.P.W. Norm*. Mineralogical Magazine 34:276-282.

Sobek A.A., Schuller, W.A., Freeman, J.R. and Smith R.M. 1978. Field and Laboratory Methods Applicable to Overburden and Minesoils. USEPA Report No. 600/2-78-054, 203 pp.

3.2.1.4 Metals¹

3.2.1.4.1 Digestion Techniques

I. Discussion of Theory

The main concern for ARD is the leaching of metals to the environment. Mineralogical information is only semi-quantitative and trace elements are usually not detected. To determine the total potential load to the environment a digestion technique is usually required to extract the metals from the geological matrix. Once extracted the metals can be determined by any of a number of spectroscopic or classical methods.

II. Application and Limitations

Digestion techniques may be used to evaluate the following typical data requirements for mines:

- Determination of heavy metals; and
- Determination of trace and major elements.

The main limitation is in the interpretation of the data produced from a particular digestion method. The selection of the digestion method(s) must be tailored to the metals of interest.

III. Base Method

Prior to analysis samples must be properly prepared. Wet samples must be dried at no more than 60°C to prevent sulphide oxidation since sulphide analysis may also be required. Samples that contain cemented lumps must be broken with a heavy rolling pin or with appropriate crushing and pulverizing equipment. The sample should be approximately 200 mesh or finer before analysis. If the sample is large, splitting should be conducted with an appropriately sized splitter box or by the cone and quarter technique.

¹ The term “metals” is used in this section to refer to elements which can include light and heavy metals, metalloids (e.g. arsenic) and non-metals (e.g. selenium)

For major and trace elements whole rock analysis (WRA) using a lithium metaborate fusion technique is preferred. In this procedure a known weight of sample (0.2 - 0.5 g) is mixed with lithium metaborate in a platinum crucible. The mixture is heated to 1000°C to produce a fusion reaction. The crucible is allowed to cool and the solid flux dissolved in nitric acid. Hydrofluoric acid may be added in addition to the nitric acid to achieve complete solubilization. The solution is made up to a standard volume and analyzed by a spectroscopic method. The fusion melt may also be analyzed directly by X-ray fluorescence analysis.

A description of digestion techniques can be found in Johnson and Maxwell (1981)

IV. Variations

A triple acid digestion can be used to liberate both major and minor elements and base metals. This procedure uses nitric, perchloric and hydrofluoric acid. Hydrofluoric acid is capable of reacting with silica to completely dissolve the silica matrices and liberate all trace elements. This acid mixture must be taken to dryness and the residue baked in order for the reaction to go to completion. Volatile species such as arsenic, antimony and mercury may be lost in this process and cannot be measured reliably by this method. The presence of high sulphide concentrations may cause precipitation of insoluble sulphates, such as barium and lead, giving erroneous results. The choice of method should take into consideration the limitations of the procedure for analysis of certain elements.

Trace elements can also be determined by an acid dissolution mixture consisting of nitric and *aqua regia*. Samples are treated with hot concentrated nitric acid to oxidize sulphide minerals. Concentrated hydrochloric acid is then added equivalent to 3 times the quantity of nitric acid in order to generate *aqua regia*. The final digestion extract is made up to a standard volume and analyzed by a spectroscopic method. The digestion is "total" for most base metals but cannot be used to replace whole rock analysis (WRA) since the dissolution is only "partial" for most major and minor elements. If volatile metals such as arsenic and antimony are present, digestion by a combination of hydrochloric acid and potassium chlorate is preferred. This digestion technique generates chlorine at a relatively low temperature which provides a highly oxidizing environment capable of dissolving many elements of interest without the loss of potentially volatile elements.

V. Cost (1998)

Digestion costs are not quoted separately but are usually included as part of the overall analysis.

VI. MEND and Relevant Publications

Johnson W.M. and Maxwell, J.A. 1981. Rock and Mineral Analysis, 2nd Edition. John Wiley & Sons, Toronto.

3.2.1.4.2 *Metal Analysis*

I. Discussion of Theory

A wide range of analytical techniques are available for the detection and quantification of metals once the sample has been properly digested for analysis. 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 main concern of ARD. Metal concentration is one of the key parameters in assessing the weathering characteristics of mine wastes. Metal analyses are applicable for the:

- Estimation of total metal loading; and
- Determination of what metals may be in ARD.

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

III. Base Method

The base method for determining metals in solution is inductively coupled atomic plasma emission spectroscopy (ICP-AES). This method is preferred since a large number of metals are analysed simultaneously with overall good accuracy. The instrument is widely available and analytical costs are competitive. These methods are described in Standard Methods, Section 3120 (1992). 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.

Inductively coupled plasma 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 are measured in the ultra violet, visible, and near infrared regions 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. 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

Atomic absorption spectrophotometry is useful for specialized analysis where a high degree of accuracy is necessary or where the analysis of only a few elements is required. 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.

Inductively Coupled Plasma Mass Spectrometry (ICP-MS) provides greater sensitivity for most elements compared to ICP-AES, however, 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.

X-ray fluorescence spectroscopy (XRF) is an ideal instrumental technique for the analysis of major and minor elements of rock samples. Samples and standards are usually prepared by lithium metaborate fusion. In XRF, an electron beam is directed at a target for the release of a primary source of X-rays. A secondary target (the sample), is then irradiated with primary X-rays resulting in emission of fluorescent, secondary X-rays. Fluorescent X-rays are emitted with characteristic energies which are used to identify the element of origin.

Neutron activation analysis (NAA) is ideal for analyzing specific elements such as gold and arsenic. The sample is reduced to a powder and analysed directly. Spectral overlap, caused by the presence of large amounts of one element relative to others, can cause measurement difficulties, a common problem with this and other spectroscopic analysis techniques. NAA uses a thermal neutron flux for activation and conversion of the elements of interest to a radioactive isotope of the same elements. Isotopes will then decay with a specific half-life resulting in the emission of gamma rays. This radiation is characteristic for each element. The quantification of an element is derived from the number of gamma rays emitted from a specific element, which is directly proportional to its concentration in the sample. Due to radiation the sample remains radioactive for some time and is not safe to use for other analysis.

V. Cost (1998)

Cost 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. 1992, 18th Edition, APHA, AWWA and WEF, Washington DC.

3.2.1.4.3 Weak Extractions

I. Discussion of Theory

Weak extractions measure the readily soluble components of mine wastes. The tests can be grouped into two general categories:

1. Selective or sequential extractions designed to quantify concentrations of elements associated with particular mineral forms; and
2. Regulatory extraction procedures for classification of wastes according to statutes (for example, the Toxicity Characteristics Leaching Procedure (TCLP) (US EPA 1993) used in the United States to determine hazardous wastes).

Category 1 is a subset of metal determinations in which the digestion procedure is tailored to specific properties of the mineral hosts. Specific examples include (MEND 2.36.3):

- Water soluble fraction by distilled or deionized water leaching;
- Exchangeable/adsorbed/bound to carbonates using sodium acetate/acetic acid;
- Total reducible using hydroxylamine hydrochloride/acetic acid; and
- Total oxidizable using hydrogen peroxide/acetic acid.

Category 2 tests are usually conducted over a 24-hour period using either fresh water or a weak non-oxidizing acid solution (e.g. acetic acid or sulphuric acid) and were originally intended to classify wastes according to regulatory criteria. The tests assume that all of the soluble salts will be dissolved under the test conditions. Fresh wastes are generally not tested by this procedure unless they are produced from a dry process since the wastes have usually undergone considerable wet processing which has removed readily soluble salts to the pond water effluent. Weathered wastes, however, will accumulate salts from oxidation/neutralization products which represent a potential load on the environment. Short-term leach tests provide an indication of the readily soluble load in the waste.

II. Discussion of MEND Research

MEND 2.36.3 Assessing the Subaqueous Stability of Oxidized Waste Rock

This project evaluated processes occurring in subaqueously disposed waste rock. A section in the report described methods available to characterize weathering products in oxidized waste rock. A sequential extraction procedure was recommended for waste rock. The extraction procedure was based on standard methods and on the work of Tessier *et al.* (1979).

III. Applications and Limitations

These tests may be used to evaluate the following typical data requirements:

- For weathered wastes or fresh wastes produced by a dry process, to determine the potential loading on the environment;
- For determining the extent of acid generation that has taken place;
- To estimate the downstream water quality in the event of an incident such as high water flow or tailing dam failure; and
- In connection with kinetic testing to remove readily soluble salts prior to kinetic testing or at the end of the kinetic test where insufficient flushing failed to liberate all of the salts.

The test procedures cannot be used to determine the rate of leaching unless leaching tests are conducted over a period of time with frequent monitoring in a controlled laboratory environment. The data could only be used to give an average leaching rate. The test does not give any information on the potential for ARD or chemical characteristics of the waste.

Results from regulatory-type tests must be interpreted with care. Regulatory procedures based on acetic acid are unsuitable for mine wastes except when a classification with respect to regulatory criteria is required. The tests are not appropriate because the solubilities of acetates are very different from sulphates. For example, lead acetate is very soluble but lead sulphate is relatively insoluble. Zinc acetate is less soluble than lead acetate but zinc sulphate is far more soluble than lead sulphate.

Metal concentrations in leachate can be useful in some cases because they are controlled by the solubility of secondary minerals in the leachate. For this reason, metal concentrations should not be converted to mg/kg equivalents because the secondary minerals are unlikely to have dissolved completely.

IV. Base Method

Sequential extraction procedures specifically for mine wastes are being researched. The work of Tessier *et al.* (1979) provides the basis for the procedures.

The base method for the regulatory-type procedures (i.e. procedures used to classify wastes according to statutes) are based on a modified ASTM 3987 Procedure which consists of a fresh water leach with a solid to water ratio of 1:4. In this procedure the moisture content of the sample is determined by drying a portion of sample at 60°C. If the collected sample has cemented together it must be crushed to pass 9.5 mm. Two-hundred grams equivalent dry weight of waste and 0.8 L of water are then added to a 1.25 L wide mouth plastic container. The sample is agitated on a rotary extractor at 10 rpm for 24 h at room temperature. After 24 hours the container is opened and the pH measured. The contents are allowed to settle and the supernatant filtered through a 0.45 µm Millipore filter paper to provide sufficient volume for analysis. The leachate is analysed for redox potential, acidity, alkalinity, sulphate and metals.

V. Variations

Variations of the base regulatory procedure are limited to composition and pH of extraction solution, duration of extraction period, solid liquid ratio and method of agitation. Examples include:

- British Columbia Special Waste Extraction Procedure (SWEP) (Province of British Columbia 1988) utilizes acetic acid as does the US EPA Method 1311 (TCLP) and several other similar tests in other Canadian provinces. As noted above, these tests must be used very cautiously;
- The BC SWEP (Province of British Columbia 1988) procedure includes a modification which uses deionized water in place of acetic acid;
- The US EPA Method 1312 (SPLP) (US EPA) 1986 uses a mixture of weak nitric and sulphuric acid; and
- The Meteoric Water Mobility Procedure (MWMP) developed by the Nevada Mining Association (1996) uses a deionized water leach on a coarse rock to indicate the concentrations of metals produced by first contact with water.

Variations on all the above tests include analyzing the leachate as the test progresses and also continuing the test beyond the specified period in the test. Descriptions and discussions of these procedures can be found at the website: www.environment.com/ard.

VI. Cost (1998)

The cost for the base procedure is \$175 to \$250/sample depending on the analysis required. Costs for variations of the procedure are slightly higher due to the added complexity of the test procedure.

VII. MEND and Relevant Publications

MEND 2.36.3 1999. Assessing the Subaqueous Stability of Oxidized Waste Rock. April.

American Society for Testing and Materials. 1990 Annual Book of ASTM Standards, Volume 2.04.

Province of British Columbia. 1988. Waste Management Act, Special Waste Regulation, B.C. Reg. 63/88.

Nevada Mining Association. 1996. Meteoric Water Mobility Procedure (MWMP), Standardized Column Percolation Test Procedure. Nevada Mining Association, Reno, NV. 5.

Tessier, A., Campbell, P.G.C. and Bisson, M. 1979. *Sequential Extraction Procedure for the Speciation of Particle Trace Metals*. Analytical Chemistry 51:844-851.

U.S. EPA, 1993. Method 1311 Toxicity Characteristic Leachate Procedure (TCLP). CFR Parts 260 to 299 (Revised November, 1993).

U.S. EPA, 1986. Method 1312 Synthetic Precipitation Leach Test for Soils. (Revised September 1986).

3.2.1.5 Physical Characteristics and Tests

3.2.1.5.1 Particle Size

I. Discussion of Theory

Particle size determination, generally done by screening, separates a mixture of various sizes of grains into two or more portions. Knowledge of the particle size distribution is of major importance for ARD prediction.

II. Applications and Limitations

Particle size may be used to evaluate the following typical data requirements for mines:

- As part of the database for ARD modelling;
- To calculate the surface area of the waste; and
- For interpretation of results from humidity cells or other kinetic tests.

The main limitation of the procedure is in the method of analysis. Dry methods tend to further reduce particle size by attrition. Wet methods also reduce the particle size of the original sample by slaking and attrition. Therefore, the particle size data and interpretation should take these factors into consideration.

III. Base Method

There are a number of procedures for particle size determination. The sieving method is the most common method used for ARD work. Most sieving methods are conducted on a dry sample to prevent clumping and adhesion of fine material to larger particles. The sample must be dried at 60°C before dry sieving. The process of sieving consists of presenting the particles to equal-sized apertures that constitute a series of go/no-go gauges (Weiss 1985). The screens are arranged in a decreasing size series with the largest sieve receiving the material first. Dry sieving is limited to a minimum size of 43 µm (325 mesh) unless special equipment is used to overcome the surface forces that occur between smaller particles.

There are a number of testing sieves on the market, one of the most common laboratory unit being the "Ro-Tap" which is able to handle up to 13 sieves and a pan which holds the material passing through the finest screen on the bottom. The "Ro-Tap" produces a gyrating motion and a tapping on the top of the unit to ensure adequate opportunity for material to be presented to the sieve opening. The unit is equipped with a timer that automatically terminates the test after any predetermined time. The recommended time for screening is 5 to 10 minutes depending on the smallest sized sieve. For example, if the smallest size is 2 mm then a total shaking time of 5 minutes should be adequate. For sizes smaller than 2 mm a shaking time of 10 minutes is recommended. To check if screening is complete the finest screen should be tapped on the side while holding it over a large piece of clean paper. Negligible material should pass through the screen, otherwise screening on the "Ro-Tap" should be continued for another 5 minutes before re-testing. At the end of the test the sieves are taken apart and each fraction weighed. The results are expressed in percent by weight of material retained or passing through the screen. The cumulative amount greater than each size is also reported. Sieve sizes should be reported in millimetre opening.

Wet sieving should be used for material finer than 38 μm (400 mesh). In this procedure the dry sample is preweighed and screened by flushing with water. Material finer than 38 μm is discarded and the material remaining on the screen is filtered, dried and weighed. The amount retained is reported as a percentage of the total.

IV. Variations

Variations of the base method include the use of alternate sieving equipment for large samples and the use of sophisticated methods for particles less than 43 μm , such as gravitational settling in a water column or centrifuging.

V. Cost (1998)

Costs for the base method range from \$40 to \$120, depending on the number of sieves used and whether wet screening is necessary.

VI. MEND and Relevant Publications

Weiss, N.L. 1985. SME Mineral Processing Handbook, Volume 1. American Institute of Mining, Metallurgical and Petroleum Engineers, Inc. Kingsport Press, Kingsport, TN.

3.2.1.5.2 Surface Area

I. Discussion of Theory

Surface area is an important parameter when estimating weathering rates (Janzen *et al.* 1997; Otwinowski 1997; MEND 1.19.2). The rate of mine waste weathering is affected by the available surface area.

II. Applications and Limitations

Surface and specific surface area may be used to evaluate the following typical data requirements:

- The specific surface area of wastes can be used for modeling weathering characteristics; and
- Specific surface area can be used to estimate the relative weathering rate in the field. For example, a particular mining process may produce more fines than another technique. This will have an impact on the weathering characteristics.

The main limitation for surface area determination is the accuracy of the calculated specific surface area. This procedure assumes specific shapes which may not be representative of the actual waste material. The relationship between particle size, surface area and weathering rates are usually not established in the laboratory for a particular waste. This may result in incorrect assumptions on the weathering rates.

III. Base Method

Surface area can be measured by instrumentation or calculated based on particle size distribution. Calculated surface area is referred to as specific surface area because the procedure assumes that particles have a specific surface shape such as spheres or cubes. Specific surface area is calculated from the specific surface shape factor, the sieve analysis and particle density (Perry and Chilton 1984). The results can be expressed in either surface per unit weight or volume.

Surface area can be measured from gas adsorption measurements. In this procedure the quantity of gas required to cover a powder with a complete monolayer of gas molecules is measured. One common method uses a Quantasorb surface area analyzer. This analyzer utilizes the Brunauer Emmett Teller (BET) method of surface area determination whereby the sample, of <2 mm, is put under vacuum and then subjected to a stream of nitrogen gas. Measured differences in the N₂ flowrate is proportional to the nitrogen adsorbed to the sample surface which allows a calculation of the surface area in m²/g of sample.

IV. Variations

Another method for determining surface area is by a gas chromatography system. Nitrogen is adsorbed on the powder in a carrier of helium gas, while the powder is in the container surrounded

by liquid nitrogen. When the coolant is removed desorption occurs and the concentration of nitrogen is measured by a conductivity cell. The surface area is calculated from the amount of nitrogen desorbed.

V. Cost (1998)

Cost for the base BET method is \$100 to \$350 depending on the number of samples and accuracy required.

VI. MEND and Relevant Publications

MEND 1.19.2 1995. Scaling Analysis of Acid Rock Drainage. December.

MEND 1.21.2 1998. Laboratory Studies of Pyrrhotite Oxidation. March.

Janzen, M.P., Nicholson, R.V. and Scharer, J.M. 1997. *The Role of Enhanced Particle Surface Area, Crystal Structure and Trace Metal Content on Pyrrhotite Oxidation Rates in Tailings*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 1, pp. 399-415.

Otwinowski, M. 1997. *Meso-Scale Characterization of the Geochemical and Physical Processes Responsible for Acid Rock Drainage*. In: Proceedings of 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 2, pp. 567-585.

Perry, P.H. and Chilton, C.H. 1984. Chemical Engineers' Handbook. 6th Edition. McGraw-Hill Book Company.

3.2.1.5.3 Freeze Thaw

I. Discussion of Theory

The freeze thaw process is a natural weathering process in northern climates. Rock fissures expand due to ice formation, producing rock fragments, which are flushed out by subsequent thawing. Repeated freeze-thaw cycles effectively expose more surface area for weathering and aid in the overall disintegration of waste rock. The resulting increase in surface area is a key factor, which affects the rate of weathering. Tests have been developed to estimate the effect of freeze-thaw on solid materials.

II. Application and Limitations

Freeze thaw testing may be used to evaluate the following typical data requirements for mines:

- Results can be used to aid in determining waste rock dump stability;

- The test can be used in conjunction with the kinetic test program. For example, the waste rock could undergo a number of freeze thaw cycles to more closely simulate what occurs under field conditions; and
- Freeze thaw data can be used to determine the overall effect on surface area by measuring the change in particle size at the end of the test.

The main limitation for the use of the test is that freeze thaw cycles do not occur throughout the dump. Below the surface, water may not freeze and in active waste rock dumps freezing is unlikely to occur due to exothermic reactions. Very little work has been conducted to correlate the effect of freeze thaw on waste rock weathering as it relates to AMD.

III. Base Method

The most common test procedure for freeze/thaw testing is ASTM D4842-90 "Standard Test Method for Determining the Resistance of Solid Wastes to Freezing and Thawing". This procedure determines the material losses produced by repeated freezing and thawing of a solid sample (usually in the form of drill core). Visual observations of the physical deterioration of the sample specimens are also noted. Triplicate samples are subjected to 12 cycles of -20°C for 24 hours followed by soaking in 4°C distilled water for 23 h. The specimens are then removed, dried and re-weighed before the cycle is repeated. The test is terminated before 12 cycles are completed if the corrected cumulative mass loss of any of the test specimens exceeds 30%. The cumulative mass loss is corrected based on the mass loss of the control specimen also run in triplicate. The control samples are subjected to a moisture chamber at 20°C for 24 hours followed by soaking with 20°C distilled water for 23 h. The control specimens are then removed, dried and re-weighed prior to the next cycle.

Reported information includes: moisture content of the specimens; average cumulative, corrected relative mass loss after 12 cycles of testing; number of cycles survived if the specimens did not survive 12 cycles of testing; and results of visual observation after each cycle.

IV. Variations

No documented variations of the base method were found in the literature. However, the base method could be modified to suit a particular application as in conjunction with laboratory or field kinetic testing.

V. Cost (1998)

The cost for the base freeze thaw procedure ranges from \$800 and \$1200 per sample depending on the number of samples.

VI. MEND and Relevant Publications

American Society for Testing and Materials. 1990 Annual Book of ASTM Standards, ASTM Designation: D4842-90, *Standard Test Method for Determining the Resistance of Solid Wastes to Freezing and Thawing*.

3.2.1.5.4 Wet/Dry (Slaking)

I. Discussion of Theory

The wet/dry process is a natural weathering process that takes place in waste rock dumps. Wetting and drying also tends to create localized areas within the dump where precipitated salts accumulate. The overall effect is an increase in surface area. The resulting increase in surface area is a key factor which affects the rate of weathering. Tests have been developed to estimate the effect of wetting and drying on the weathering of solid materials.

II. Application and Limitations

Wet/dry slaking tests may be used to evaluate the following typical data requirements for mines:

- Results may be used to aid in determining waste rock dump stability; and
- Wet/dry testing can be used to determine the effect on surface area by measuring the change in particle size before and after wet dry testing.

The main limitation for the use of the test is that wet/dry cycles do not occur throughout the dump. Below the surface, drying may not occur. Very little work has been conducted to determine the effect of the wet/dry process on waste rock weathering as it relates to ARD in the field

III. Base Method

The base method is ASTM D4843-88 "Standard Test Method for Wetting and Drying Test for Solid Wastes". This procedure determines the material losses produced by repeated wetting and drying of a solid sample (usually in the form of drill core). Visual observations of the physical deterioration of the sample specimens are also recorded. Triplicate test samples are subjected to 12 cycles consisting of drying at 60°C for 24 hours in a nitrogen environment followed by soaking with 20°C distilled water for 23 hours. The specimens are removed from the water and the cycle repeated. The water containing detached particles is evaporated to dryness and the weight loss of the specimen recorded. The test is terminated before 12 cycles are completed if the corrected cumulative mass loss of any of the test specimens exceeds 30%. The cumulative mass loss is corrected based on the mass loss of the control specimen which is also run in triplicate. The control specimens undergo the same treatment as the test specimens with the exception that they are stored in a 20°C moisture chamber while the test specimens undergo 60°C nitrogen atmosphere drying.

