



MEND MANUAL
VOLUME 5 – TREATMENT
MEND 5.4.2e

Editors:

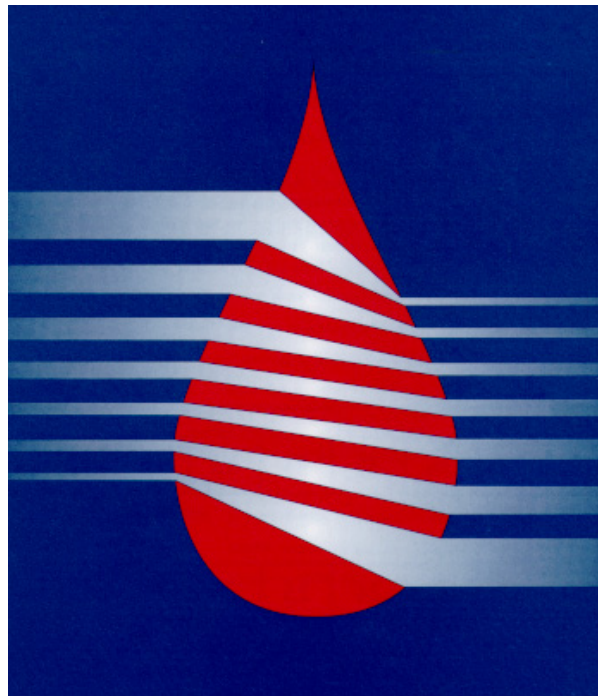
Gilles A. Tremblay
Charlene M. Hogan

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 5

**TREATMENT
ACTIVE AND PASSIVE**

AUTHORS OF THE MEND MANUAL

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

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

ACKNOWLEDGEMENTS

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 David Orava of SENES Consultants Limited (Active Treatment) and Randy Fischer of URS Norecol Dames & Moore (Passive Treatment) in the preparation of Volume 5 of the Manual.

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

Bernard Aubé	Noranda Inc.
Geneviève Béchar	Natural Resources Canada (CANMET)
Grant Feasby	Lakefield Research Limited
Craig Ford	Inmet Mining Corporation
Quentin Hamilton	Knight Piésold Consulting Engineers
Walter Kuit	Cominco Ltd.
Nural Kuyucak	Golder Associates Ltd.

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:

Gilles Tremblay

Natural Resources Canada (CANMET)
555 Booth Street
Ottawa, Ontario
K1A 0G1

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 * 10 ⁶)	Waste Rock (tonnes * 10 ⁶)
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 * 10 ⁶)	Waste Rock (tonnes * 10 ⁶)
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.