Reported information includes: moisture content of the specimens; average cumulative, corrected relative mass loss after 12 cycles of testing; number of cycles survived if the specimens did not survive 12 cycles of testing; and results of visual observation after each cycle.

IV. Variations

Another procedure for determining a sample's resistance to wetting and drying is the Slake-Durability Index (Franklin *et al.* 1979). This procedure assesses the sample's resistance to weakening and disintegration when subjected to two standard cycles of drying and wetting. The procedure entails placing a sample consisting of 10 rock lumps, each weighing about 50 g into a rotating drum. The drum and contents are dried at 105°C to a constant weight. The drum is coupled to a motor and mounted in a trough which is partially immersed in water. The drum is rotated at 20 rpm for 10 minutes. The drum and sample are reweighed and the cycle repeated. The slake-durability index (second cycle) is calculated as the percentage ratio of the final to initial dry sample weights. The disadvantage of this procedure is the effect of attrition by the action of the rotary drum.

V. Cost (1998)

The cost for the base freeze-thaw procedure ranges from \$700 and \$1,200 per sample depending on the number of samples.

VI. MEND and Relevant Publications

American Society for Testing and Materials. 1990 Annual Book of ASTM Standards, ASTM Designation: D4843-90, *Standard Test Method for Wetting and Drying Test for Solid Wastes*.

Franklin, J.A., Vogler, U.W., Szlavin, J., Edmond, J.M. and Bieniawski, Z.T. 1979. *Suggested Methods for Determining Water Content, Porosity, Density, Adsorption and Related Properties and Swelling and Slake-Durability Index Properties*. International Journal of Rock Mechanics and Mining Sciences and Geomechanic. Vol 16, pp. 141-156.

3.2.2 KINETIC GEOCHEMICAL TESTS

Kinetic geochemical tests are used to obtain information on the rate at which weathering occurs in the materials to form secondary minerals and release contaminants to the environment. The tests can be pure scientific experiments in which the rate of oxidation of specific minerals is assessed under controlled conditions, but are more commonly laboratory studies of weathering of actual mine wastes, or large-scale studies of proposed remediation technologies.

Kinetic tests in general are intended to simulate weathering behaviour in wastes to predict characteristics such as sulphide oxidation rates, carbonate depletion rates, acid generation lag times, and metal leaching rates. The simplest use of kinetic tests is to confirm the results of static testing though this is a very limited application.

MEND projects specifically carried out in the area of kinetic geochemical tests are listed in Table 3.2-2.

**Table 3.2-2
Projects on Kinetic Geochemical Tests**

MEND Project	Title
1.16.1a	Investigation of Prediction Techniques for Acid Mine Drainage
1.16.1b	Acid Rock Drainage Prediction Manual
1.16.4	Evaluation of Static and Kinetic Prediction Test Data and Comparison with Field Monitoring Data
1.19.1	Long Term Acid Generation Studies: Cinola Project British Columbia
1.19.2	Scaling Analysis of Acid Rock Drainage
1.61.3	Column Leaching Characteristics of Cullaton Lake B and Shear (S) - Zones Tailings Phase 2: Cold Temperature Leaching

3.2.2.1 Humidity Cells

I. Discussion of Theory

When first proposed, the intent of humidity cells was to provide a kinetic equivalent to static tests primarily for coal mine spoil (Sobek *et al.* 1978). The test material was placed in a chamber which allowed continuous aeration, first with humid air then with dry air. The cycle was designed to mimic conditions that might occur as a result of periodic wetting following a precipitation event. At the end of a fixed cycle (usually 7 days), the entire test material was thoroughly leached for 1 hour under agitated conditions and the leachate analyzed for products indicative of sulphide oxidation and acid leaching. The processes occurring during the 7-day cycle were as follows:

1. At the beginning of the cycle, the crushed sample is moist from the previous rinsing. The pore water chemistry is influenced by the processes occurring in the previous cycle;

2. During the moist air cycle, wet conditions are maintained in the particle interstices. Oxidation of sulphides occurs but oxidation products generally remain dissolved in the pore water immediately adjacent to the particles. No transport of acidic products occurs. Any acidic pore water in the vicinity of acid neutralizing minerals reacts with these minerals;
3. During the dry air cycle, pore water evaporates. This leads to concentration of dissolved ions in the pores and probably precipitation of salts on particle surfaces. Hydrated precipitates may partially dehydrate and stabilize (e.g. $\text{Fe}(\text{OH})_3 \rightarrow \text{FeOOH} + \text{H}_2\text{O}$). Again, no significant transportation of dissolved products occurs; and
4. As leaching occurs, concentrated pore waters are diluted and some precipitates dissolved. Usually, the liquid-to-solid ratio is high enough that chemical saturation does not occur. Oxidation products are transported away from the mineral grains and come into contact with neutralizing minerals. The leachate is usually allowed to remain in contact with the sample to ensure dissolution of oxidation products and thorough contact with neutralizing minerals.

While this method does not accurately simulate real conditions in the field, it does at least provide an oxidation rate for the whole sample. Recent adaptations to the humidity cell method (MEND 1.16.1b) have resulted in a humidity cell which is a hybrid between a humidity cell and a leach column (Section 3.2.2.2). In this case, the sample is placed in a short column and leached without agitation. Due to channelling and limited contact time, this leads to incomplete removal of oxidation products and incomplete contact of acidic leachate with acid consuming minerals. Oxidation rates are therefore likely to be underestimated.

II. Discussion of MEND Research

MEND 1.16.1b Acid Rock Drainage Prediction Manual

This is a manual of methods used for ARD Prediction. It describes methods for waste rock and tailings.

III. Applications and Limitations

Humidity cells may be used to evaluate the following typical data requirements:

1. Correlation of static test predictions with observed release of acidity. For example, given an ABA result, prediction of whether acid release (i.e. $\text{pH} < 5$) will actually occur (e.g. MEND 1.16.4);
2. Trend in rate of oxidation. Monitoring of sulphate release (expressed on a weight or surface area basis) indicates rate of oxidation;
3. Rates of acid generation and acid consumption (absolute and relative). The rate of buffering mineral removal can indicate when the rock will actually generate acid (e.g. Day *et al.* 1997;

- Ferguson and Morin 1991);
4. Evaluation of the minerals involved in acid generation and acid consumption. Detailed analysis of leachate can indicate the types of reactions occurring (e.g. Li 1997);
 5. Metal and metalloid leaching rates. Test specific rates can be calculated. Comparison of pH and metal concentrations can indicate pH control on limiting metal concentrations (e.g. MEND 1.19.1); and
 6. Evaluation of galvanic effects. Galvanic effects occur when sulphides of different types are in direct electrical contact. The electrochemical potential of each sulphide determines the sequence of oxidation (e.g. MEND 1.32.1; Li 1997).

The main limitations associated with humidity cells are linked to the duration of testing and application of the test data. Reaction rates in cells are slow under pH neutral conditions since sulphide oxidation is abiotic. Buffering mineral consumption is also slow resulting in long lag times to actual release of acidity, possibly leading to a conclusion that acid would never be released. The lag time to acid release increases exponentially as the NP/AP value for the test material approaches 1 (Morin and Ferguson 1991). Generally, projects require the information in less than a year, however, as NP increases and NP/AP increases, it is likely that stable non-acidic leachate chemistry will continue for several years or decades.

Humidity cell results cannot be applied directly to full-scale field conditions. Numerous factors vary between laboratory and field conditions including particle size (distribution and composition), liquid:solid ratio, temperature and air flow. Humidity cell data can be used as input to a model.

IV. Base Method

The suggested base method procedure is described in MEND 1.16.1b (Section 6.4-2 to 6.4-7). This is an accepted procedure though it is only partially consistent with the original intent of humidity cells (ASTM). A summary of a typical procedure follows.

1. Prior to the test, the test material should be submitted for ABA, TIC, metal, size fractions and petrographic determinations. Size fractions analysis can be useful to estimate the relative exposed surface areas of different tests conducted at the same time. Analysis of individual size fractions for ABA may be useful if partitioning of sulphur and NP between the size fractions is suspected.
2. The construction of the cell depends on whether the sample is tailings or waste rock. For tailings samples, no standard dimensions have been suggested (Figure 3.2-2). The sample rests on a perforated acrylic disk and plastic mesh. Air is pumped into the side of the cell through an inlet port (approx. 1 L/min) and passes over the sample and exits through a

plexiglass disk at the top of the cell. Drains at the base and sides of the cell allows collection of leachate produced by percolation and runoff, respectively. Approximately 1 kg of sample is placed in each cell.

For waste rock, the cell is constructed from plexiglass pipe (10 cm dia x 20 cm h) (Figure 3.2-3). The sample rests on a perforated acrylic disk and plastic mesh. Air is pumped into the base of the cell through an inlet port (approx. 1 L/min), passes through the sample, and exits through a plexiglass disk at the top of the cell. A drain at the base of the cell allows collection of leachate. Approximately 1 kg of <math><1/4\text{''}</math> rock is placed in each cell.

3. Both types of cell are operated on a three-day moist, three-day dry cycle. Air is moistened by passing through an air stone in warm deionized water. The air is dried by passing through a silica gel column desiccator. On the seventh day, approximately 500 mL of deionized water is added to the cell, and allowed to sit for one hour. The water is decanted off. A portion of the leachate is analyzed for pH, conductivity, sulphate and alkalinity. The balance is filtered (0.45 μm filter), preserved and analyzed using inductively coupled argon plasma (ICAP) and atomic absorption spectroscopy (AAS).
4. The duration of the test is partly determined by the geochemical characteristics of the test materials and the particular objectives of the study. Rocks containing high sulphur concentrations and low neutralization potential are likely to produce acidity very rapidly (within a few weeks) and the long-term decrease of sulphate concentrations can be monitored shortly thereafter. If NP is present in the form of carbonate and sulphur concentrations are high (several percent), a rule of thumb is acid release may occur after 2 times the NP. For examples, if the NP is 20 kg/t, acidic conditions may not be apparent for 40 weeks. As NP/AP approaches 1, the lag time to acid release increases exponentially. Few reliable examples of acid production for test materials with NP/AP>1 have been documented. Morin *et al.* (1995) developed the following equation for a study of 14 acid producing humidity cells:

$$\text{NP/AP} = 0.00033t^2 \quad \text{where } t \text{ is lag time in weeks}$$

In the same study, it was estimated that, on average, 28% of the NP was available to buffer acidity. Almost all tests should be planned for at least 20 weeks to allow stable conditions to develop, though tests typically run for at least a year.

Interpretation of cell leachate may include the following:

- Trend in pH to determine whether acidic leachate was produced and an evaluation of the buffering reactions;

- Recalculation of parameter (sulphate, metals) concentrations on a mass (mg/kg/s) or surface area (mg/m²/s) basis to evaluate trends and determine sulphide and carbonate consumption rates, and metal release rates;
- Determination of trends in mole ratios (e.g. SO₄/(Ca+Mg+2K+2Na)) to evaluate relative rates of oxidation and buffering; and
- Determination of trends in mole ratios to evaluate changes in buffering mineral reactions (e.g. Ca/Mg).

Figure 3.2-4 illustrates typical results for long term humidity cells (MEND 1.19.1).

Early indications of acid release (other than a transition to low pH) can be indicated by SO₄/(Ca+Mg+2K+2Na) ratios increasing from less than 1 to greater than 1. Examination of this ratio can also indicate the NP/AP at which acid generation would ideally occur (ignoring factors which might limit availability of sulphide or acid buffering minerals). The critical NP/AP would be approximately the reciprocal of SO₄/(Ca+Mg+2K+2Na).

V. Variations

ASTM-D5744-96 (1996) describes humidity cell designs for rock and tailings in detail. The overall procedure is similar to the MEND 1.16.1b procedure except that the test design is described in detail.

The following variations of humidity cells may be considered:

- Removal of process pore water (tailings only). Flotation tailings are usually strongly alkaline because lime is added in the process. Since lime is highly soluble it does not provide useful long-term buffering capacity but will delay the onset of long-term leaching conditions in humidity cells. It is therefore advisable to rinse the sample with deionized water before starting the test. This also removes other process chemicals which may interfere with interpretation of the test, such as copper or zinc sulphate. Failure to account for the presence of process chemicals may lead to unstable results in the first 10 weeks or so;
- Replacing full flushing with trickle leaching. This is believed to result in a closer approximation of natural processes, though the “cell” becomes a short column;
- Replacing moist/dry air cycles with continuous moist air. This modification has been suggested for climates where drying is not expected (MEND 1.19.1);
- Changing the flushing frequency. The flushing frequency may be decreased to less than once per week to simulate infrequent flushing for example due to leaching of a tailings beach following drought conditions. An example of a comparative study is given in Day *et al.* (1997);

- Bacteria spiking. Addition of bacteria may be considered for the first flush to ensure that iron and sulphur oxidizing bacteria are present. The culture should be prepared from acidic waste at the site since the bacterial population will be site specific. Culturing of bacteria active under non-acidic conditions is probably not practical. Spiking of rock samples containing high concentrations of carbonate with acidophilic bacteria is unlikely to accelerate oxidation;
- Neutralization potential removal. Removal of carbonate minerals using sulphuric acid flushes may be considered to accelerate the trend to acid generation and evaluate the effectiveness of less available carbonate in acid neutralization. The procedure carries certain risks since the sulphide minerals are not removed at the same rate and may be more reactive than would occur if oxidation had kept pace with carbonate removal. Also, evaluation of sulphide oxidation becomes difficult because residual acid leaching masks true sulphate release from sulphide oxidation. Use of other mineral acids (e.g. hydrochloric) may result in sterilization and is therefore not recommended (Day *et al.* 1997); and
- Lower or higher than ambient temperatures. Humidity cells are usually conducted in laboratories at room temperature (20°C). Humidity cells have been conducted using refrigerated or freezing conditions (MEND 1.61.3). Freezing conditions require special procedures since complete freezing may result in exclusion of oxygen due to encapsulation in ice.

Specific tests are available to evaluate oxidation rates under well-constrained conditions. These tests are generally used for research purposes (e.g. MEND 4.6.5a,b,c; Tibble and Nicholson 1997; Eidså *et al.* 1997).

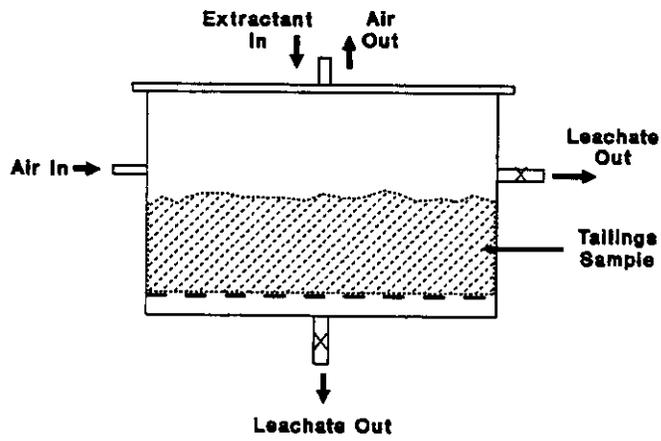
VI. Cost (1998)

Costs of humidity cells are dependent on a number of laboratory specific factors. The largest costs may be due to chemical analysis of leachates and particularly metals. Costs may be reduced by analyzing leachates for indicator parameters (e.g. electrical conductivity (EC) and pH) during stable conditions and archiving leachates for follow-up analyses. A typical analytical scheme might involve analyses of pH and EC on a weekly basis, SO₄, Ca, Mg, alkalinity and acidity every two weeks, and determination of a more complete metal suite every four weeks. Typical costs for such a program would vary from \$1500 to \$2500 (1996 CDN\$). Most laboratories offer lower prices for larger test programs due to economies of scale.

VII. MEND and Relevant Publications

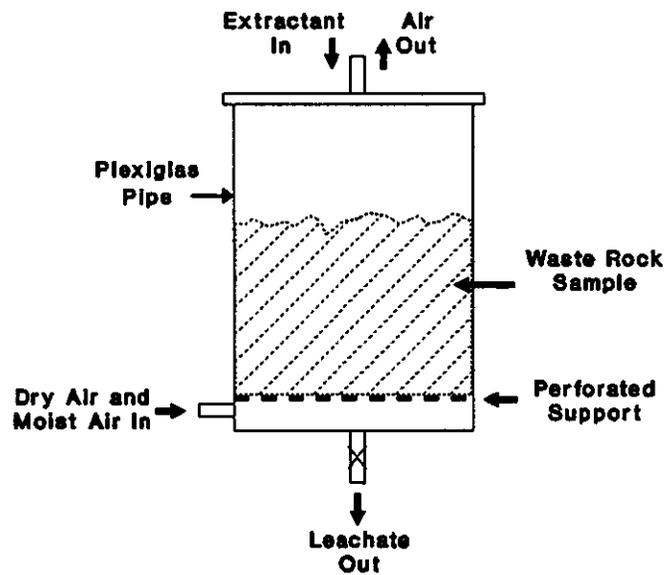
- | | |
|--------------|--|
| MEND 1.16.1 | 1989. Investigation of Prediction Techniques for Acid Mine Drainage. November. |
| MEND 1.16.1b | 1991. Acid Rock Drainage Prediction Manual. March. |

Figure 3.2-2 Humidity Cell for Tailings



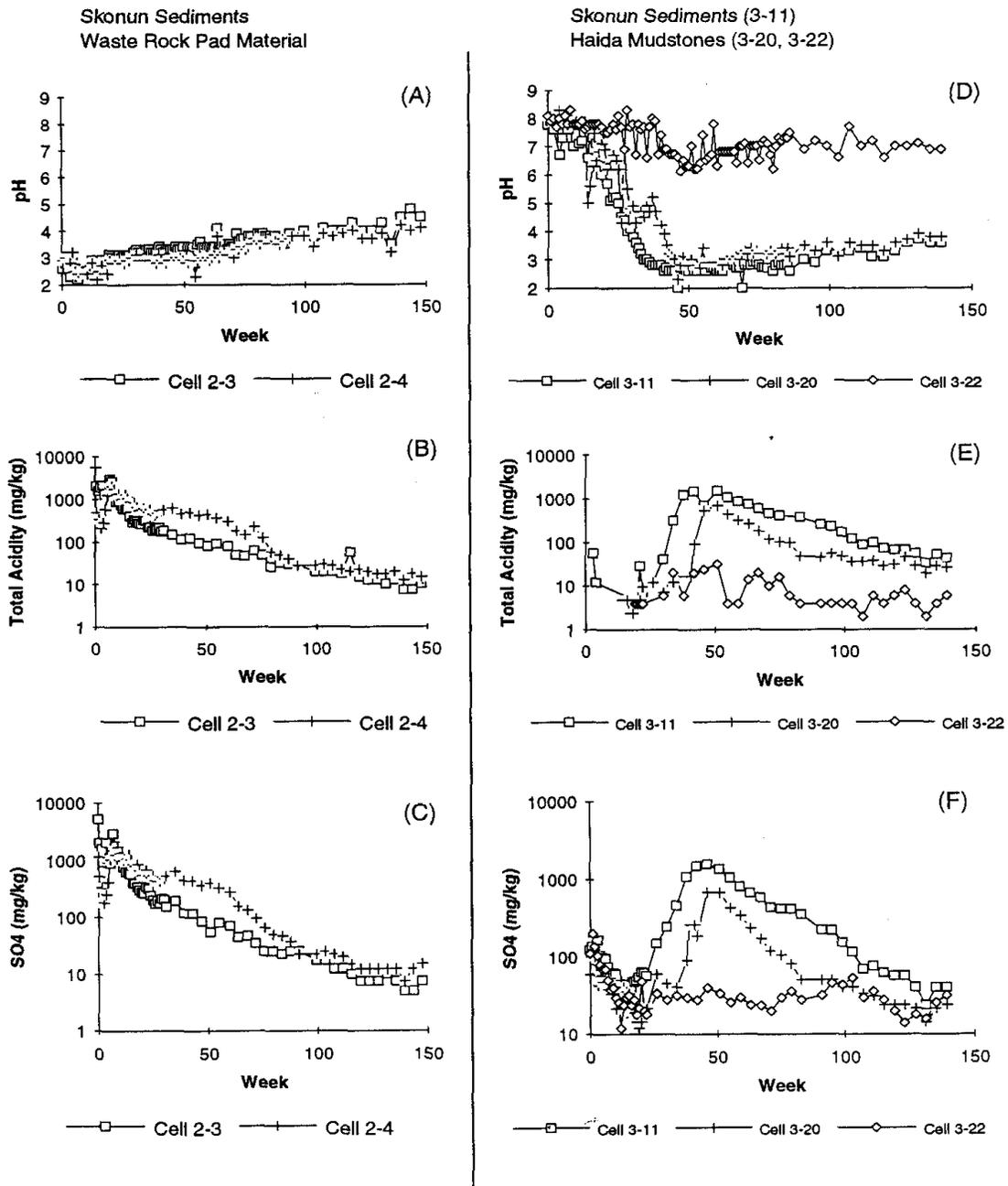
Source: MEND 1.16.1b

Figure 3.2-3 Humidity Cell for Waste Rock



Source: MEND 1.16.1b

Figure 3.2-4 Results for 140-Week Humidity Cells



Source: MEND 1.19.1

- MEND 1.16.4 1995. Evaluation of Static and Kinetic Prediction Test Data and Comparison with Field Monitoring Data. December.
- MEND 1.19.1 1994. Long Term Acid Generation Studies: Cinola Project British Columbia. March.
- MEND 1.21.2 1998. Laboratory Studies of Pyrrhotite Oxidation. March.
- MEND 1.32.1 1993. Prediction and Prevention of Acid Rock Drainage from a Geological and Mineralogical Perspective. October.
- MEND 1.61.3 1997. Column Leaching Characteristics of Cullaton Lake B and Shear (S) – Zones Tailings Phase 2: Cold Temperature Leaching. June .
- MEND 4.6.5a,c 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 of Sulphide Waste Rock: The Oxygen Consumption Method. December.

American Society for Testing and Materials. 1996. ASTM Designation: D 5744 – 96, *Standard Test Method for Accelerated Weathering of Solid Materials Using a Modified Humidity Cell*, ASTM, West Conshohocken, PA. 13p.

Day, S., Hope, G. and Kuit, W. 1997. *Waste Rock Management Planning for the Kudz Ze Kayah Project, Yukon Territory: 1. Predictive Static and Kinetic Test Work*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 1, pp. 81-98.

Eidså, G., Briseid, T. and Ese, H. 1997. *Pyrite Oxidation Measured by Oxygen Consumption and Carbon Dioxide Production in Laboratory Respirometer Tests*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 1, pp. 319-331.

Ferguson, K.D. and Morin, K.M. 1991. *The Prediction of Acid Rock Drainage - Lessons from the Database*. In: Proceedings of the 2nd International Conference in the Abatement of Acidic Drainage. Montreal, Québec. 16 to 18 September. Vol 3, pp. 83-106.

Morin, K.A., Hutt, N.M. and Ferguson K.D. 1995. *Measured Rates of Sulphide Oxidation and Acid Neutralization in Kinetic Tests: Statistical Lessons From the Database*. In: Sudbury '95 – Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 2, pp. 525-536.

Li, M.G. 1997. *Neutralization Potential Versus Observed Mineral Dissolution in Humidity Cell Tests for Louvicourt Tailings*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 1, pp. 149-164.

Sobek A.A., Schuller, W.A., Freeman, J.R. and Smith R.M. 1978. Field and Laboratory Methods Applicable to Overburden and Minesoils. USEPA Report No. 600/2-78-054, 203 pp.

Tibble, P.A. and Nicholson, R.V. 1997. *Oxygen Consumption on Sulphide Tailings and Tailings Covers: Measured Rates and Applications*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 1, pp. 647-661.

3.2.2.2 Columns

I. Discussion of Theory

Kinetic tests in general are intended to simulate weathering behaviour in waste to predict characteristics such as sulphide oxidation rates, carbonate depletion rates, acid generation lag times, and metal leaching rates. The simplest use of kinetic tests is to confirm the results of static testing though this is a very limited application. Humidity cells (Section 3.2.2.1) are intended to provide a direct measurement of acid generation and consumption rates under fully oxygenated conditions such as the immediate exposed surface of a tailings deposit. However, they do not provide a simulation of leaching conditions in wastes which may be partially or fully saturated and oxygen-deprived. Columns are generally set-up to address these issues.

The theory of columns more closely resembles that of leaching processes in waste deposits. The following processes occur:

- Oxidation of iron sulphide mineral grains occurs resulting in release of acidity, sulphate and iron to pore waters;
- Normally downward moving leachate entrains the weathering products and also dissolves other minerals;
- Acidic leachate attacks other minerals resulting in release of additional components to solution but also change in pH; and

- The chemistry of leachate emerging at the base of the column reflects processes occurring throughout the column.

Since liquid-to-solid ratios may be low, chemical saturation may occur. In carbonate buffered columns, saturation may occur with respect to carbonate and gypsum. In acidic columns, other types of sulphates may be saturated (e.g. lead and barium).

Due to the configuration of columns, channelling of leachate along preferential flow paths may occur. Leachate may also be channelled down the sides of the column.

The terms “column” and “lysimeter” are often used interchangeably. Whereas columns usually have a high ($\gg 1$) length to diameter ratio, lysimeters may be described as “basins” which have a low (< 1) length to diameter ratio (MEND 1.16.1b).

II. Discussion of MEND Research

MEND 1.16.1b Acid Rock Drainage Prediction Manual

This is a manual of methods used for ARD Prediction although limited information on the design of tailings columns was provided.

MEND 1.61.3 Column Leaching Characteristics of Cullaton Lake B and Shear (S) - Zones Tailings Phase 2: Cold Temperature Leaching,

This study investigated leaching of tailings at low temperatures (2°C and 10°C) to simulate the effect of placement of a waste rock cover on the tailings and expected seasonal freeze-thawing of the tailings. The results were compared to earlier tests conducted at room temperature. The low temperature tests were conducted in a walk-in refrigerator. The tests were conducted in clear acrylic columns (12.5 cm dia x 80 cm h). The tailings were inoculated with *Thiobacillus ferrooxidans* and leached with natural lake water. The tests indicated that the acidity generated at low temperatures was delayed and less severe than at room temperatures.

MEND 2.22.2a Évaluation en laboratoire de barrières sèches construites à partir de résidus miniers

This study was the first component of a project to evaluate dry barriers placed on tailings to limit oxidation. The laboratory study began with a thorough investigation of the hydraulic properties of the candidate cover materials. The chemical effects of the cover systems were investigated using plexiglass columns 1.7 m high. Each column was operated in duplicate. One column of each duplicate was fully instrumented with time domain reflectometry (TDR) probes and thermocouples. The second column did not have any instruments. Various cover combinations involving fine tailings, sand layers, concrete sand and desulphidized tailings were investigated. Some experimental

problems were encountered including leaks. The study concluded that 1 m layer of fine material saturated to greater than 90% sandwiched between two sand layers can reduce the oxygen flux by a factor of 1000 or more.

MEND 2.36.2 Hydrogeochemistry of Oxidised Waste Rock from Stratmat Site, New Brunswick

This study investigated the effect of flooding oxidized waste rock using laboratory leach columns (20 cm dia x 130 cm h). The test was conducted in three stages. In the first stage, the column was filled with 20 L of deionized water and 25 kg of oxidized waste rock was placed in the column. After waiting for the solids to settle, a supernatant sample was collected and analyzed. In the second stage, the water was re-circulated from bottom to top until electrical conductivity stabilized. The column was then drained completely and the water analyzed. Using zinc as a trigger, the column was then recharged with 20 L of water and recirculated. If the zinc was lower than the trigger, the column was recharged with water and the supernatant monitored for six months. The test was performed in duplicate. The sequential release of various metals in response to pH changes and depletion of sulphate was observed.

III. Applications and Limitations

Leach columns may be used to fulfil several specific objectives which are generally correlated to waste management strategies:

- Correlation of static test predictions with observed release of acidity. For example, given an ABA result, prediction of whether acid release (i.e. pH<5) will actually occur;
- Prediction of metal release rates under various conditions;
- Evaluation of blending with alkaline materials to delay or prevent acid release;
- Comparison of leaching rates for subaerially and subaqueously disposed wastes. Subaqueous columns may be designed in various configurations to evaluate stagnant or well-oxygenated conditions;
- Evaluation of oxidation rates beneath a low permeability cover;
- Evaluation of codisposal of waste rock and tailings; and
- Evaluation of oxidation rates under a variety of temperature regimes. Columns may be set up to simulate low temperatures (e.g. northern regions) and warm humid conditions (e.g. tropical, equatorial).

Columns may also be used to provide data for other objectives as listed for humidity cells, Section 3.2.2.1, Applications and Limitations. However, columns cannot be used to provide the same information as humidity cells because trickle leaching introduces random effects due to flow path

development and chemical saturation may limit the concentration of some ions in leachates. For example, gypsum saturation precludes interpretation of molar ratios such as $\text{SO}_4/(\text{Ca}+\text{Mg}+2\text{K}+2\text{Na})$. Models such as MINTEQA2 (Allison *et al.* 1991), WATEQ4F (Bell *et al.* 1987) or PHREEQC (Parkhurst 1995) can be used to determine whether chemical saturation is occurring, although the limitations of these models particularly for high ionic strength must be considered.

Column data cannot be applied directly to field conditions without consideration of scaling factors to account for differences in particle sizes, liquid:solid ratios, temperatures, air flow, configuration, operational practices, etc. The latter factor is particularly relevant when attempting to evaluate control technologies such as covers and blending which are strongly dependent on field conditions.

IV. Base Method and Variations

No base method has been defined since columns are designed to address site-specific objectives. The suggested method procedure is described in MEND 1.16.1b, Section 6.4-12 to 6.4-15. In general, the procedure consists of placement of sample in a column, leaching and collection of leachate for analysis. If possible, the column should be constructed from clear plastic to allow the sample to be observed as the test proceeds. Prior to the test, the test material should be submitted for acid-base accounting, total inorganic carbon, metal, size fractions and petrographic determinations. Size fractions analysis can be useful to estimate the relative exposed surface areas of different tests conducted at the same time. Analysis of individual size fractions for ABA may be useful if partitioning of sulphur and NP between the size fractions is suspected.

Factors to be considered in designing columns are:

1. The size of the columns. The most commonly used design is 25 cm (dia) x 120 cm (h), but smaller and much larger (6 m high) columns can be used. As the size increases, the results require less scaling for full-scale conditions. However, other issues should be considered such as the ability to adequately characterize the large volume, the development of flow paths (hence the effect on chemistry) and the likelihood of chemical saturation;
2. Wall effects. The ratio of the column diameter to the size of the largest particles should be considered in the design. If the ratio is low, a significant proportion of the leachate may run down the walls of the column rather than contacting the sample. A general guideline is that the ratio should not be less than 6, but performance under project specific conditions should be considered;
3. Sampling ports. Leachate is usually sampled at the base of the column (Figure 3.2-5). Sampling ports may also be installed in the sides of the column to monitor parameters, such as pH and EC. Ports may also be installed at the interface of layers in studies of covers. Pore space oxygen concentrations can also be measured;

4. The type of leachate. Generally, deionized water is used. Alternatives may include simulated precipitation, water obtained from another leach column and water obtained from the site;
5. The leaching rate. The flow rate may be based on a specific liquid:solid ratio or simulated precipitation. The flow rate should generate enough sample for analysis and provide at least a pore volume turnover for the sampling frequency. Excessive flow rates may dilute parameters of interest making them undetectable in the leachate;
6. Subaqueous columns. If the columns will provide a continuous standing water column above the sample, the method of water flow needs to be considered with reference to probable site conditions. Possible options are for circulation above the sample (Type 1 in Figure 3.2-5) or circulation within the sample (Type 2). Alternate flooding followed by exposure may also be investigated (Type 4); and
7. Air flow. Air or another gas may be forced through the column from the base or side ports (coarse materials only). The gas may be humidified or dry.

The duration of the test is strongly dependent on the objectives of the study. Highly reactive wastes are likely to produce useful results rapidly, as was noted for humidity cells (Section 3.2.2.1, Base Method).

With all column tests, leaching of weathering products accumulated in storage may take several weeks or months depending on the characteristics of the test material and the rate of liquid addition. Therefore, the test needs to be long enough to allow stable conditions indicative of active sulphide oxidation to develop. The end-point of subaqueous columns is probably determined by the development of stable conditions consistent with the measured oxygen flux throughout the column. Upon completion of a column test, the test material may be removed and examined to view internal oxidation, dissolution and precipitation textures. Chemical analyses of the material used prior to the test are also appropriate.

Interpretation of column leachate may include the following:

- Trend in pH to determine whether acidic leachate was produced and an evaluation of the buffering reactions;
- Recalculation of parameter (sulphate, metals) concentrations on a mass (mg/kg/s) or surface area (mg/m²/s) basis to evaluate trends and determine sulphide and carbonate consumption rates, and metal release rates;
- Determination of trends in mole ratios (e.g. SO₄/(Ca+Mg+2K+2Na)) to evaluate relative rates of oxidation and buffering;

- Determination of trends in mole ratios to evaluate changes in buffering mineral reactions (e.g. Ca/Mg);
- Calculation of metal release rates; and
- Profiles of pH, EC, DO, O₂ in column sampling ports.

Figure 3.2-5 illustrates typical presentation of results for long term column leach tests used to evaluate limestone addition to delay acid generation.

V. Cost (1998)

Costs of column tests are extremely dependent on the number of tests and laboratory specific factors. The largest cost is often due to chemical analysis of leachates, particularly metals. For larger tests, costs for set-up labour and materials and monitoring can be a significant proportion of the overall cost. The use of clear plastic columns is preferred but adds significantly to the construction costs.

Analyzing leachates for indicator parameters (e.g. electrical conductivity (EC), pH and Eh during stable conditions and archiving leachates for follow-up analyses may reduce analytical costs. A typical analytical scheme might involve analyses of pH and EC on a weekly basis, sulphate, Ca, Mg, alkalinity and acidity every two weeks, and determination of a more complete metal suite every four weeks.

Costs for a 20-week column study may vary from \$2000 for a small column to more than \$5000 for a larger column.

VI. MEND and Relevant Publications

- | | |
|--------------|---|
| MEND 1.16.1b | 1991. Acid Rock Drainage Prediction Manual. March. |
| MEND 1.61.3 | 1997. Column Leaching Characteristics of Cullaton Lake B and Shear (S) - Zones Tailings Phase 2: Cold Temperature Leaching. June. |
| MEND 2.22.2a | 1996. Évaluation en laboratoire de barrières sèches construites à partir de résidus miniers. March. |
| MEND 2.36.2 | 1999. Hydrogeochemistry of Oxidised Waste Rock from Stratmat Site, New Brunswick. March. |

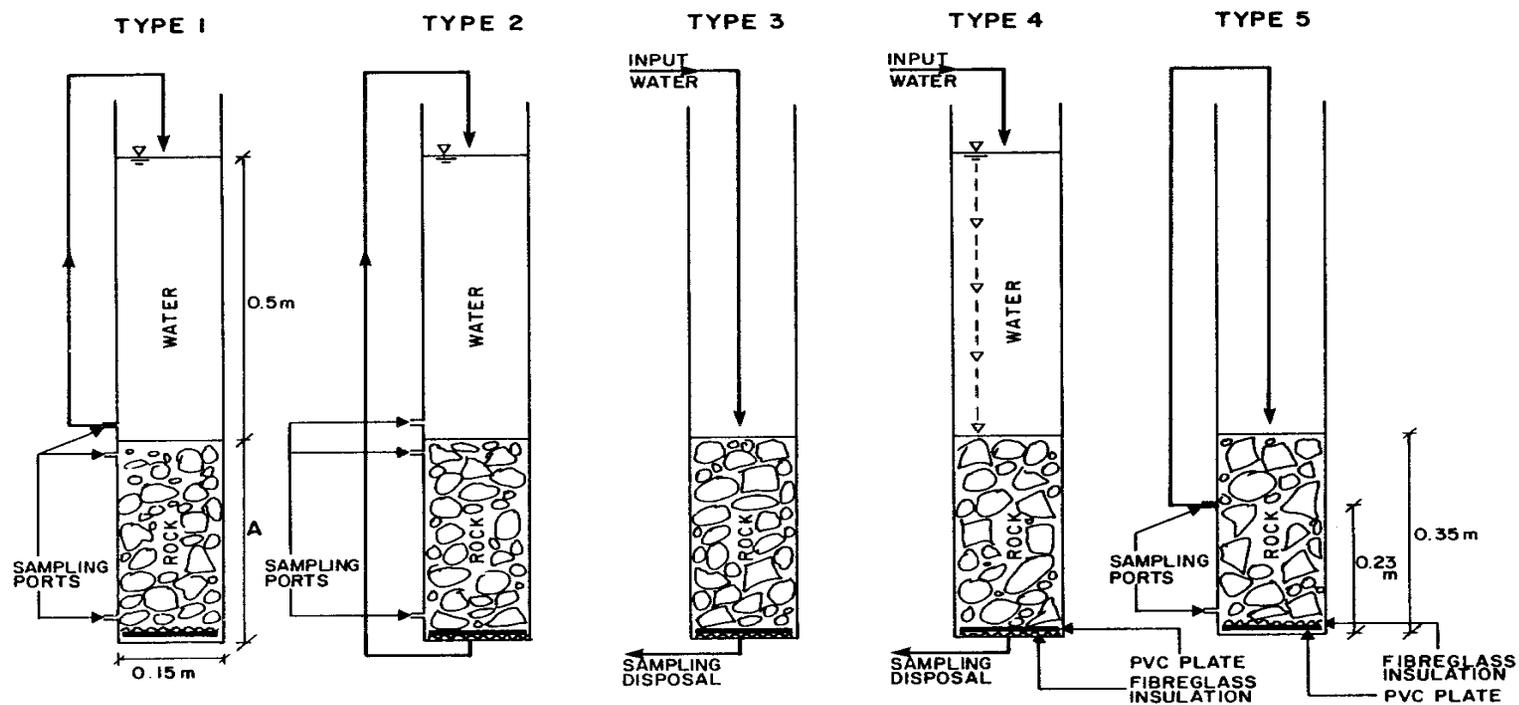
British Columbia Acid Mine Drainage Task Force Report. 1989. Draft Acid Rock Drainage Technical Guide. Volume 1, August.

Allison, J.D., Brown, D.S. and Novo-Gradac, K.J. 1991. MINTEQA2/PRODEFA2: A Geochemical Assessment Model for Environmental Systems – Version 3.0 User's Manual. U.S. Environmental Protection Agency Report EPA/600/3-91/021, 106 p.

Bell, J.W., Nordstrom, D.K. and Zachman, D.W. 1987. WATEQ4F – A Personal Computer FORTRAN Translation of the Geochemical Model WATEQ2 with Revised Data Base. U.S. Geological Survey Open-File Report 87-50, 108 p.

Parkhurst, D.L. 1995. PHREEQC – A Computer Model for Geochemical Calculations. U.S. Geological Survey Water-Resources Investigations Report 95-4227, 143 p.

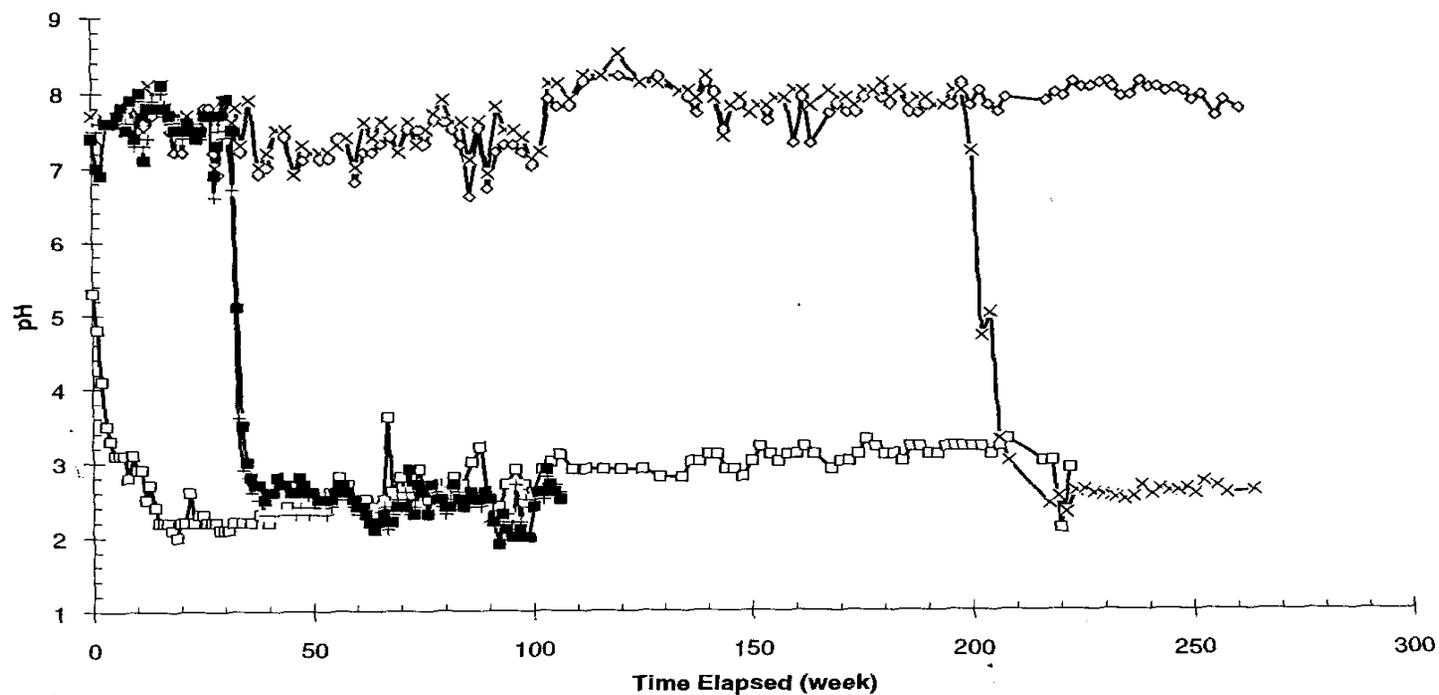
Figure 3.2-5 Examples of Column Experiments



Note: Height varied with treatments

Source: British Columbia Acid Mine Drainage Task Force Report, 1989

Figure 3.2-6 Limestone Mixing Study – pH Levels in Leachate



LEGEND

- Column 1,
Control
- ◇ Column 2, 6.6%
Limestone
- × Column 3, 3.3%
Limestone
- + Column 4, 0.8%
Limestone
- Column 5,
Layered

Source: MEND 1.19.1

3.3 FIELD METHODS

As most studies of acid generation and metal leaching involve laboratory tests conducted under ideal conditions which commonly differ substantially from site conditions, observation of weathering behaviour under site conditions are an essential component of “ground-truthing” results obtained in the laboratory. This approach can be observed throughout studies completed for the MEND program. Some examples of MEND projects dealing with obtaining data from field observations are given in Table 3.3-1.

**Table 3.3-1
Projects Based on Field Observations**

MEND Project	Title
1.12.1b	DBARD for Paradox: Developments in DBARD, the Database for Acid Rock Drainage
1.14.2b	Sampling and Monitoring Data from the Mine Doyon South Waste Rock Dump.
1.15.2a	MINEWALL 2.0 Users Manual
1.15.2c	Application of MINEWALL 2.0 to Three Mine Sites,
1.16.1a	Investigation of Prediction Techniques for Acid Mine Drainage
1.16.4	Evaluation of Static and Kinetic Prediction Test Data and Comparison with Field Monitoring Data
1.17.1a,b,c,d	Hydrogeochemical Investigation of Reactive Tailings at the Waite Amulet Tailings Site, Noranda, Québec.
1.19.1	Long Term Acid Generation Studies: Cinola Project British Columbia
1.22.1a	Field Procedures Manual: Gas Transfer Measurements Waste Rock Piles Heath Steele Mines New Brunswick
1.27.1a	Guide for Predicting Water Chemistry from Waste Rock Piles
1.32.1	Prediction and Prevention of Acid Rock Drainage from a Geological and Mineralogical Perspective
1.44.1	History of Eskay Creek Mine's Waste-Rock Dump from Placement to Disassembly
2.12.1	Louvicourt Man-Made Lakes Disposal
2.13.1a*	Wet Barriers on Pyritic Uranium Tailings
2.22.2a	Évaluation en laboratoire de barrières sèches construites à partir de résidus miniers
2.23.2d	A Geochemical, Hydrogeological and Hydrological Study of the Tailings Impoundment at the Falconbridge Limited, Kidd Creek Division Metallurgical Site, Timmins, Ontario.
2.31.1b	Engineering Design and Construction Phase IV: Composite Soil Cover Acid Waste Rock Study Heath Steele Mines
4.1.1	Field Sampling Manual for Reactive Sulphide Tailings.

* Open file report

The most notable developments include DBARD which allows comparisons for different sites, designs for small and large scale field tests (MEND 1.19.1; MEND 2.31.1) and development of methods for investigating the weathering rate of mined surfaces (MEND 1.15.2.c).

3.3.1 TAILINGS

I. Discussion of Theory

Field methods for the prediction of acid production from sulphidic tailings make best use of the present state of knowledge about the sulphide oxidation process. The methods involve specific field observations and measurements, field-based test procedures, the review and assessment of surface and groundwater quality data, and additional sampling and analytical testing.

At active tailings management areas, the placement of tailings is planned, technically-based and carried out to provide a stable chemical and physical environment for the sulphide tailings over the long term. Field methods are applied at these sites to assess the performance of acid production control measures. The field methods are also applied post-closure to monitor performance and assess the need (if any) for additional acid production prevention and control measures (Volume 4).

Subaqueous disposal involving the placement of fresh sulphide tailings under a water cover is effective and for practical purposes prevents sulphide oxidation (although subaqueous disposal does not completely stop oxidation). During active tailings placement, ongoing environmental monitoring data (i.e. tailings water cover quality data, treatment plant influent quality data) can be used to identify the onset of acid production from exposed tailings or other sources. The surface of tailings at closed flooded tailings management areas can, however, become exposed under conditions such as severe drought. The effects (if any) on sulphide oxidation and acid production can be readily assessed by field methods.

At other tailings management areas, a portion of the tailings surface may be exposed over an extended period of time between tailings placement and the implementation of closure works such as the application of an engineered cover. Field methods are used during the active life of the tailings management areas and post-closure to broadly assess the level of oxidation and effects, and identify the need (if any) for mitigative measures.

At historic tailings management areas, field methods are used to identify the need for, and provide the basis of, detailed investigations and the development of mitigative ARD prevention/control strategies.

Field methods need to be applied diligently taking into consideration the physical characteristics of tailings management areas and the properties and characteristics of the tailings and variations across the basin.

II. Discussion of MEND Research

MEND projects involving the field investigation and assessment of ARD potential/production at active tailings management areas indirectly discuss field methods. As an example, in MEND 1.16.1a *Investigation of Prediction Techniques for Acid Mine Drainage*, Appendix 12 shows the type of information that should be collected. The information includes: details on the sampling location; history of the sample; relationship of the sample to existing porewater/seepage/pond water quality; mineralogy; static or dynamic testing data; and factors that may have added to or mitigated acid production.

MEND 2.12.1 Louvicourt Man-Made Lakes Disposal

The Louvicourt Mine is located 20 km east of Val d'Or, Québec. Tailings from the massive sulphide copper-zinc-gold ore contained 30 to 50% pyrite, 5 to 24% carbonates and 0.6% sphalerite. This study modelled flooding of the tailings with 0.3 m of water (Li *et al.* 1997). Various scenarios were considered including stagnant conditions, fully oxygenated water cover, downward infiltration of water and resuspension of tailings. The modelling showed that in a worst-case scenario, discharge water quality would meet provincial and federal water quality objectives. Field tests have been started but results have not been released.

MEND 2.13.1a Wet Barriers on Pyritic Uranium Tailings

In 1995, the Quirke Mine Waste Management Area (WMA) in Elliot Lake, Ontario was decommissioned (Kam *et al.* 1997). The WMA contains approximately 45 million tonnes of pyrite-bearing (5%) uranium tailings and waste rock. Complete flooding of the tailings was considered to be the most effective approach to minimize acid generation. A series of internal dykes were constructed and the tailings were flooded in individual cells. The first cell was constructed in 1992 and pore water and surface water were extensively monitored to assess the performance of the water cover. Prior to flooding the tailings were a source of acidity. The monitoring indicated improvement in both surface and pore water quality.

MEND 2.22.2a Évaluation en laboratoire de barrières sèches construites à partir de résidus miniers

This study involved construction of six tailings test cells in 1995 subsequent to a laboratory study of candidate cover materials. The cells were lined with geomembrane to capture drainage. Three-layer covers were installed in five of the cells. The top and bottom layers were sand. The intermediate layers were constructed from clean tailings (three cells), silty soil and a mixture of bentonite and clean tailings. The sixth cell was a control (uncovered). The cells were instrumented to measure water content, matric suction, oxygen flux and chemical composition of the leachate.

MEND 2.23.2d A Geochemical, Hydrogeological and Hydrological Study of the Tailings Impoundment at the Falconbridge Limited, Kidd Creek Division Metallurgical Site, Timmins, Ontario.

This study investigated the interactions between tailings pore water, pore gas and solids for a mixed sulphide-rich and natrojarosite tailings. The monitoring indicated that jarosite is chemically unstable in the neutral pH and low Eh environment, causing release of several elements including Mn, Fe, Zn, Pb and As. Sulphide oxidation modelling indicated that the most intense oxidation will occur in the first 20 years but the residence time for reaction products in the pore prior to discharge may exceed 1000 years.

MEND 4.1.1. Field Sampling Manual for Reactive Sulphide Tailings.

This manual describes equipment and QA/QC procedures for the sampling of sulphide tailings.

III. Applications and Limitations

Observations of site conditions and the review of environmental data, which can detect the onset of acidic drainage should be a component of ARD prediction projects and ongoing proactive monitoring programs.

The primary requirements are that the physical and chemical characteristics of the tailings and the tailings environment be reasonably well understood. These characteristics would include: depth to water table; depth of vadose zone; predicted performance of cover if present; pore water quality; sulphide depletion; and NP and AP values through the tailings column. In addition, there also needs to be a reasonable understanding of the variations in conditions that can influence tailings oxidation, such as seasonal variations in water levels and surface erosion.

IV. Method

Field methods applicable to the prediction of acid production from tailings include the following:

- Descriptions of tailings mineralogy, if practical;
- Visual inspections of tailings management areas and adjacent land/watercourses. Existing conditions should be documented for future reference and changes in conditions noted (i.e. vegetation die-back, presence of precipitates, hardpan formation);
- Visual (in-hand) inspections of tailings and field measurements (i.e. pH and conductivity of groundwater and ponded water, run-off and seepage, paste pH);
- As appropriate, test pit excavations or borings in the tailings to determine: the extent of surface cracking; the depth of oxidation; and the depth to the water table;

- Samples can be collected through the tailings column from test pits or bore hole core and analyzed to provide data regarding: sulphide, NP and AP levels through the column; porewater quality; pore gas; and bacterial activity;
- Geophysical methods;
- *In situ* measurements of the atmospheric oxygen flux (Tibble and Nicholson 1997);
- The installation of piezometers and lysimeters to allow continued monitoring of porewater quality and pore gas; and
- The field monitoring of test plots or full scale application of covers.

The above information can, in some cases, be used to develop an inventory of residual, exposed tailings, and approximate the historic rate of acid production.

V. Cost (1998)

Simple field tests are often carried out in conjunction with routine site inspections.

Field tests involving test pitting in tailings and the collection of up to ten samples can be readily accomplished. Field work for extensive sampling or sophisticated monitoring programs can extend over a week or more at an overall cost in the order of \$5000/day.

Costs for field test plots are site dependent.

VI. MEND and Relevant Publications

MEND 1.16.1a	1989. Investigation of Prediction Techniques for Acid Mine Drainage. November.
MEND 1.21.2	1998. Laboratory Studies of Pyrrhotite Oxidation. March.
MEND 2.12.1	To be published. Louvicourt Man-Made Lakes Disposal.
MEND 2.13.1a	To be published. Wet Barriers on Pyritic Uranium Tailings
MEND 2.22.2a	1996. Évaluation en laboratoire de barrières sèches construites à partir de résidus miniers. March.

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 4.1.1 1989. Field Sampling Manual for Reactive Sulphide Tailings. November.

Kam, S.N., Knapp, R.A., Balins, J.K. and Payne, R.A. 1997. *Interim Assessment of Flooded Tailings Performance Quirke Mine Waste Management Area*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 2, pp. 853-870.

Li, M.G., Aubé, B. and St-Arnaud, L. 1997. *Considerations in the Use of Shallow Water Covers for Decommissioning Reactive Tailings*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 1, pp. 115-130.

Tibble, P.A. and Nicholson, R.V. 1997. *Oxygen Consumption on Sulphide Tailings and Tailings Covers: Measured Rates and Applications*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 2, pp. 647-661.

3.3.2 WASTE ROCK

3.3.2.1 Existing Piles and Natural Weathering

I. Discussion of Theory

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

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

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

The reader is referred to Volume 2 of this Manual for description and discussion of sampling of waste rock piles.

II. Discussion of MEND Research

MEND 1.41.4 Whistle Mine Waste Rock Study.

This study investigated a 5 million tonne waste rock pile located at the Whistle Mine, northern Ontario. Samples were obtained from the pile by excavation and drilling. Sampling ports were installed in the boreholes and lysimeters were installed in the test pits. Water quality data were obtained from seepage locations, wells and lysimeters. The study provided useful conclusions on the comparison between field conditions and laboratory tests. A hydrological study determined water residence times in the pile. Critical data requirements for assessment of waste rock piles were identified as: (1) structural information, such as grain size, porosity, water content, distribution of material and dump construction; (2) acid generation potential of the waste rock; and (3) a detailed site water balance.

MEND 1.32.1 Prediction and Prevention of Acid Rock Drainage from a Geological and Mineralogical Perspective

The report provides some guidance on field techniques. Recommendations are also provided in MEND 1.16.1b.

MEND 1.44.1 History of Eskay Creek Mine's Waste-Rock Dump from Placement to Disassembly

The report describes disassembly of a 100,000-tonne valley-fill rock pile located at Eskay Creek Mine in northwestern British Columbia. Several techniques are described to examine residual mineralogy in a pile that began to generate acid within two years of placement. The dump was found to contain fine grained material that limited infiltration, though isolated pebbles were found to have a significant role in enhancing infiltration.

III. Applications and Limitations

Observations of existing site conditions should, if possible, be a part of ARD prediction projects. The main requirement for such studies is that the geology of the older waste pile or natural rock

exposure should be relevant to the proposed mine. In the case of comparing old mine workings to proposed or existing newer mines, comparisons may not be relevant if the new mine will be an open pit exploiting lower grade mineralization but the old mine used underground methods to follow high grade zones. Nonetheless, even in such cases, examination of individual samples of oxidized wastes can be used.

When attempting to use natural weathering features to predict behaviour in waste rock piles, the following differences between natural (e.g. talus) and waste rock should be considered:

- Physical breakage by natural processes (freeze-thaw, heating-cooling, gravity) compared to use of equipment and explosive. These will relate to rate of release of reactive minerals and the mineralogical composition of size fractions;
- Availability of oxygen and moisture. In fractured rock masses, oxygen and moisture may be less available due to tighter fractures;
- Intimacy of mineralogical contact. Contact between conductive minerals in particular is greater in natural outcrops than would be expected in rock piles resulting in stronger and larger galvanic cells; and
- Degree of mixing. Mining tends to result in mixing of rock from different sources. Natural features may not show the same degree of mixing.

IV. Method

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

- Description of rock mineralogy in field hand samples, including reactivity of carbonates determined by fizz reaction with dilute hydrochloric acid;
- Observation of preferential exposure of minerals along exposed fractures and other zones of weakness;
- Observation of large and small-scale weathering features on rock fragments including oxidation coatings (colour and type) and efflorescent minerals. Table 3.3-2 provides some examples of common coatings, additional information can be found in Jambor and Blowes (1994);
- Measurement of paste pH on rock fines (1:1 (v/v) water:solid mixture) determined to assess the availability and acidity of soluble oxidation products. A paste pH of less than 5, that is rapidly reached, indicates the presence of acidity. The pH of the water used in the test should be determined beforehand;
- Measurement of pH and total dissolved solids for seepage, observations and collections of precipitates and rock corrosion by seepage;

- Description of presence or absence of vegetation cover; and
- Observation of variations in snow cover as an indication of heat production.

Guidance on field methods relevant to coal mines is also provided by Sobek *et al.* (1978).

V. Cost (1998)

Field observations are usually collected during routine site inspections. No additional costs are incurred. Normally, a small mine site can be described thoroughly in one full day on site.

Table 3.3-2
Interpretation of Oxidation Coatings

Coating Description	Mineral or Chemical Compound	Interpretation
Yellow associated with iron sulphide	Jarosite	Strongly acidic oxidation products
Orange and dark brown associated with iron sulphide	Limonite	Iron sulphide weathering
Light orange as a coating on carbonates	Limonite	Formed from iron carbonate
Light brown on rock surfaces	Limonite	Formed by slow weathering of silicates
White associated with pyrite	Iron sulphate	Strongly acidic coating
Green or blue	Basic copper carbonate or copper sulphate	Formed by weathering of copper minerals in alkaline or acidic conditions

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

VI. MEND and Relevant Publications

- MEND 1.16.1 1989. Investigation of Prediction Techniques for Acid Mine Drainage. November.
- MEND 1.16.1b 1991. Acid Rock Drainage Prediction Manual. March.
- MEND 1.32.1 1993. Prediction and Prevention of Acid Rock Drainage from a Geological Mineralogical Perspective. October.
- MEND 1.41.4 1997. Whistle Mine Waste Rock Study. December.
- MEND 1.44.1 1997. History of Eskay Creek Mine's Waste-Rock Dump from Placement to Disassembly. May.

Jambor J.L. and Blowes, D.W. 1994. Short Course Handbook on Environmental Geochemistry of Sulphide Mine Wastes. Mineralogical Association of Canada. Waterloo, Ontario, May.

Sobek, A.A., Schuller W.A., Freeman J.R. and Smith R.M. 1978. Field and Laboratory Methods Applicable to Overburden and Minesoils. USEPA Report No. 600/2-78-054, 203 pp.

3.3.2.2 Waste Rock Test Piles

I. Discussion of Theory

Kinetic tests in general are intended to simulate weathering behaviour in waste rock to predict characteristics such as sulphide oxidation rates, carbonate depletion rates, acid generation lag times, and metal leaching rates. The simplest use of kinetic tests is to confirm the results of static testing, though this is a very limited application.

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

Processes occurring in a rock pile can include:

- Build-up of soluble weathering products due to oxidation of sulphide minerals;
- Release of oxidation products by rainfall or snow melt;
- Partial or complete neutralization of acid products due to contact with silicate and carbonate minerals;
- Freezing of the pile during sub-zero conditions; and
- Restriction of oxidation by application of covers.

II. Discussion of MEND Research

MEND 1.19.1 Long Term Acid Generation Studies: Cinola Project British Columbia,

This project specifically compared weathering rates under strongly acidic conditions in humidity cells to waste rock piles (20 to 30 tonnes) composed of similar materials. It was concluded that weathering rates were comparable when corrected for the differences in particle sizes. The test piles were constructed from run-of-mine (small-scale) rock and documented strong seasonal variations in pH and dissolved components such as sulphate and a variety of metals (Figure 3.3-1). Over a five year period, a general increase in pH and decrease in sulphate release was found. MEND 1.27.1a *Guide for Predicting Water Chemistry from Waste Rock Piles* provided a follow-up interpretation of the data.

MEND 2.31.1b Engineering Design and Construction Phase IV – Composite Soil Cover Acid Waste Rock Study Heath Steele Mines

This study evaluated placement of an engineered soil cover on a test waste rock pile (14,000 tonnes) that had been relocated to a lined basin so that performance of the cover could be monitored. The cover resulted in decreased oxygen concentrations in the pile (from 20% to 1%) and decreased infiltration (to 2% of incipient during heavy rain). An additional conclusion was that it would take 30 years to flush 1 pore volume of the pile.

MEND 2.32.1 Kutcho Creek Project: Blending and Segregation, Acid Generation Testwork

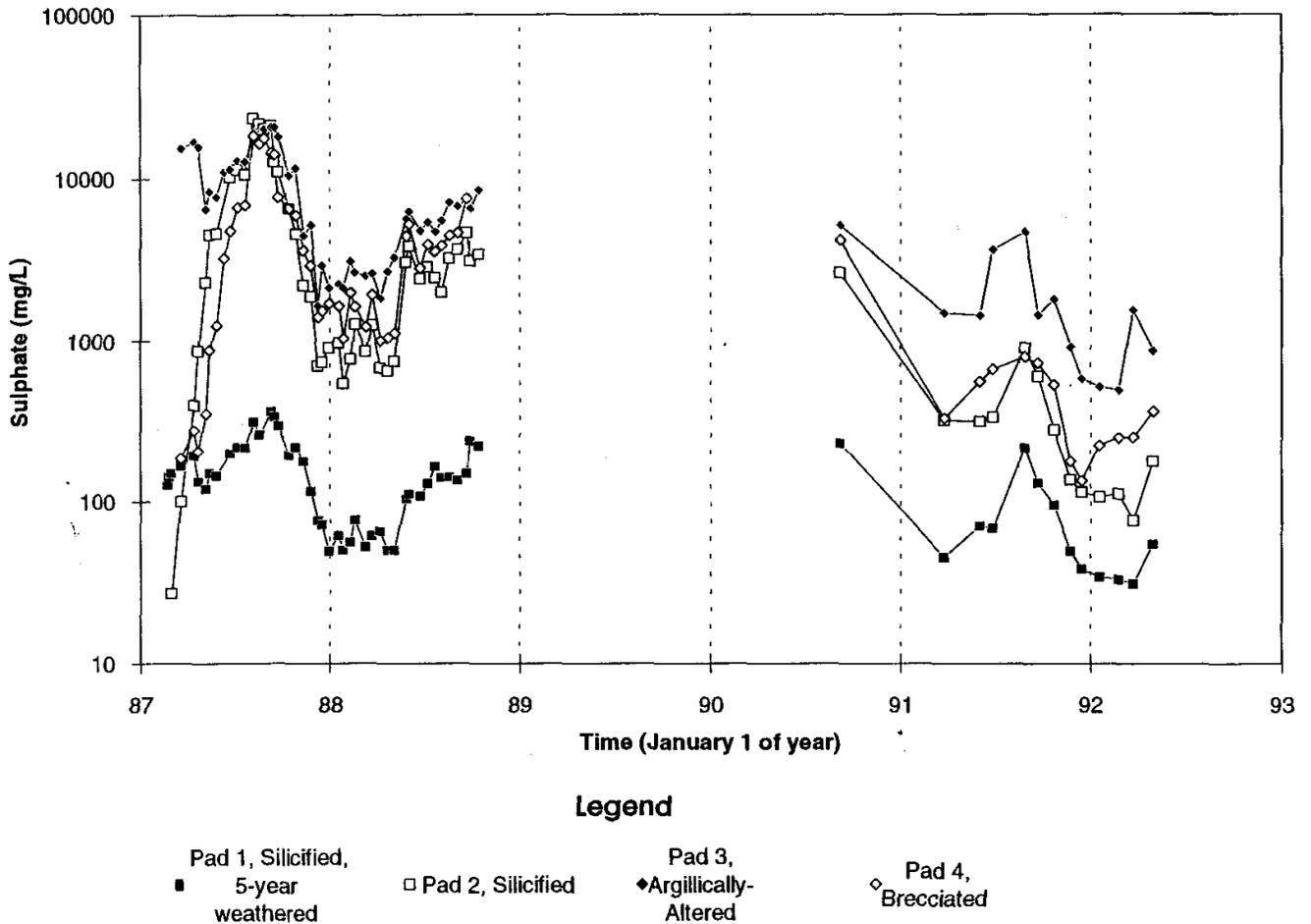
This project constructed 20 tonne tests on waste rock placed in layers to evaluate mitigation of acidity using rock blends at the Kutcho Creek site, British Columbia. A non-engineered soil cover was also placed on one pile. The results from the test work demonstrated seasonal effects but were inconclusive with respect to the blending technology.

III. Applications and Limitations

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

1. Initial characterization. For larger tests, characterization of the material prior to testing becomes difficult;
2. Monitoring. Leachate samples need to be collected on a regular basis. If the site is remote, sampling costs may be high;
3. Seasonal effects. Seasonal effects, particularly in small piles, can be severe thereby obscuring the other features of interest such as long-term reduction in release of oxidation products;
4. Duration of tests. Since the test is conducted under site conditions, the test may take much longer than the same test under laboratory conditions if the site experiences very cool conditions in part of the year;
5. Robustness. As with any field test, the test piles need to be carefully protected from damage by extreme climatic conditions and vandalism;
6. Similarity to full-scale rock piles. It cannot be assumed that the test piles will behave the same as full-scale piles. Table 3.3-3 provides a comparison of differences between small and large rock piles; and
7. Testing of ARD control alternatives. Small-scale tests cannot reliably evaluate ARD control alternatives since duplication of operational conditions is difficult.

Figure 3.3-1 Waste Rock Pads – Sulphate Concentrations in Leachate



Source: MEND 1.19.1

**Table 3.3-3
Comparison of Processes in Test and Full-Scale Rock Piles**

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

Notes: Features of full-scale waste rock dumps from MEND 1.11.1
Relative terms compare test and full-scale piles

Source: MEND 1.19.1, Table 7-5

IV. Method

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

No standard method for test piles has been described. MEND 1.19.1 provides a design resembling a leach pad (Figure 3.3-2). The test pile was constructed on a liner with a drain layer and a slotted leachate collection pipe wrapped in geo-sock. Leachate was collected in a covered pail equipped with a siphon to prevent the bucket from overflowing. The advantage of this design is that it has been observed to last for many years without maintenance. The disadvantage is that the conical shape does not allow even distribution of flow through the entire rock mass.

MEND 2.32.1 used a wooden crib type design. Again, the crib was lined to allow leachate collection (Figure 3.3-3). The main advantages of this design are that all rock in the pile receives the same incident precipitation and the slats in the crib sides allow free movement of air into the rock. The disadvantages are that it requires greater construction effort, the design is not as robust as that shown in MEND 1.19.1 and there is probably a limit to the size of sample that can be contained by the crib.

MEND 2.31.1b describes a sophisticated design for a 14,000 tonne pile with an engineered soil cover. The pile was placed on an impermeable Fabrene membrane with a 150 cm thick protective cover. Additional design details are shown in Figure 3.3-4.

None of the designs are particularly recommended. If the tests will be operated over an extended period, or a larger test (>50 t) is planned, the MEND 1.19.1 method is recommended because it is more robust than the MEND 2.32.1 design (for example, see Bethune *et al.* 1997). If the test pad is to be used to evaluate a cover material it should probably be constructed using a design similar to MEND 1.19.1 (but the sample would be placed as a thin flat layer rather than a tall cone) or MEND 2.31.1b. The cover will need to extend over the edges of the material to avoid “edge effects”.

Precipitation and temperature monitoring is recommended. As a minimum, precipitation should be determined to allow leachate volumes to be estimated. A direct measure of leachate volume is preferred since this allows chemical loads to be calculated. If it is not practical to measure flows directly, they can be estimated from the area of the pad and evaporation. For longer term projects, a relationship between site precipitation and precipitation at a nearby permanent monitoring station can be developed (e.g. MEND 1.19.1).

Generally, the leachate should be sampled and analyzed at least once a month. The sampling frequency should be increased during periods of high precipitation or the freshet to evaluate short-term changes. If personnel are on-site continually, leachate pH, total dissolved solids (or EC), and Eh can be monitored weekly and derived relationships between TDS and other parameters used to obtain data for other parameters (e.g. MEND 1.27.1a).

Interpretation of pad leachate may include the following:

- Trend in pH to determine whether acidic leachate was produced and evaluation of the buffering reactions;
- Recalculation of parameter (sulphate, metals) concentrations as loads (mg/s), on a mass (mg/kg/s) or surface area (mg/m²/s) basis to evaluate trends and determine sulphide and carbonate consumption rates, and metal release rates;
- Determination of trends in mole ratios (e.g. SO₄/(Ca+Mg+2K+2Na)) to evaluate relative rates of oxidation and buffering;
- Testing of mineral saturation using aqueous equilibrium models, such as MINTEQA2 (Allison *et al.* 1991);
- Determination of trends in mole ratios to evaluate changes in buffering mineral reactions (e.g. Ca/Mg); and
- Development of site specific relationships between metal concentrations and pH (MEND 1.27.1a).

Early indications of acid release (other than a transition to low pH) can be revealed by SO₄/(Ca+Mg+2K+2Na) ratios increasing from less than 1 to greater than 1.

VI. Cost (1998)

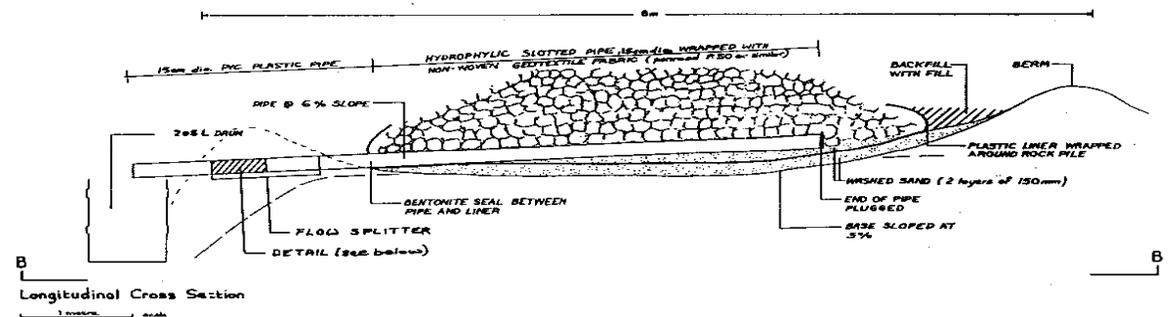
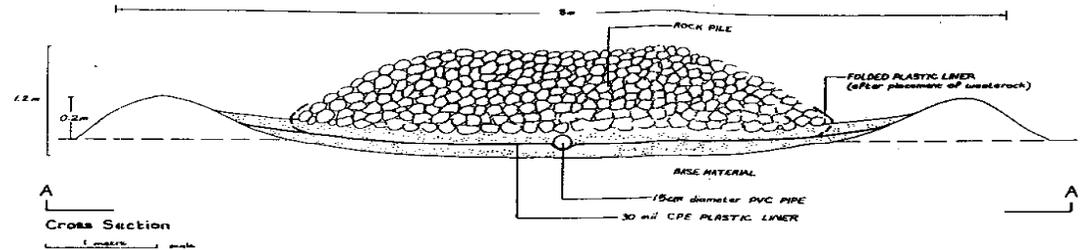
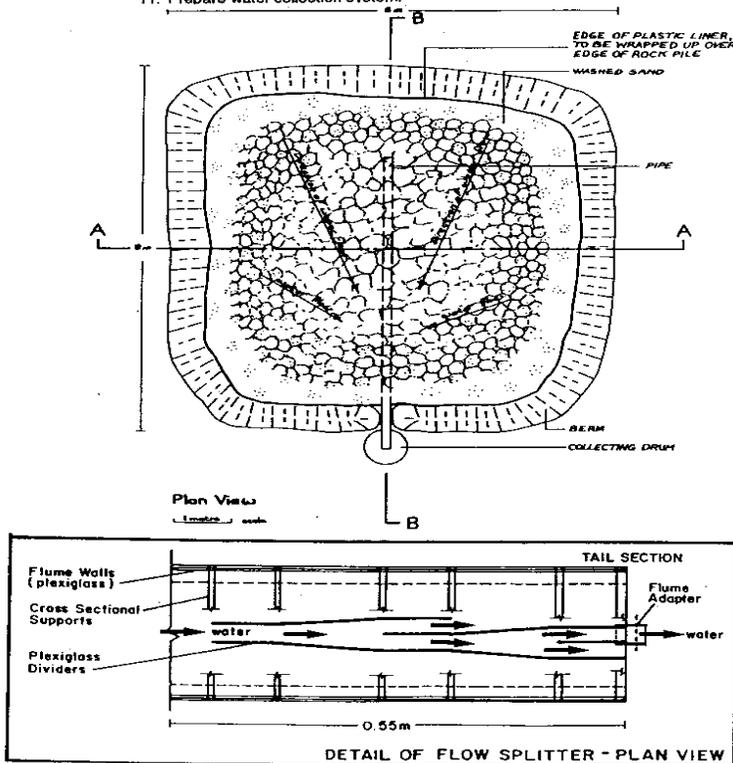
Initial capital costs are dependent on the location and the types of materials. Material costs are typically in the order of C\$1500/pad excluding freight. Monitoring costs may be high if special visits by a technician are required.

Waste rock pile sampling by drilling may cost up to \$10,000 per hole.

Figure 3.3-2 Construction of Waste Rock Pad

Construction Procedure

1. Prepare base and side berms.
2. Place 150 mm layer washed sand.
3. Place 30 mil CPE plastic liner.
4. Place 150 mm layer washed sand.
5. Place 15 cm dia. hydrophylic slotted pipe wrapped in geotextile fabric.
6. Place PVC plastic pipe through liner and berm opening and connect to hydrophylic pipe.
7. Form bentonite seal.
8. Place max. 500 mm layer of waste rock by hand on sand and around hydrophylic pipe.
9. Place waste rock in nominal 500 mm lifts.
10. Wrap plastic liner against side and around perimeter of waste rock pile.
11. Prepare water collection system.



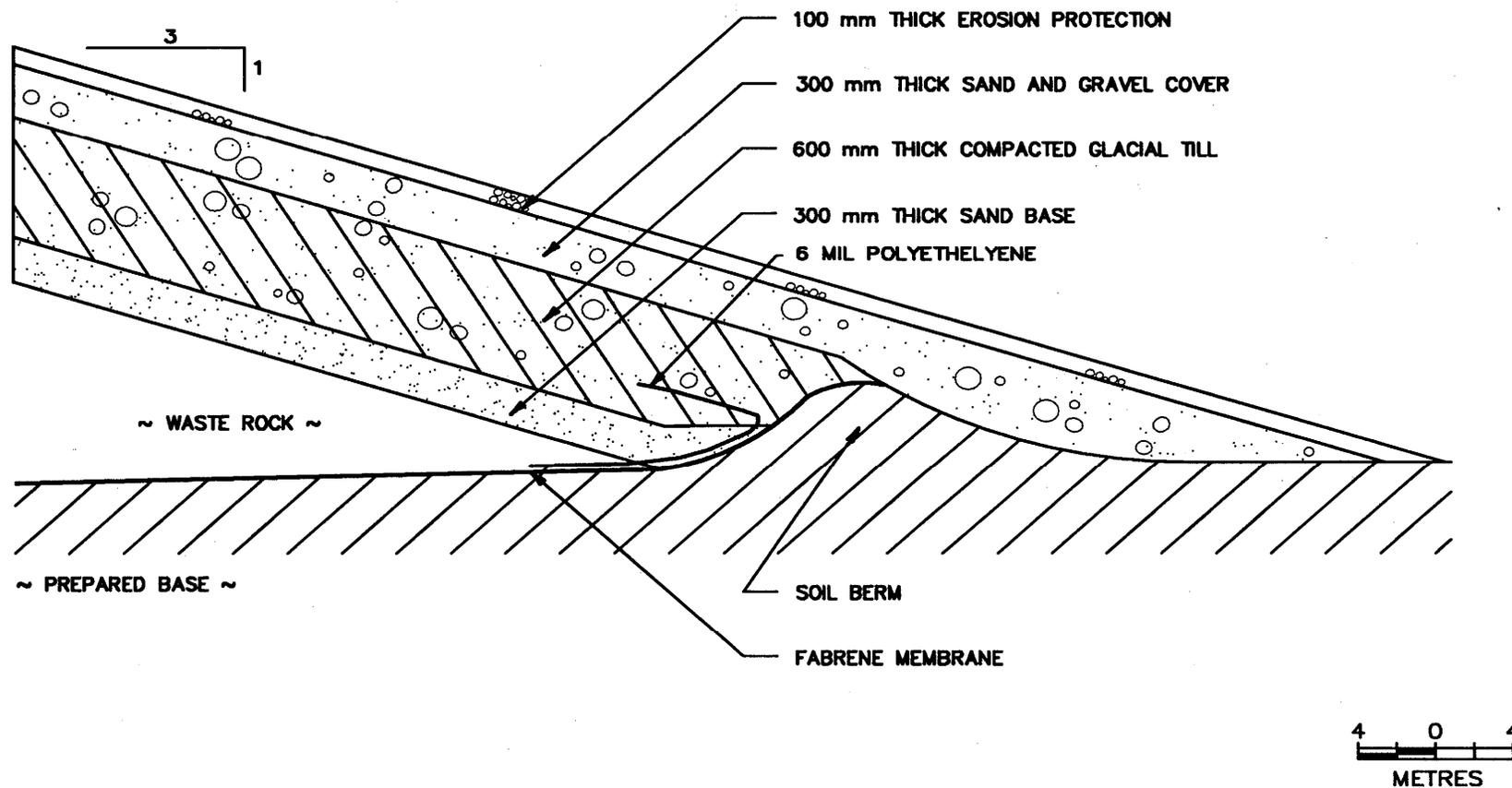
Source: MEND 1.19.1

Figure 3.3-3 Wood Crib Design



Source: MEND 2.32.1

Figure 3.3-4 Cover Construction Detail



Source: MEND 2.31.1b

VII. MEND and Relevant Publications

- MEND 1.11.1 1991. Critical Literature Review of Acid Drainage From Waste Rock. April.
- MEND 1.19.1 1994. Long Term Acid Generation Studies: Cinola Project British Columbia. March.
- MEND 1.27.1a 1996. Guide for Predicting Water Chemistry from Waste Rock Piles. July.
- MEND 2.31.1a 1992. Heath Steele Waste Rock Study, Phases I to III. March.
- MEND 2.31.1b 1994. Engineering Design and Construction Phase IV– Composite Soil Cover Acid Waste Rock Study Heath Steele Mines. November .
- MEND 2.31.1b 1996. Monitoring Report Phase IV – Composite Soil Cover Acid Waste Rock Study Heath Steele Mines. March.
- MEND 2.31.1c 1998. Monitoring Program 1995-96 Phase V – Composite Soil Cover on Waste Rock Pile 7/12 at Heath Steele, New Brunswick. February.
- MEND 2.32.1 1992. Kutcho Creek Project: Blending and Segregation, Acid Generation Testwork. March. British Columbia Acid Mine Drainage Task Force Report.

Allison, J.D., Brown, D.S. and Novo-Gradac, K.J. 1991. MINTEQA2/PRODEFA2: A Geochemical Assessment Model for Environmental Systems – Version 3.0 User's Manual. U.S. Environmental Protection Agency Report EPA/600/3-91/021, 106 p.

Bethune, K.J., Lockington, D.A. and Williams. D.J. 1997. *Acid Mine Drainage: Comparison of Laboratory Testing to Mine Site Conditions*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 1, pp. 305-318.

3.3.2.3 Comparison with Other Sites and Similar Geological Environments

I. Discussion of Theory

Deposits of commodities amenable to mining are formed under geological conditions in the precipitation of variable quantities of acid generating and acid consuming minerals. In general, the conditions of formation and the resulting types of minerals can be used to classify different deposits according to their origin. Physical and chemical laws apply to all sites. In theory, classification of deposits according to susceptibility to acid mine drainage would result in a system that might allow a

preliminary prediction of acid drainage potential based solely on geological characteristics. This would allow mining companies to make a preliminary decision on possible issues associated with development of a mine at a particular site.

It is unlikely that comparisons of a proposed project with other projects would provide a definitive indication of potential for release of acid mine drainage. Other factors need to be considered including the type of mining proposed, the location of ore within the mineralized system, and local climatic factors. Comparison of adjacent properties is not likely to be reliable if, for example:

- The two deposits are in the same geological system but one is epithermal gold mineralization whereas the other is porphyry copper mineralization;
- One deposit is an existing underground mine whereas the proposed mine is a large open pit; and
- One deposit is hosted by sedimentary rocks and the other is hosted by intrusive igneous rocks.

However, comparisons of deposits in widely separated regions is valid if the geological environments are similar.

II. Discussion of MEND Research

Two MEND Projects have investigated correlations of susceptibility to acid mine drainage to mineral deposit types.

MEND 1.32.1 Prediction and Prevention of Acid Rock Drainage from a Geological and Mineralogical Perspective

This study resulted in a simple classification scheme for mineral deposits based on their mineral composition. The study concluded that the comparison is useful.

MEND 1.16.4 Evaluation of Static and Kinetic Prediction Test Data and Comparison with Field Monitoring Data

This project used the Database for Acid Rock Drainage (DBARD, MEND 1.12.1b) to evaluate actual correlations. This report concluded that ABA results were not correlated with mineral deposit types and that such comparisons were therefore of limited benefit. This conclusion partly reflected a limitation of the database since it was not possible to screen out results caused by severe sampling biases. The conclusions were based on individual sampling results not weighted averages which might have removed these effects.

III. Applications and Limitations

As noted above, geological comparisons may allow a preliminary classification of ARD potential for a particular deposit primarily for the purpose of identifying potential issues early on in property development.

The main limitation of such comparisons is that it provides only a limited preliminary assessment and site specific data will always be needed to support engineering decisions. Although databases are being assembled (for example, DBARD, MEND 1.12.1b), there is a lack of supporting data for such comparisons.

IV. Method

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

- Age of the mineralization and host rocks;
- Main rock types that are expected to be exposed during mining;
- Types and proportions of reactive minerals in each rock type;
- Occurrence of the reactive minerals;
- Physical weatherability of the rock;
- Likely mining method; and
- Climatic information (i.e, temperature range, precipitation patterns).

Having assembled this information it can then be compared with data for similar projects. Table 3.3-4 summarizes existing knowledge of the classification of genetic deposit types according to acid rock drainage susceptibility.

V. Cost (1998)

The costs of the comparison are small unless a large research effort is required to obtain the necessary information for the comparison.

Table 3.3-4
Classification of Common Mineral Deposit Types According to AMD Susceptibility

Deposit Type	Susceptibility Range			Reference
	High	Medium	Low	
Volcanogenic massive sulphide, any type	A/M			
Coal formed in saltwater environment	A	M		1
Coal formed in freshwater environment			A/M	1
Skarn		A/M		
Limestone-hosted lead and zinc		M		
Epithermal vein – volcanic hosted		A/M		
Epithermal vein – sediment hosted				
Geologically oxidized ore deposits, any type		M	A	
Magmatic sulphide deposits	A/M			
Mesothermal vein		M	A	
Porphyry (alkalic)			A/M	
Porphyry (calc-alkalic)		A/M		

Notes: A = Acidic drainage
M = Metals/metalloids, regardless of acidity
1 – Carrucio *et al.* (1977)

VI. MEND and Relevant Publications

MEND 1.12.1b 1996. DBARD for Paradox: Developments in DBARD, the Database for Acid Rock Drainage. March.

MEND 1.16.4 1995. Evaluation of Static and Kinetic Prediction Test Data and Comparison with Field Monitoring Data. December.

MEND 1.32.1 1993. Prediction and Prevention of Acid Rock Drainage from a Geological and Mineralogical Perspective. October.

Caruccio, F.T., Ferm, T.C. Horne, J., Geidel, G. and Baganz, B. 1977. Paleoenvironment of Coal and its Relation to Drainage Quality. U.S. Environmental Protection Agency Report EPA-600/7-71-067, 108 pp.

3.3.3 MINE WORKINGS

3.3.3.1 Existing Workings

I. Discussion of Theory

Determination of the weathering characteristics of rock in the field is the objective of predictive test work. Examination of existing mine workings can provide valuable information regarding the longer term behaviour of waste rock without conducting extended testing under laboratory or field

conditions. The main limitation of this approach is that the existing workings may not be similar to the workings for which the predictions are required. In this case, the information collected must be limited to exposures of individual rock types.

There is no natural analog to mine workings such as exists for waste rock (Section 3.3.2.1). Naturally-formed faces (such as cliffs, river banks, outcrops) are formed under different conditions and should not be applied to predictions for mine workings.

Examination of old mine workings can provide weathering information relevant to time scales varying from a few years to several centuries (in historical mining areas). These provide an obvious analog to proposed mines. The main limitations to be considered are the similarities of the various workings being compared. Variations in mining methods can have a significant effect on the characteristics of mine walls.

II. Discussion of MEND Research

MEND 1.27.1a Guide for Predicting Water Chemistry from Waste Rock Piles

This project investigated a method for predicting water quality from old mines in general to assist with closure planning. The method could also be applied to understanding mine drainage for new mines planned for the same mineral deposit.

III. Applications and Limitations

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

IV. Method

In general, methods applicable to assessment of mine surfaces can include:

- Description of rock mineralogy in field hand samples, including reactivity of carbonates determined by fizz reaction with dilute hydrochloric acid;
- Observation of preferential exposure of minerals along exposed fractures and other zones of weakness;
- Observation of large and small-scale weathering features on rock surfaces including oxidation coatings (colour and type) and efflorescent minerals. Some examples of common coatings were provided in Table 3.3-2; and

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

V. Cost (1998)

Field observations are usually collected during routine site inspections. No additional costs are incurred. Normally, a small mine site can be described thoroughly in one full day site inspection depending on access.

VI. MEND and Relevant Publications

MEND 1.27.1a 1996. Guide for Predicting Water Chemistry from Waste Rock Piles. July.

3.3.3.2 Wall Washing

I. Discussion of Theory

Oxidation of mine walls proceeds in the same fashion as waste rock. During dry periods, the oxidation products buildup on the immediate exposed surfaces and in fractures available to oxidation by atmosphere. During flushing events (precipitation, groundwater leaching), the soluble oxidation products are leached and affect mine water quality.

The principle of wall-washing is to estimate the rate of oxidation of the walls by simulating precipitation on the walls. A section of wall is isolated, water is sprayed on the wall and the resulting leachate is collected.

II. Discussion of MEND Research

MEND 1.15.2c Application of MINEWALL 2.0 to Three Mines Sites

The method was developed to support the MINEWALL (Version 2.0) model (MEND 1.15.2a,b). It is a modification of a method previously developed by Morth *et al.* (1972). At present, results for the method have been reported for three open pit mines in British Columbia (Equity Silver Mines' Main Zone Pit, Noranda Mineral's Bell Mine, BHP Canada's Island Copper Mine) (MEND 1.15.2c).

III. Application and Limitations

The method can be applied to any project where existing mine walls are exposed to oxidation. Most pit walls are suitable. Some underground walls may not be suitable since the slope of the wall may prevent collection of the leachate. The main limitation is the lack of an extensive database showing reproducibility of the results, and possible difficulties with applying the method under different conditions.

IV. Base Method

The method involves careful isolation of an area of mine wall so that water can be applied and collected. The following method is suggested:

1. Select approximately 1 m² of mine surface. Ideally, the area should encompass one rock type and not contain major variations in mineralogy or physical features. The total area should be measured and the number and length of fractures estimated. From site knowledge, the depth of oxidation in fractures should also be estimated;
2. The selected area should be isolated using an inert weather resistant substance (e.g. putty, caulking) which will adhere to the rock surface and allow leachate to run to a collection point. The collection point is usually a short section of tubing at the lowest point of the isolated area (Figure 3.3-5); and
3. A known volume of water is sprayed evenly over the entire isolated area. The volume of water recovered is measured, preserved and submitted for analysis. The volume of water applied depends on the volume of water required for analysis (usually 500 mL).

Interpretation of the results involves recalculation to estimate oxidation rates on an area and time basis. To include time in the calculation, the time between leaching events needs to be estimated. This can be done either by determining the time since the last rainfall, or by covering the isolated area to prevent contact by precipitation and artificially leaching using a fixed frequency.

V. Cost (1998)

Material costs for setting up a wall washing station are small. The main costs are for technician time to set up and wash the stations. The estimated set-up time is about four hours. Rinsing takes about 30 minutes.

VI. 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.

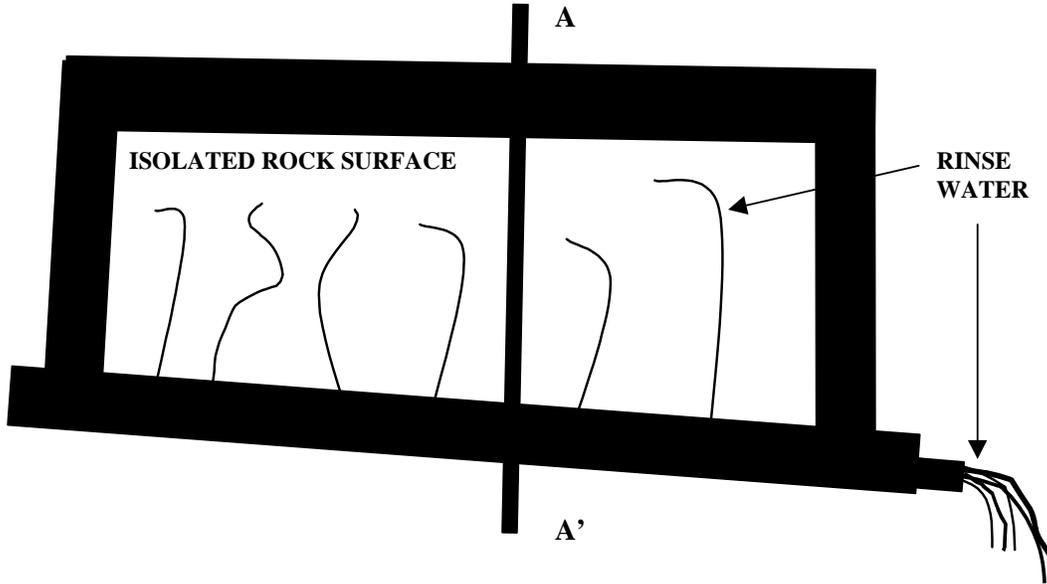
MEND 1.15.2c 1995. Application of MINEWALL 2.0 to Three Mine Sites. September.

Morth, A.H., Smith, E.E. and Shumate, K.S. 1972. Pyrite Systems: A Mathematical Model. Contract Report for U.S. Environmental Protection Agency, EPA-R2-72-002.

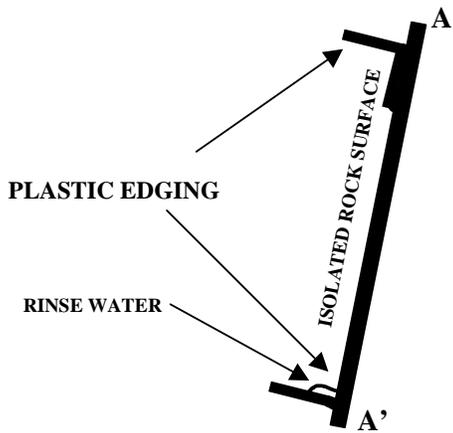
Price, W.A. 1997. Draft Guidelines and Methods for the Prediction of Metal Leaching and Acid Rock Drainage at Minesites in British Columbia.

Figure 3.3-5 Diagram of Minewall Station Assembly

PLAN VIEW



CROSS-SECTION A-A'



Source: From Price (1997)

3.4 MODELLING

The MEND program has contributed significant advances to numerical modelling of weathering processes in mine facilities by sponsoring projects on all three major types of sources (tailings, waste rock and mines). MEND supported the development, testing, validation and dissemination of the RATAP model through several reports and technology exchange workshops.

Similarly, MEND sponsored the development of MINEWALL, the first publicly-available model to predict water quality in pit lakes and drainage from underground mines. This model is being updated to model chemical interactions in the mine water.

MEND has also contributed to several projects intended to model various processes in waste rock piles. These have varied from empirical approaches to strictly theoretical discussions. MEND also sponsored development of the first phase of the SOILCOVER model designed to predict the behaviour of soil covers placed on reactive tailings and waste rock. This model is being used globally and is regarded as one of the most powerful tools currently available.

Reports prepared by MEND on modelling are listed in Table 3.4-1.

**Table 3.4-1
Projects on Modelling**

MEND Project	Title
1.11.1	Critical Literature Review of Acid Drainage from Waste Rock
1.14.2c	Heat Transfer during Acid Mine Drainage Production in a Waste Rock Dump, La Mine Doyon (Québec)
1.14.2d	Water Budget for the Waste Rock Dump at La Mine Doyon, (Québec)
1.14.3e	Peer Review of MEND Studies Conducted from 1990 to 1994 on Acid Mine Drainage at Mine Doyon South Waste Rock Dump
1.15.2b	MINEWALL 2.0 – Literature Review and Conceptual Models
1.15.2c	Application of MINEWALL 2.0 to Three Mine Sites
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”
1.19.2	Scaling Analysis of Acid Rock Drainage
1.21.1a	Critical Review of the Reactive Acid Tailings Assessment Program (RATAP.BMT2)
1.22.1b	Assessment of Gas Transfer-ANSTO Model at Heath Steele Mines
1.25.1	Soilcover Users Manual Version 2.0
1.27.1a	Guide for Predicting Water Chemistry from Waste Rock Piles
1.42.1	Critical Review of Geochemical Processes and Geochemical Models Adaptable for Prediction of Acidic Drainage from Waste Rock
1.51.1	Quantitative Analysis of Chemical and Biological Kinetics for the Acid Mine Drainage Problem
1.51.2	Nonlinear Modelling of Chemical Kinetics for the Acid Mine Drainage Problem and Related Physical Topics
PA-1*	Hydrogeology of Waste Rock Dumps
PA-2*	Metal Transport and Immobilization at Mine Tailings Impoundments

* MEND Associate Project

3.4.1 TAILINGS

I. Discussion of Theory

The principal objectives of predictive (computer) modelling of the behaviour of sulphide tailings under various conditions are to mathematically describe the interactions of chemical reactions and the migration of tailings pore water in an effort to predict future drainage quality and thereby provide a basis for decision making regarding ARD prevention and control measures.

Table 3.4-2 provides a listing of physical and geochemical processes. The latter are fundamentally important as they determine the rate at which the physical mass transfer processes proceed.

**Table 3.4-2
Physical and Chemical Processes Affecting AMD in Tailings**

Physical Processes	Chemical Processes
<ul style="list-style-type: none"> • Oxygen diffusion • Saturated/unsaturated water flow • Diffusion of oxidation products from reactive surface 	<ul style="list-style-type: none"> • Oxidation of sulphide minerals • Dissolution of buffering minerals • Oxidation/reduction reactions • Radioactive decay • Ion exchange/adsorption • Secondary mineral precipitation • Catalysis by bacteria, galvanic interactions and temperature

Predictive modelling of the acid production process taking into account geochemical and physical processes can be undertaken using quantitative and mechanistic models. Quantitative prediction may be made using empirical and deterministic models. Empirical models are based on statistical relationships as may be defined by regression and correlation analyses between parameters of interest (e.g. metal concentrations in ARD) and other variables such as time. This method requires that a suitable database be developed. The objective in statistically assessing the data is to identify a key variable that can be related to ARD quality. This predictive method relies on field measurements and may not account for the complex geochemical interactions that affect future ARD quality. Models that are based on the statistical assessment of data from a site are by nature site-specific. The methodology, however, can be applied to other sites.

Examples of empirical and engineering models related to acidic drainage from tailings are WATAIL (MEND 2.13.3), RATAP (MEND 1.21.1) and MINTOX (MEND PA-2). These models use simplifying assumptions such as uniform properties and simplified geometry to predict the overall physical and chemical behaviour of the tailings. As the models do not include detailed geochemistry,

they have limited predictive capabilities. However, results can be quite useful in examining the effects of dominant processes and the comparison of tailings management options.

Mechanistic predictive models are based on the theoretical equations that have been developed to describe the processes that control acid production. Scientifically-based mechanistic models include kinetic, thermodynamic equilibrium, and mass transport models. Deterministic models apply scientific principles such as the conservation of mass, momentum and energy. Solving the theoretical equations is challenging and necessitates the simplification of parameters through the use of simplified geometry, homogeneity and idealized initial conditions and boundary conditions. Parameter estimates (i.e. chemical reaction rates, mass transfer coefficients) have a critical role in mechanistic modelling, and are often based on laboratory studies, physical models and field experiments in some cases.

The predictive capability of mechanistic models can be significantly improved by applying probabilistic uncertainty analyses to examine the sensitivity of predicted values to one or more parameters or assumptions.

Thermodynamic equilibrium models are static models of an aqueous solution. Examples include MINTQA2 and PHREEQC. The data requirements include water analyses, temperature and pH. The models are used to estimate the concentration (activities) of aqueous species, and solve for the distribution of mass among various dissolved aqueous species and complexes. They provide saturation indices (SI values) for various minerals which are present or may form. Model users can examine the effect of changes in temperature or pressure and let the solution react with one or more minerals. These models are quite flexible and are widely used.

Mass transfer models are dynamic models of a closed system, and provide predictions of fluid composition over time as the system progresses towards equilibrium. The data requirements include fluid composition, and the mass and surface area of the minerals. The models account for changes in fluid composition as minerals react or dissolve, and the formation or dissolution of secondary minerals.

Coupled mass transfer and flow models are dynamic models of any open system. These models can simulate a variety of geochemical processes. The data requirements include aqueous composition as a function of initial mineralogy, flow rates, and temperature changes over time. They consider flow, solute transport, and heat transport. This group of models represent a hybrid between hydrology and geochemistry – some models focus on geochemistry while others emphasize hydrology. These models tend to be quite complex, a factor which in some instances limits their application.

Support models are used to calculate thermodynamic or physical-chemical properties or parameters, or perform mass balances and include physical models used to investigate oxygen transport.

II. Discussion of MEND Research

MEND research has led to numerous advancements in the predictive modelling of tailings. The capabilities of the various approaches and computer models for predicting acidic drainage from tailings have been demonstrated at numerous sites. The development of prediction methods is a continuous process, and further advancements are expected.

MEND 1.42.1 Critical Review of Geochemical Processes and Geochemical Models Adaptable for Prediction of Acidic Drainage from Waste Rock

This is a critical review of geochemical processes and models which are adaptable for the prediction of waste rock. The report describes the geochemical processes that occur in acid-generating waste rock piles and evaluates geochemical computer models with regards to their abilities to describe the geochemical processes and their applicability to the prediction of seepage quality from waste rock piles. Most of the models were originally developed for the prediction of ARD from tailings. The prediction models that were reviewed were classified into the following groups:

- Thermodynamic equilibrium (e.g. MINTQA2 (Allison *et al.* 1991), PHREEQC (Parkhurst 1995), WATEQ4F (Bell *et al.* 1987));
- Mass transfer (e.g. EQ3/6 (Wolery 1992));
- Coupled mass transfer and flow (e.g. MINTRAN (Frind and Molson 1994), PHREEQM (Appelo and Postma 1993));
- Support models (e.g. BALANCE (Parkhurst *et al.* 1982)); and
- Engineering models (e.g. WATAIL (MEND 2.13.3), ACIDROCK (Scharer *et al.* 1994).

MEND 1.42.1 raised the following points about the geochemical modelling of waste rock which are applicable to the predictive modelling of mine wastes in general.

Data Requirements

- Datasets should be collected to increase understanding (e.g. field and laboratory data);
- Methods for determining the reaction mechanisms and the reactive surface area of sulphide should be improved;
- The database of thermodynamic equilibrium constants for important minerals in acid mine drainage should be improved; and

- More research should be conducted to obtain kinetic rate data for precipitation, co-precipitation and dissolution reactions; inhibitive and catalytic effects should be included in kinetic rate equations; and kinetic rate equations should address transitions between diffusion and surface-controlled reactions and redox disequilibrium in the aqueous phase.

Application of Existing Models

- Existing geochemical models should not be used with the objective of predicting water chemistry from waste rock piles, but can be used to improve understanding and to perform comparisons between decommissioning scenarios;
- The application of mass transfer models (e.g. EQ6, PATHARC) on well-defined oxidizing waste rock should be encouraged; and
- Empirical models based on laboratory and field tests should be used and further developed to compensate for the limitations of presently available geochemical models.

MEND 1.21.1C USER'S MANUAL – RATAP.BMT3

This is a User's Manual for the Reactive Acid Tailings Assessment Program (RATAP.BMT3) model that can be used for several solid, aqueous and gaseous constituents, and to assess the rate and quantity of acid generation from base metal tailings. The model can also be used to evaluate the short and long-term benefits of tailings management options (such as placement of a cover), and can facilitate the development of alternative reclamation or close-out strategies.

The program for development of the RATAP model covered about an eight-year period, and consisted of:

- Associated literature reviews and research studies; model development and validation at several tailings sites in Elliot Lake, Ontario;
- Critical review (e.g. MEND 1.21.1a);
- Technical workshops (MEND 1.21.1b); and
- The preparation of a User's Manual (MEND 1.21.1c).

The RATAP model and its supporting documentation are commercially available from CANMET.

The RATAP model was developed to answer the following types of questions:

- How much time is required to oxidize the sulphide minerals in a tailings area?;
- How long will acid generation be a problem for a tailings area?;
- What is the flux of acidity and metals from a tailings area?;

- How will the design of a cover or the presence/addition of buffering minerals such as calcite and gypsum affect the acid flux from a tailings area?; and
- What is the uncertainty associated with the estimates of fluxes of acidity and metals from a tailings area?

The RATAP model considers the following processes:

- Kinetics of chemical and biological oxidation of sulphide minerals as a function of water temperature, oxygen concentration, mass of sulphide, pH, phosphorus concentration, carbon dioxide content, and moisture content;
- Oxygen pore-gas diffusivity and its control on the oxygen flux into the tailings;
- Shrinkage of the sulphide mineral grains as they oxidize (using "shrinking particle" kinetics);
- Depth-dependent differences in the chemical characteristics of the tailings;
- Temperature variations with depth in the unsaturated zone;
- Kinetic reactions between pore water and relevant solid minerals;
- Pore water transport of metals and aqueous constituents; and
- Dissolution of solids present (minerals) or formed (precipitates) (MEND 1.21.1c).

Dynamic expressions are used for modelling sulphide oxidation kinetics, mass transport and energy transport. Equilibrium concepts are used for modelling solid dissolution, aqueous speciation, ionic balance (neutralization/buffering), ion exchange and adsorption processes. Empirical expressions are used to model periodic (seasonal) variations in temperature and atmospheric precipitation.

The RATAP model allows simulations of over several hundred years. The model provides concentration predictions for: numerous metals (aluminum, arsenic, calcium, copper, iron, magnesium, potassium, zinc); aqueous species (carbonate, sulphate); sulphide minerals (pyrite, pyrrhotite, chalcopyrite, sphalerite, arsenopyrite); buffering minerals and precipitates (calcite, ferric hydroxide, aluminum hydroxide, gypsum); gaseous constituents (oxygen, carbon dioxide), as well as an estimate of the acidity. Predictions are available from different depths into the unsaturated and saturated zones. As the RATAP model simulates one tailings basin at a time, larger tailings basins containing several cells, or beaches and slimes, may need to be split into several smaller areas and simulated on an individual basis.

The model has been designed to run within a probabilistic framework that can address uncertainty regarding the input data. Some of the input parameters can be described using a distribution function, and the model will provide statistical information (i.e. mean, minimum, maximum, probability distribution function) for the predicted concentrations. The characteristics of a dry cover

on the tailings can be specified using several of the input parameters (e.g. porosity, water content, thickness, mineral content). The tailings can also be modelled under the assumption that they are highly saturated (e.g. flooded tailings).

Part II of MEND 1.21.1c is directed at an informed user of the model, and explains how to prepare input data, and run and calibrate/validate the model at a specific site, or for a specific application. Part III provides additional details regarding the input/output capabilities and probabilistic features.

MEND 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

This report is the final report for a four-year study (1985 to 1989) of the Waite Amulet tailings in northwestern Québec. The objective of Phase 1 (1985) was to define the tailings hydrogeology, geochemistry and biochemistry through a field program involving drilling, sampling and use of geophysical methods. The objectives of Phase 2 (1986) were to continue the field program and finalize the definition of tailings hydrogeology, evaluate the geochemistry of the unsaturated zone and propose measures for controlling oxidation. Phase 3 (1987) objectives were to assess water and metal balance in the tailings, evaluate gaseous oxygen profiles in different areas of the tailings, and relate the mineralogy of the tailings to the unsaturated porewater geochemistry. Phase 4 (1988 to 1989) objectives were to develop a realistic metal and water balance, and evaluate porewater evolution and transport mechanisms using a numerical flow model. The report provides a discussion of the important factors affecting acid mine drainage within the context of interpretation of the results of laboratory and field studies. Appendix C contains a description of:

- The flow model (FLONET) developed by the University of Waterloo;
- Geochemical modelling of tailings porewater using the equilibrium speciation model MINTEQ; and
- Modelling of infiltration and run-off using the model HELP.

Effective oxygen diffusion coefficients in the range of 3.0 to 4.2×10^{-7} m²/s were calculated from theoretical best-fits of the measured oxygen profiles. Based on these values, sulphide oxidation in the unsaturated zone was predicted to continue for the next 600 years.

Geochemical calculations using the equilibrium speciation model MINTEQ were carried out to examine the formation of precipitates and secondary minerals (ferric hydroxide, goethite, lepidocrocite) in the unsaturated zone. The modelling indicated that tailings water in the shallow unsaturated zone is saturated with gypsum and supersaturated with respect to sodium and potassium jarosites, goethite and lepidocrocite, as well as anglesite (lead sulphate).

A two-dimensional steady-state finite element flow model (FLONET) was developed and applied to simulate the porewater flow. The flow modelling showed the effect of anisotropy in the hydraulic properties as a result of layers of slimes. The flow was predominantly horizontal and shallow. Flow in the central portion of the impoundment was predominantly downwards towards, and along, the tailings-clay interface. The geotechnical and hydrogeochemical characteristics of the clayey subsoil were thoroughly investigated.

A water balance evaluation was performed using the HELP model. Linear regression analyses were used to identify correlations between the loadings of the measured constituents and the seepage flow.

This work also formed the basis for the design of tests plots for soil covers at the site (MEND 2.21.2).

III. Applications and Limitations

Computer modelling of ARD generation and migration from tailings can be applied to the assessment of waste management options. Simulation of various scenarios, such as the placement of dry covers, flooding tailings, can be useful in determining the most cost-effective management option for the mitigation of ARD.

Models may also be used to determine the total amount of acidity produced over time and the time period over which acid generation takes place. Models are generally limited by a lack of site specific data (particularly for proposed mines) or by highly variable data. Uncertainty in the input data may be addressed by probabilistic modelling.

IV. Base Method

The approach and method used to model acid generation in tailings depends on the type of modelling proposed. Empirical models, for example, rely on correlations between observed parameters whereas mechanistic models are supported by currently accepted scientific theory of the processes controlling ARD generation. The modelling approach most suited to a particular site depends on a number of factors such as the required accuracy and reliability of predictions, and the availability of site specific information (i.e. physical and chemical characterization of the tailings, water chemistry, rate data for acid generation and neutralization.).

Each model requires specific data with respect to the physical and chemical characteristics of the tailings system. Generally, equilibrium models such as MINTEQ require information on the water chemistry. This includes pH, redox potential or Eh, dissolved species (metals, sulphate, chloride, ammonia, organics, etc.). Other data on potential or actual solid phases (e.g. ferric hydroxide) may also be required.

V. Variations

Different types of modelling can be considered depending on the objectives. Examples are the effect of a certain parameter on acid generation or the comparison of management options. These types of investigations could include the application of more than one form of model, or very complex models.

VI. Cost (1998)

Geochemical modelling of tailings is typically carried out by a consulting company. The cost can range widely and depends on the complexity of the site, the questions to be answered and the type of model to be used.

Alternatively, some models are not proprietary and can be purchased for use by interested parties. Some models are in the public domain (such as WATAIL), while others are available for purchase. Purchase prices vary widely and can range from \$700 to \$100,000. RATAP costs approximately \$10,000. Additional information on model costs can be found in MEND 1.42.1, Appendix F.

VII. MEND and Relevant Publications

- | | |
|--------------|--|
| MEND 1.17.1d | 1990. 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. |
| MEND 1.21.1a | 1990. Critical Review of the Reactive Acid Tailings Assessment Program (RATAP.BMT2). April. |
| MEND 1.21.1b | 1990. Workshop on Modelling of Reactive Tailings Sponsored by the MEND Prediction Committee, Final Report. August. |
| MEND 1.21.1c | Users Manual (RATAP.BM2) |
| MEND 2.13.3 | 1993. WATAIL 1.0 User's Manual. A Tailings Basin Model to Evaluate Transient Water Quality of Acid Mine Drainage. Open file. |
| MEND PA-2 | 1997. Metal Transport and Immobilization at Mine Tailings Impoundments. March. |

Appelo, C.A.J. and Postma, D. 1993. Geochemistry, Groundwater and Pollution. A.A. Balkema, Rotterdam, 536p.

Allison, J.D., Brown, D.S. and Novo-Gradac, K.J. 1991. MINTEQA2/PRODEFA2, A Geochemical Assessment Model for Environmental Systems – Version 3.0 User's Manual. U.S. Environmental Protection Agency Report EPA/600/3-91/021, 106 p.

Bell, J.W., Nordstrom, D.K. and Zachman, D.W. 1987. WATEQ4F – A Personal Computer FORTRAN Translation of the Geochemical Model WATEQ2 with Revised Data Base. U.S. Geological Survey Open-File Report 87-50, 108 p.

Frind, E.O. and Molson, J.W. 1994. *Modelling of Mill-Tailings Impoundments*. In: Short Course Handbook on Environmental Geochemistry of Sulphide Mine Wastes. (Eds. J.L. Jambor and D.W. Blowes), Mineralogical Association of Canada. Waterloo, Ontario. May. pp. 19-58.

Parkhurst, D.L., Plummer, L.N. and Thorstenson, D.C. 1982. BALANCE – A Computer Program for Calculating Mass Transfer for Geochemical Reactions in Ground Water. U.S. Geological Survey Water-Resources Investigations Report 82-14, 29 p.

Parkhurst, D.L. 1995. PHREEQC – A Computer Model for Geochemical Calculations. U.S. Geological Survey Water-Resources Investigations Report 95-4227

Scharer, J.M., Pettit, C.M., Chambers, D. and Kwong, E.C. 1994. *Mathematical Simulation of a Waste Rock Heap*. In: Proceedings of the 3rd International Conference on the Abatement of Acidic Drainage. U.S. Dept of Interior, Bureau of Mines, Special Publication. SP 06A-94, Vol 1, pp. 30-39.

Wolery, T.J. 1992. EQ3/6 – A Software Package for Geochemical Modelling of Aqueous Systems. Lawrence Livermore National Laboratory, CA.

3.4.2 WASTE ROCK

I. Discussion of Theory

Coarse mine wastes, which may include run-of-mine (ROM) wastes, low grade ore stockpiles, rubble in open pits, construction fill, and processing plant wastes (for example, coal washing coarse rejects) are all potential sources of acid rock drainage. These wastes are typically complex due to highly variable geochemical, mineralogical and physical characteristics.

Figure 3.4-1 illustrates the overall processes affecting the quality of leachate emerging from a waste rock pile. The main interacting factors are geology, climate (meteorology) and hydrogeology. Geology controls the overall chemical characteristics of the waste and the mining methods used to extract ore and waste rock. Climate controls the distribution of precipitation, release of water to the

pile, heating and cooling and to a degree air movement around and within the pile. Finally, hydrogeology controls how water flows through the rock pile whether it originates by infiltration or groundwater. Internally important factors include construction of the piles, the flow of water within the piles, movement of oxygen and heat, chemical reactions, and contaminant entrainment and transport.

Figure 3.4-1 also shows that geochemical processes are coupled to other physical processes. In various cases, the coupling is one way (single arrow), two way (double arrow) or weak (dashed arrows). A good example of a two-way coupled process is that of the relationship between geochemical processes and movement of oxygen and heat within the pile. The oxidation of sulphide minerals requires oxygen, the availability of which is controlled by the movement of air through the pile. However, air movement is also controlled by temperature differences within the pile that are caused by the exothermic reactions that occur during sulphide oxidation.

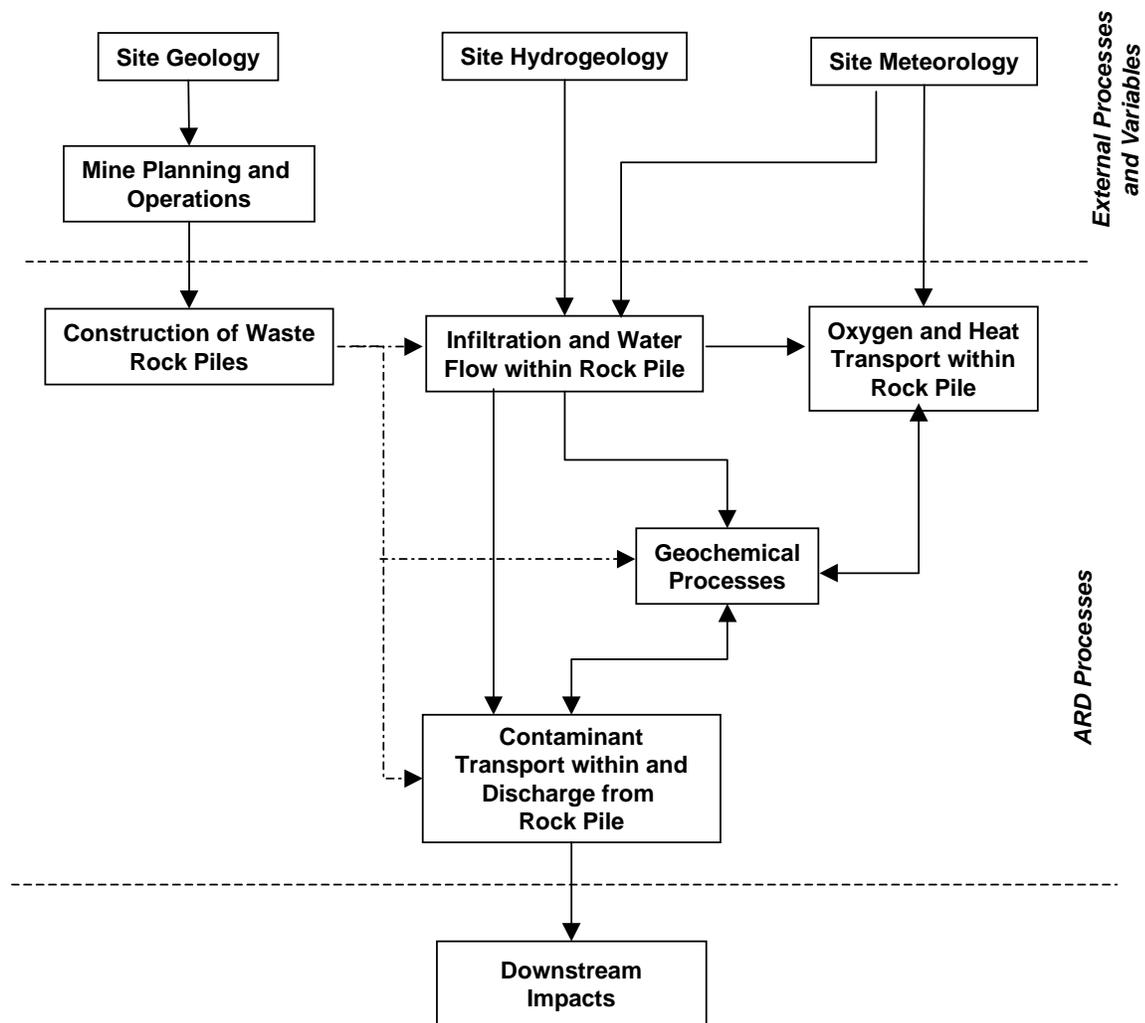
Comprehensive “deterministic” waste rock models need to consider all the processes and links shown in Figure 3.4-1. A deterministic model uses entirely theoretical relationships to describe the processes. Researchers in this field generally agree that some of the processes are well understood (e.g. flow in unsaturated materials, pyrite oxidation mechanism) while other processes have received inadequate attention (e.g. development of flow channels, acid consumption by silicates). Until all processes are well-defined and can be modelled, fully deterministic computer models are unlikely to become available. As a result, most current modelling approaches are partly or completely “empirical” and rely at least partially on site-specific relationships. If assessments of the behaviour of waste rock dumps are required, it should be realized that no reliable modelling approaches are available.

II. Discussion of MEND Research

MEND has directed research on several fronts in an effort to develop predictive models for waste rock piles. This has included field studies, literature reviews, and evaluations of deterministic and empirical approaches to modelling the geochemical behaviour of waste rock.

Field studies have included evaluations of existing models at Heath Steele, New Brunswick (MEND 1.22.1b) and at La Mine Doyon, Québec (MEND 1.14.2; 1.14.3e-f). The former was part of an investigation of an engineered soil cover placed on acid generating rock. The Mine Doyon study was part of an intensive research effort for uncontrolled acid generating waste rock.

Figure 3.4-1 ARD Modelling of Waste Rock Piles



Source: From MEND 1.26.1

MEND 1.11.1 Critical Literature Review of Acid Drainage from Waste Rock

This study produced a summary of the current state of knowledge of information on processes in waste rock dumps while MEND 1.26.1 provided an overview of the types of models available and their applications (Section 3.4.1, Discussion of MEND Research). MEND 1.42.1 was a review exclusively of geochemical processes in waste rock dumps, whereas MEND PA-1 summarized current knowledge of the hydrogeology of waste rock dumps.

MEND 1.27.1a Guide for Predicting Water Chemistry from Waste Rock Piles

This report describes an exclusively empirical approach to predicting leachate chemistry using relationships between easily measured parameters. This study was based on an approach described by Morin and Hutt (1994).

MEND 1.19.2 Scaling Analysis of Acid Rock Drainage

This project evaluated scale-up factors and particle size effects for oxidation of pyrite using fractal mathematics. An important conclusion of the work was the finding that the shrinking core model was predicted to underestimate oxidation rates.

III. Applications and Limitation

Possible applications of waste rock modelling might include:

- Prediction of the overall long-term acidity of waste rock dumps to determine whether acidic leachate will be released, the duration of its release and lag times before the release of leachate. In some cases, this may be adequate, but high metal concentrations may be associated with non-acidic drainage so that prediction of pH alone is not always adequate;
- Prediction of the chemistry of leachate from waste rock dumps in the short and long term to estimate environmental impacts; and
- Evaluation of the effect on leachate chemistry of remedial measures such as waste rock blending, alkaline addition, dry covers and underwater disposal for fresh and oxidized rock.

Currently, only very crude predictions are possible. The first two objectives cannot be met except in uncommon conditions where the waste rock is physically, lithologically, mineralogically and chemically homogeneous. Under these conditions relatively simple relationships can be used to predict leachate chemistry.

The major limitation of all the modelling methods described in Section IV below is that data are not available to validate the predictions. Most modelling approaches are applicable to existing waste rock dumps where field data are available to calibrate the models. Prediction of the behaviour of proposed waste rock dumps is extremely difficult because no field data are available to calibrate the models.

IV. Base Method

The purpose of this section is to provide examples of approaches to waste rock modelling which are currently available to meet the objectives listed in Section III above. Table 3.4-3 summarizes how each model can be used, typical input data and the principal reference source. There is no base method. Modelling methods that are not readily available or are still being developed are not presented. Also, models which may be components of larger models are not discussed. MEND 1.42.1, *Critical Review of Geochemical Processes and Geochemical Models Adaptable for Prediction of Acidic Drainage from Waste Rock*, describes and tested a variety of component models.

**Table 3.4-3
Waste Rock Modelling Approaches**

Modelling Approach	Examples of Input Data Required	Source or Suggested References	Cost for Software
1. Static geochemical testing results	<ul style="list-style-type: none"> • ABA data for the waste rock dump weighted on a mass basis 	AMD-TIME, Ziemkiewicz (1994)	\$0 – Setup for each project
2. Static and kinetic testing results	<ul style="list-style-type: none"> • ABA Data. • Weathering rates from laboratory tests. • Precipitation • Infiltration estimates • Residence time estimates 	MINTEQA2, Morin and Hutt (1994)	\$0 – Setup for each project
3. Field monitoring data	<ul style="list-style-type: none"> • Same as 2, above; and • Multi-year water quality data for waste rock dump, including flow information 	MEND 1.27.1	\$0 – Setup for each project
4. Combinations of empirical relationships and mechanistic models	<ul style="list-style-type: none"> • Pile characteristics • Precipitation • Infiltration estimates • Weathering rates from lab. tests 	Q-ROCK, SRK, Vancouver, BC ACIDROCK, SENES Consultants Ltd., Richmond Hill, ON	Contact sources
5. Physical models	<ul style="list-style-type: none"> • Pyrite oxidation rate • Waste dump dimensions • Particle size distribution • Climate data 	MEND 1.22.1 MEND 1.14.3	?

1. Empirical Methods Using Static Geochemical Testing Results

In a well-mixed dump composed of one major rock type, static geochemical testing results may be used. Static geochemical testing includes but is not limited to acid-base accounting (ABA) since factors such as mineralogy must be factored into the prediction. It can be assumed that if the bulk NP/AP of the dump is less than 1, acidity will be released. For NP/AP less than 2, acid generation is theoretically possible but not known. This approach is not reliable for NP/AP greater than 2 since

any lithological variations must be considered, particularly if acid generating massive sulphide rock is mixed with acid consuming rock. For simple rock mixtures, if NP/AP is greater than 2, acid generation is not expected.

Bennett *et al.* (1997) presented a simple model of waste rock dump geochemistry using a stochastic simulation of waste placement. The model was used to predict the potential for acidic seepage in any vertical section.

2. Empirical Methods Combining Static and Kinetic Test Results

Simple empirical models have been proposed to provide predictions of leachate water quality. A simple approach accounting for kinetic geochemical production rates (from laboratory or field testing), site precipitation, infiltration, leachate residence time and rock particle flushing was described by Morin and Hutt (1994). The next step in this type of modelling is to correlate geochemical production rates with other geochemical characteristics and lithological variations so that the contribution of different rock types can be considered (Day *et al.* 1997).

Chemical predictions in this type of approach are produced using mass balance type calculations. This may result in highly erroneous predictions if the solution is over-saturated. Equilibrium speciation models, such as MINTEQA2 can be used to investigate whether the predicted solution chemistry is over-saturated with respect to any minerals. This commonly occurs under non-acidic conditions where heavy metal concentrations are limited by the solubility of carbonates, hydroxides and oxyhydroxides.

This type of modelling can be performed using spreadsheets.

3. Empirical Methods Using Field Monitoring Data

MEND 1.27.1a, *Guide for Predicting Water Chemistry from Waste Rock Piles*, described a completely empirical approach to predicting future leachate chemistry for existing rock piles based on a method described by Morin and Hutt (1994). The approach involves development of relationships between commonly measured variables such as pH and sulphate, and variables for which predictions are required. Some examples are provided in Figure 3.4-2. These relationships may be related to mineralogy. The method can only be applied at sites with existing large (>1000) monitoring data sets spanning several years. Flow data should also be available.

This approach may be combined with models which use static and kinetic predictive testwork data.

4. Combination of Empirically-Determined Relationships and Mechanistic Models

Models have been developed which attempt to model the main geochemical and physical processes by calibrating the results to existing field and laboratory data. The approach uses mechanistic models for processes which are well understood (e.g. oxygen diffusion), and empirical models for other processes (e.g. sulphide oxidation and acid neutralization). An example is Q-ROCK which models the processes shown in Figure 3.4-3. The model is proprietary and therefore not generally available.

A second model in this class is ACIDROCK (Scharer *et al.* 1994) which uses MEND's RATAP model for reactive tailings as its basis. It is more deterministic than Q-ROCK but still relies on calibration using field data. This model is also proprietary.

Model ARD-UU (Lin *et al.* 1997) is a 3-dimensional, 3-phase kinetic field model. It has not been validated.

5. Physical Models

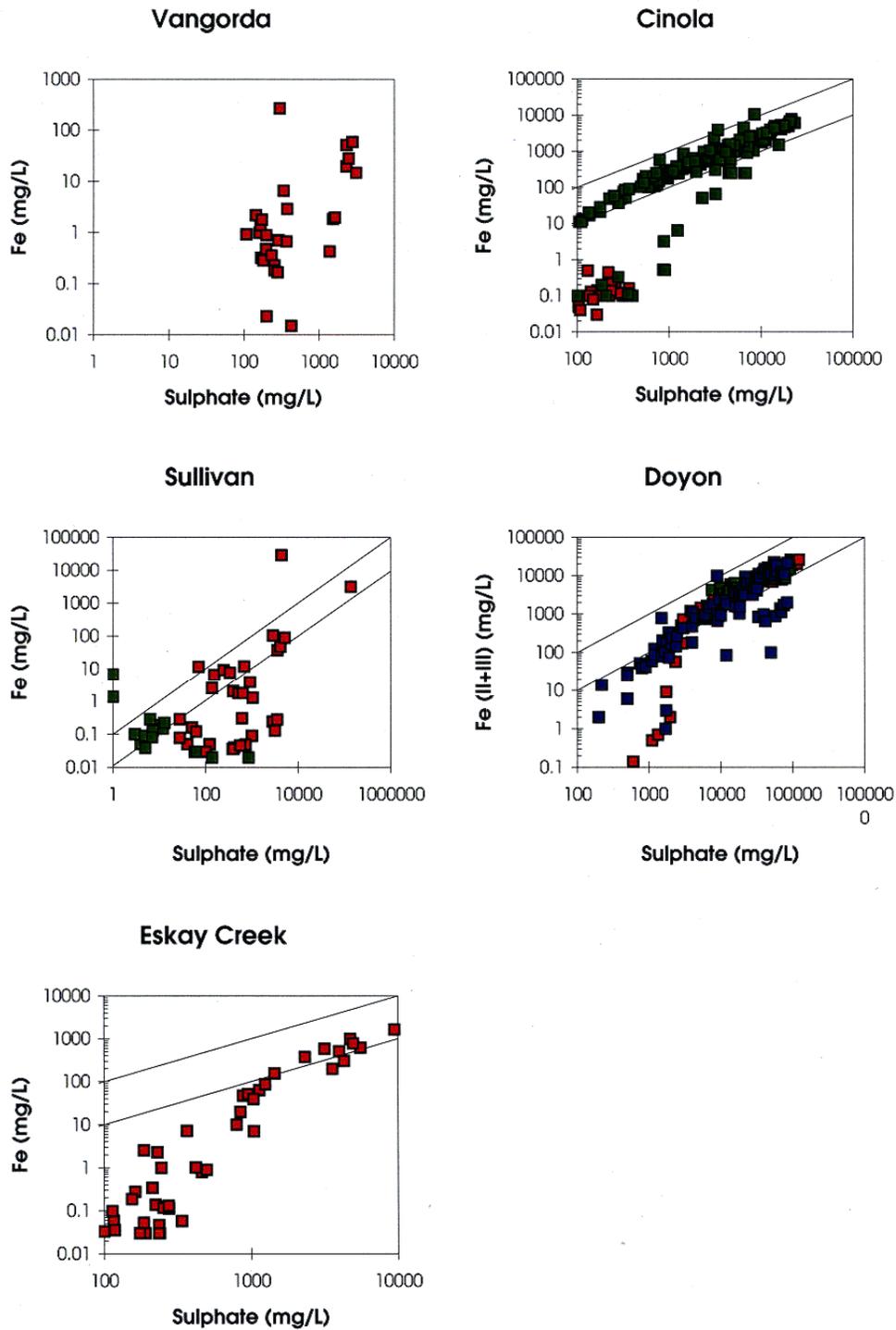
MEND has investigated two models that are limited primarily to physical processes (water, air, oxygen and heat flow) with limited consideration of geochemical processes (except for pyrite oxidation). The FIDHELM model was developed by the Australian Nuclear Science Technology Organization (ANSTO) and has been tested by MEND at the Heath Steele Mine in New Brunswick (MEND 1.22.1a,b). The TOUGH AMD model was developed as part of MEND 1.14.2 which constituted part of the studies at La Mine Doyon in Québec. Neither model is purely deterministic but requires site-specific empirically determined inputs. FIDHELM is the better developed of the models.

The advantage of the purely physical models is that they can be used to investigate specific remediation methods. FIDHELM can be used to evaluate the effect of placement of dry covers on acid generating waste rock.

V. Cost (1998)

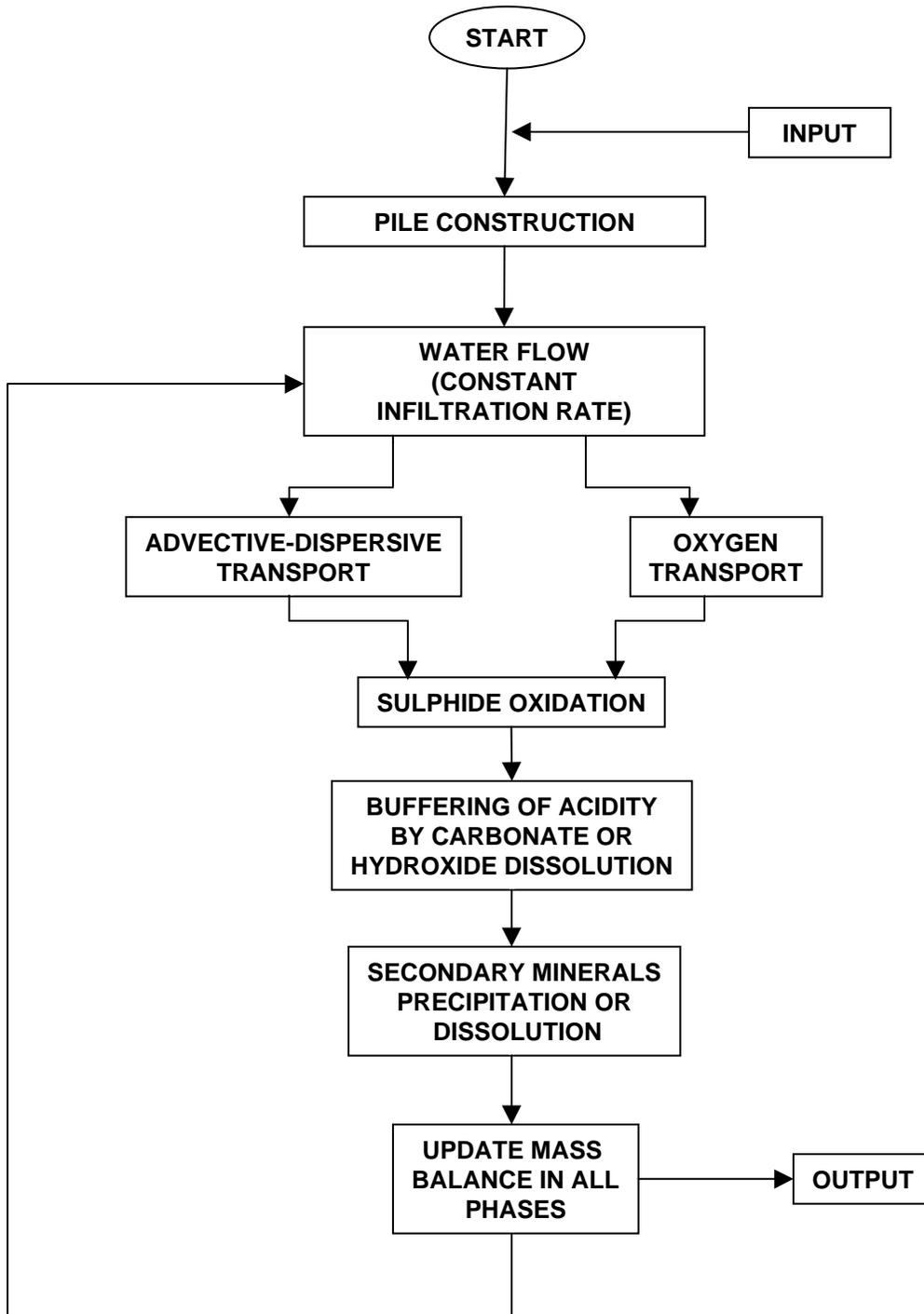
Software costs for the individual models are shown in Table 3.4-4. These amounts do not include the potentially large costs for data collection or time required to manipulate and calibrate the models.

Figure 3.4-2 Examples of Field Monitoring Data – Sulphate versus Iron



Source: MEND 1.27.1a

Figure 3.4-3 Flowchart of Processes Simulated by the Q-ROCK Model



Source: From MEND 1.26.1

VI. MEND and Relevant Publications

- MEND 1.11.1 1991. Critical Literature Review of Acid Drainage from Waste Rock. April.
- MEND 1.14.2c 1997. Heat Transfer during Acid Mine Drainage Production in a Waste Rock Dump, La Mine Doyon (Québec). March 1994, revised August 1997.
- MEND 1.14.2d 1997. Water Budget for the Waste Rock Dump at La Mine Doyon, (Québec). March 1994, revised August 1997.
- MEND 1.14.3 1996. Peer Review of MEND Studies Conducted from 1990 to 1994 on Acid Mine Drainage at Mine Doyon South Waste Rock Dump. November.
- MEND 1.19.2 1995. Scaling Analysis of Acid Rock Drainage. December.
- MEND 1.22.1a 1994. Field Procedures Manual: Gas Transfer Measurement – Waste Rock, Heath Steele New Brunswick. March.
- MEND 1.22.1b 1997. Assessment of Gas Transfer-ANSTO Model at Heath Steele Mines. July 1997.
- MEND 1.26.1 Rock Pile Water Quality Modelling. Phase 1 – Final Draft Report. Prepared for BC Ministry of Energy Mines and Petroleum Resources. October 1995.
- MEND 1.27.1a 1996. Guide for Predicting Water Chemistry from Waste Rock Piles. July.
- MEND 1.42.1 1995. Critical Review of Geochemical Processes and Geochemical Models Adaptable for Prediction of Acidic Drainage from Waste Rock. April.
- MEND PA-1 1995. Hydrology of Waste Rock Dumps. July.

Bennett, M.W., Kempton, J.H. and Maley, P.J. 1997. *Applications of Geological Block Models to Environmental Management*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 1, pp. 291-303.

Lin, C-K., Trujillo, E.M. and White III, W.W. 1997. *A Three-Dimensional, Three-Phase Geochemical Kinetic Model for Acid Rock Drainage*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 2, pp. 479-495.

Day, S., Hope, G. and Kuit, W. 1997. *Waste Rock Management Planning for the Kudz Ze Kayah Project, Yukon Territory: 1. Predictive Static and Kinetic Test Work*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 1, pp. 81-98.

Morin, K.A. and Hutt, N.M. 1993. *The Use of Routine Monitoring Data for Assessment and Prediction of Water Chemistry*. In: Proceedings of the 17th Annual Mine Reclamation Symposium. Port Hardy, British Columbia. 4 to 7 May. pp. 191-201.

Scharer, J.M., Pettit, C.M., Chambers, D. and Kwong, E.C. 1994. *Mathematical Simulation of a Waste Rock Heap*. In: Proceedings of the 3rd International Conference on the Abatement of Acidic Drainage. U.S. Dept of Interior, Bureau of Mines, Special Publication. SP 06A-94, Vol 1, pp. 30-39.

3.4.3 MINE WORKINGS

I. Discussion of Theory

Mine workings are well known as sources of poor quality water which may include strongly acidic, non-acidic or alkaline contaminated drainage. Zinc and arsenic contaminated non-acidic drainages are particularly common for underground mines where neutralization of drainage waters occurs between the mineralized zone and the discharge point. The water may originate from active pumping of operational (or temporarily closed) workings, free drainage of flooded abandoned workings and discharge to groundwater from both operational and abandoned mine workings. Sources of poor quality water in mines may include:

- Oxidation and leaching of reactive minerals in fractured mine walls;
- Oxidation and leaching of broken rock in the mine (e.g. bench rubble, muck, slope failure, collapse, collapse due to pillar removal);
- Oxidation and leaching of backfill (i.e. rock or tailings returned to the mine for support or disposal purposes); and
- Contaminated water entering the pit from other sources (e.g. waste rock runoff, tailings pond seepage, plant site runoff, contaminated groundwater from other sources).

The chemistry of mine water may be altered by mixing with non-contaminated or alkaline water sources (e.g. precipitation, groundwater, introduced surface water, water treatment plant effluent) and interaction with natural acid neutralizing (calcareous or dolomitic) rocks.

The approach taken to modelling of mine water quality should account for these three processes (MEND 1.15.2):

- The chemical load added and removed to and from the mine by various water inputs and outputs;
- The additional load provided by oxidation and leaching of rock in the walls and broken rock; and
- The geochemical evolution of the water while it is in the mine resulting from physical (eg, mixing of waters from different sources), chemical (e.g. precipitation due to changes in pH and oxidation-reduction potential) and biological (e.g. bacterial) processes.

In general, the chemical concentration ($C_{m,t}$) of one dissolved component (m) at a given time (t) is predicted by summing the loads from each source:

$$C_{m,t} = \frac{C_{m,t-1} \cdot V_{t-1} + \sum(Q_{i,t} \cdot c_{m,i,t}) + \sum(M_{j,m,t}) + M_e}{V_t}$$

where: V_t is the total volume of mine water at time t;

$Q_{i,t}$ is the flow of water from the *i*th water source at time t;

$c_{m,i,t}$ is the concentration of the *m*th component in the *i*th water source at time t;

$M_{j,m,t}$ is the mass of the *m*th component added from the *j*th leaching sources at time t;

M_e is a general term indicating removal or addition due to evolution processes.

Loads added are indicated by positive terms. Loads removed are indicated by negative terms. Several different pit lake modelling studies have been reported, for example, Bursey *et al.* (1997) and Atkins *et al.* (1997). However, the models all use the same approach with refinements based on adjusting the final dissolved load using speciation models and physical modelling (e.g. Hamblin *et al.* 1997). Physical factors can be very complex depending on ice formation, wind and temperature of inflowing water. The emphasis on defining the degree of mixing and formation of chemical precipitates is probably not always appropriate given that the source terms may not be well-defined.

Figure 3.4-4 illustrates the various sources and flows schematically for an operating open pit mine.

II. Discussion of MEND Research

MEND 1.15.2b MINEWALL 2.0 – Literature Review and Conceptual Models

This project resulted in development of a computer model (MINEWALL 2.0) to predict water chemistry for operating and closed open pit and underground mines. The project reports include a literature review on previous knowledge of processes in mine walls, an explanation of the principles of the model and a users manual for the software. MINEWALL 2.0 is the only comprehensive software currently available for prediction of mine water.

III. Applications and Limitation

The MINEWALL 2.0 software has been coded to allow many different scenarios to be modelled for most types of mines. These scenarios can include:

- Operating mine with active pumping;
- Operating mine with water loss to groundwater;
- Natural flooding of mine at closure;
- Accelerated flooding of mine at closure; and
- Static conditions after the mine is flooded.

The program has 37 predefined chemical parameters that can be modelled simultaneously. When defining the pit geology, the characteristics of up to 10 geological units may be specified. The main limitations of the software are:

- It has not been validated by comparing long-term predicted behaviour to observed behaviour (a limitation of all mine waste models which lack well-monitored sites for validation);
- Only three open pit mine case histories using the model have been reported;
- The model was developed for open pit mines and has not been tested on underground mines;
- The model uses essentially an empirical approach which requires several site specific assumptions. Some empirical estimates must be obtained by fitting existing condition; and
- The model is not linked to a speciation model such as MINTEQA2 to determine if precipitation occurs.

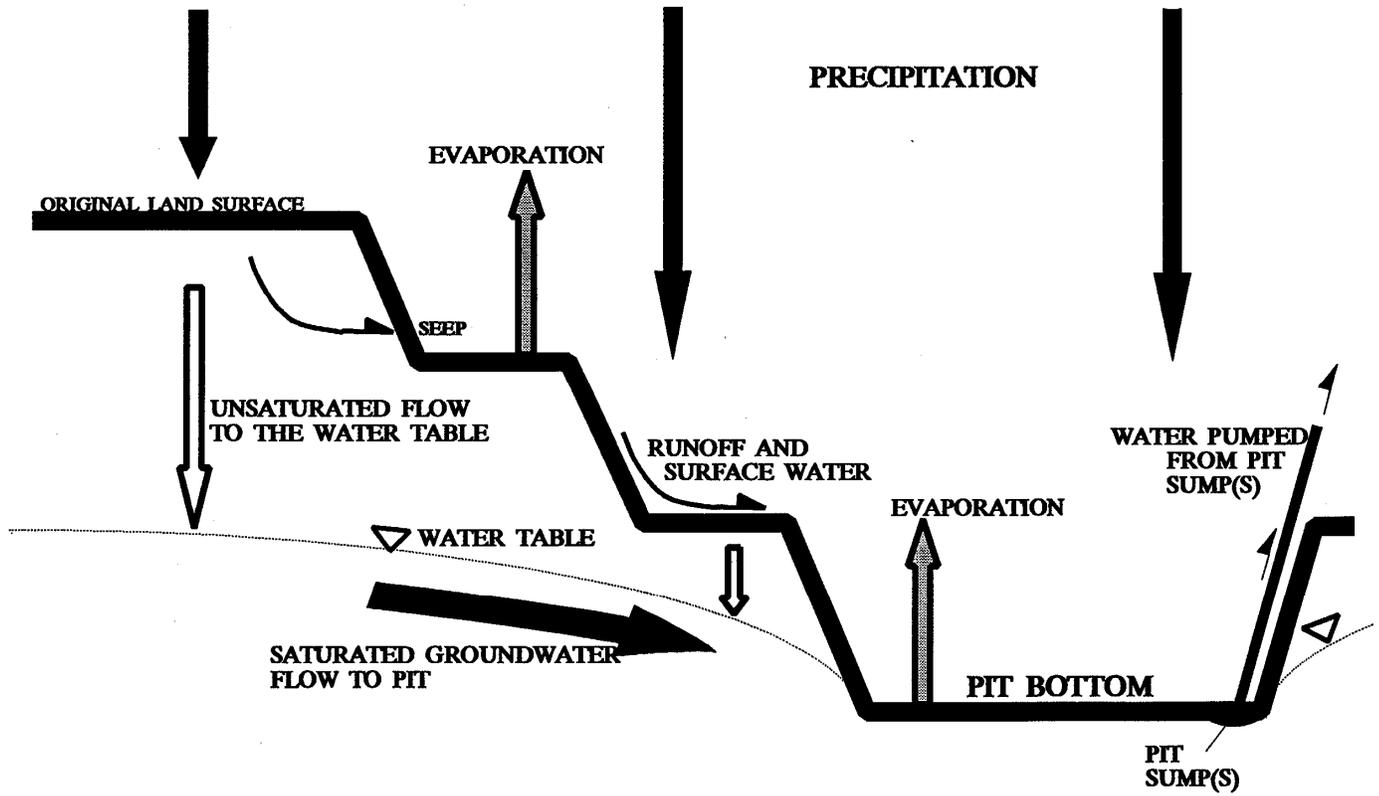
IV. Base Method

A detailed discussion of the use of the MINEWALL 2.0 software is provided in MEND 1.15.2a, *MINEWALL 2.0 – Users Manual*. The software is menu driven, provides access to data input screens resembling spreadsheets and has on-line help. No programming knowledge is required to run the software.

Figure 3.4-5 shows a flowchart for operating the model. Table 3.4-4 provides a checklist of data requirements. The majority of the inputs are relatively straightforward. Some exceptions are:

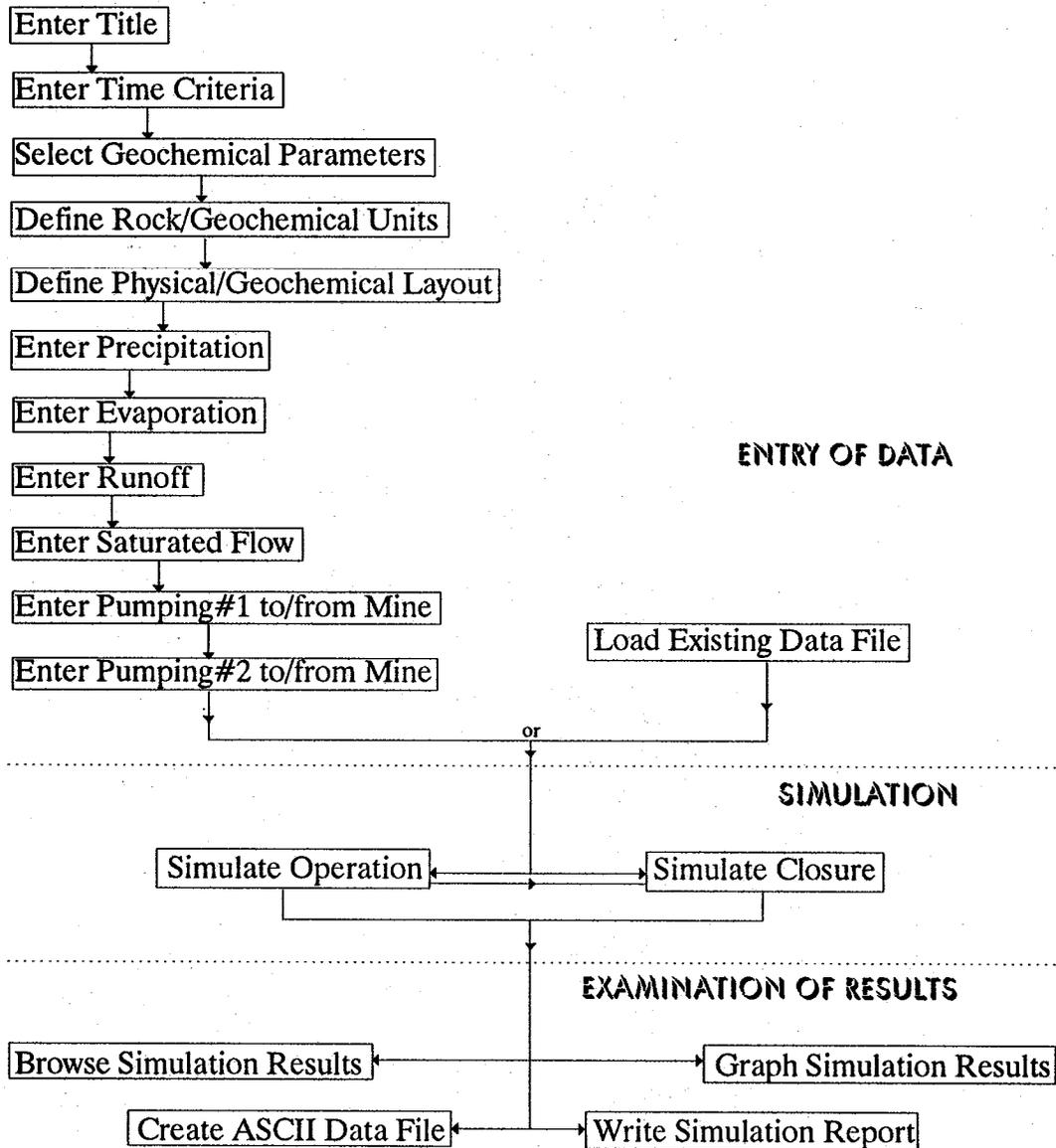
- Percent of fracture surfaces for each rock types flushed by unsaturated flow weekly, monthly, and yearly. These values have been estimated at 20 to 30%, 0 to 5% and 70 to 80%, respectively;
- Average rates of acid production per unit area for pit walls. These can be estimated directly using the Wall Washing Stations field method (Section 3.3.3.2) or estimated from laboratory tests calculated for surface areas;

Figure 3.4-4 Conceptual MINEWALL Model of an Open Pit Mine During Operation



Source: MEND 1.15.2b

Figure 3.4-5 MINEWALL Flowchart for Simulation of an Open-Pit or Underground Mine



Source: MEND 1.15.2a

Table 3.4-4
Checklist of Anticipated Data Requirements⁽¹⁾

PHYSICAL

- Number of geochemically distinct rock units exposed in the walls, their exposed surface area, their orientation within the mine, their elevation, the slope of each unit from horizontal, and the length of time each has been exposed to air
- Physical dimensions of the pit or underground workings including wall-surface areas and mine volumes at selected elevations
- Weekly temperatures throughout the average year
- Weekly precipitation throughout the average year
- Weekly flow of water into/through the mine throughout the average year
- Weekly flow of groundwater from the saturated zone (beneath the water table) into the mine throughout the average year
- Fracture spacing and fracture depth for each rock unit
- Percentage of fracture surface for each rock unit that is flushed by unsaturated flow (see above) weekly, yearly, and not at all during operation
- Inventory of all loose rock in the pit area, including total rock surface area

After Closure

- Weekly flow of any water diverted into the mine upon closure throughout the year
- Estimated steady-state flow of water through the mine and water elevation after closure and re-establishment of hydraulic equilibrium

GEOCHEMICAL

- Average weekly rates of acid generation and metal leaching for a unit area of wall for each rock unit and for each loose-rock pile throughout the average year
- All kinetic and equilibrium controls on water chemistry
- Decay rate of aforementioned rates through decades of years
- Average amount of reactive acid-generating minerals exposed on a unit area of each rock unit
- Average amount of reactive acid-neutralizing minerals exposed on a unit area of each rock unit
- Depth of oxidation within wall fractures for each rock unit
- Occasional full chemical analyses of any groundwater from monitor wells, in-mine seeps, and the cumulative mine water (includes pH, specific conductance, alkalinity, acidity, sulphate, chloride, phosphate, dissolved metals such as calcium and copper, total metals)

⁽¹⁾ Source: MEND 1.15.2c

- Kinetic and equilibrium controls on geochemistry. The model allows metal concentrations to be calculated on a mass basis (without considering controls), assuming a kinetic rate law, assuming a single fixed equilibrium concentration, or by assuming an empirical relationship between pH and metal concentration. The first is the most direct approach and requires no further assumptions; and
- Depth of oxidation in fractures. This estimate requires some knowledge of the penetration of oxygen into fractures. Observations of visible oxidation in pit walls is required. The value may vary from a few millimetres to several metres depending on the nature of the rock fractures.

Results may be browsed either in tabular format or in graphs.

V. Variations

At present, no other models are available in the public domain to predict mine water quality. The MINEWALL approach is relatively simple and not based on complex theory. A spreadsheet approach can be used for modelling if MINEWALL is not suitable for a specific aspect. An example might be the presence of a very large volume of backfill. While MINEWALL does allow broken rock to contribute to mine water chemistry, it does not appear to allow backfill to be easily modelled.

VI. Cost (1998)

The MINEWALL model and user's manual can be obtained on diskette from MEND for \$30.

VII. 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.

Atkins, D., Kempton, J.H., Matin, T. and Maley, P. 1997. *Limnologic Conditions in Three Existing Nevada Pit Lakes: Observations and Modeling Using CE-QUAL-W2*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 2, pp. 697-713.

Burse, G.G., Mahoney J.J., Gale, J.E., Dignard, S.E., Napier, W., Riehm, D. and Downing, B. 1997. *Approach Used to Model Pit Filling and Pit Lake Chemistry on Mine Closure – Voisey's Bay, Labrador*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 1, pp. 255-275.

Hamblin, P.F., Stevens, C.L. and Lawrence, G.A. 1997. *Vertical Transport in Brenda Mines Pit Lake*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 1, pp. 367-383.

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*

-
- 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*

-
- 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
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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
- 1.17.1b Hydrogeochemical Investigation of Reactive Tailings at the Waite Amulet Tailings Site, Noranda, Québec, Phase 2 - 1986 Program, July 1987. \$25
- 1.17.1cV.1 Hydrogeochemical Investigation of Reactive Tailings at the Waite Amulet Tailings Site, Noranda, Québec, Phase 3 - 1987 Program, Volume I Report, May 1988. \$25

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- 1.17.1cV.2 Hydrogeochemical Investigation of Reactive Tailings at the Waite Amulet Tailings Site, Noranda, Québec, Phase 3 - 1987 Program, Volume II - Appendices, March 1988. \$25
- 1.17.1c Sup Hydrogeochemical Investigation of Reactive Tailings at the Waite Amulet Tailings Site, Noranda, Québec, Phase 3 - 1987 Program, Supplementary Report, March 1989. \$25
- 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
- 1.44.1 History of Eskay Creek Mine's Waste-Rock Dump from Placement to Disassembly, May 1997. \$40
- 1.51.1 Quantitative Analysis of Chemical and Biological Kinetics for the Acid Mine Drainage Problem, June 1994. \$30
- 1.51.2 Nonlinear Modelling of Chemical Kinetics for the Acid Mine Drainage Problem and Related Physical Topics, October 1993. \$25
- 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). \$20
- 1.61.2 Acid Mine Drainage in Permafrost Regions: Issues, Control Strategies and Research Requirements, July 1996. \$25

- 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

Associate Projects/Projets associés

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

PREVENTION AND CONTROL/PRÉVENTION ET CONTRÔLE

- 2.11.1a Subaqueous Disposal of Reactive Mine Wastes: An Overview, June 1989. \$25
- 2.11.1a Ben A Preliminary Assessment of Subaqueous Tailings Disposal in Benson Lake, British Columbia, March 1990. \$25
- 2.11.1a And A Preliminary Assessment of Subaqueous Tailings Disposal in Anderson Lake, Manitoba, March 1990. \$25
- 2.11.1a Man A Preliminary Assessment of Subaqueous Tailings Disposal in Mandy Lake, Manitoba, March 1990. \$25
- 2.11.1b Geochemical Assessment of Subaqueous Tailings Disposal in Buttle Lake, British Columbia, March 1990. \$25
- 2.11.1b And Geochemical Assessment of Subaqueous Tailings Disposal in Anderson Lake, Snow Lake Area, Manitoba, September 1990. \$25
- 2.11.1b Man Geochemical Assessment of Subaqueous Tailings Disposal in Mandy Lake, Flin Flon Area, Manitoba, September 1990. \$25
- 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
- 2.11.1d A Critical Review of MEND Studies Conducted to 1991 on Subaqueous Disposal of Tailings, July 1992. \$25
- 2.11.1e Review of MEND Studies on the Subaqueous Disposal of Tailings (1993-95), May 1996. \$25
- 2.11.2a Literature Review Report: Possible Means of Evaluating the Biological Effects of Sub-Aqueous Disposal of Mine Tailings, March 1993. \$25
- 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
- 2.11.5ab Shallow Water Covers - Equity Silver Base Information Physical Variables (diskette included) , May 1996. \$35
- 2.11.5c Geochemical Assessment of the Equity Silver Tailings Pond, August 1996. \$35
- 2.11.9 Design Guide for the Subaqueous Disposal of Reactive Tailings in Constructed Impoundments, March 1998. \$50

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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
- 2.13.2c Inondation artificielle du parc de résidus miniers Solbec Cupra: Études microbiologique et chimique - Rapport final, Mars 1994. \$35
- 2.15.1a Flooding of Pre-Oxidized Mine Tailings: Mattabi Case Study, June 2000. \$35
- 2.15.3 Laboratory Study of Particle Resuspension, Oxidation and Metal Release in Flooded Mine Tailings, November 1998. \$35
- 2.17.1 Review of Use of an Elevated Water Table as a Method to Control and Reduce Acidic Drainage from Tailings, March 1996. \$35
- 2.18.1 Review of Water Cover Sites and Research Projects, September 1997. \$30
- 2.20.1 Evaluation of Alternate Dry Covers for the Inhibition of Acid Mine Drainage from Tailings, March 1994. \$30
- 2.21.1 Development of Laboratory Methodologies for Evaluating the Effectiveness of Reactive Tailings Covers (diskette included), March 1992. \$40
- 2.21.2 Field Evaluation of the Effectiveness of Engineered Soil Covers for Reactive Tailings: Volume 1- Laboratory and Field Tests & Volume 2 - University Contracts, October 1993. \$60 (both reports)
- 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. \$40
- 2.22.2a Évaluation en laboratoire de barrières sèches construites à partir de résidus miniers, mars 1996. \$30
- 2.22.2b Études de laboratoire sur l'efficacité de recouvrement construites à partir de résidus miniers, avril 1999. \$30
- 2.22.2c Études sur les barrières sèches construites à partir de résidus miniers, Phase II - Essais en place (inclus disquettes) novembre 1999. \$40
- 2.22.4aE Construction and Instrumentation of a Multi-Layer Cover Les Terrains Aurifères, February 1999. \$40
- 2.22.4aF Construction et instrumentation d'une couverture multicouche au site Les Terrains Aurifères Québec, Canada, février 1999. \$40
- 2.22.4bE Field Performance of the Les Terrains Aurifères Composite Dry Covers, March 2000. \$40
- 2.22.4bF Suivi du Comportement du Recouvrement Multicouche Les Terrains Aurifères, mars 2000. \$40
- 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
- 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. \$35
- 2.23.3 Investigation of the Porous Envelope Effect at the Fault Lake Tailings Site, May 1995. \$40
- 2.24.1 Manual of Methods Used in the Revegetation of Reactive Sulphide Tailings Basins, November 1989. \$20
- 2.25.1a Reclamation of Sulphide Tailings Using Municipal Solid Waste Compost: Literature Review and Recommendations, July 1992. \$25
- 2.25.1b Reclamation of Sulphide Tailings Using Municipal Solid Waste Compost: Laboratory Studies, June 1995. \$35
- 2.25.3 Evaluation of the Use of Covers for Reducing Acid Generation from Strathcona Tailings, September 1997. \$40
- 2.31.1a Heath Steele Waste Rock Study, Phases I to III, March 1992. \$40
- 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
- 2.35.2a Evaluation of Techniques for Preventing Acidic Rock Drainage: First Milestone Research Report, October 1993. \$35
- 2.35.2b Evaluation of Techniques for Preventing Acidic Rock Drainage: Final Report, January 1997. \$40
- 2.36.1 Review of In-Pit Disposal Practices for the Prevention of Acid Drainage - Case Studies, September 1995. \$40
- 2.36.2a Hydrogeochemistry of Oxidised Waste Rock from Stratmat Site, N.B., March 1999. \$40
- 2.36.2b Hydrology and Solute Transport of Oxidised Waste Rock From Stratmat Site, N.B. March 1999. \$40
- 2.36.3 Assessing the Subaqueous Stability of Oxidized Waste Rock, April 1999. \$40
- 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. \$40
- 2.37.2 Methods for Delaying the Onset of Acidic Drainage – A Case Study Review. Final Report, March 2001. \$25
- 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
- 3.21.1b Metals Removal from Acid Mine Drainage by Ion Exchange, June 1995. \$35
- 3.21.2a Metals Removal from Acidic Drainage - Chemical Method, March 1996. \$20
- 3.22.1 Canada-Wide Survey of Acid Mine Drainage Characteristics, December 1994, (includes diskette). \$40
- 3.32.1 Acid Mine Drainage - Status of Chemical Treatment and Sludge Management Practices, June 1994. \$30
- 3.42.2a Characterization and Stability of Acid Mine Drainage Treatment Sludges, May 1997. \$40
- 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
- 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, March 1994. \$30

Associate Projects/Projets associés

- 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

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- 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

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- 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
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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

- BC.01 5th Annual BC MEM - MEND 2000 Metal Leaching /ARD Workshop. *Risk Assessment and Management*. Vancouver, December 1998. \$50
- 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.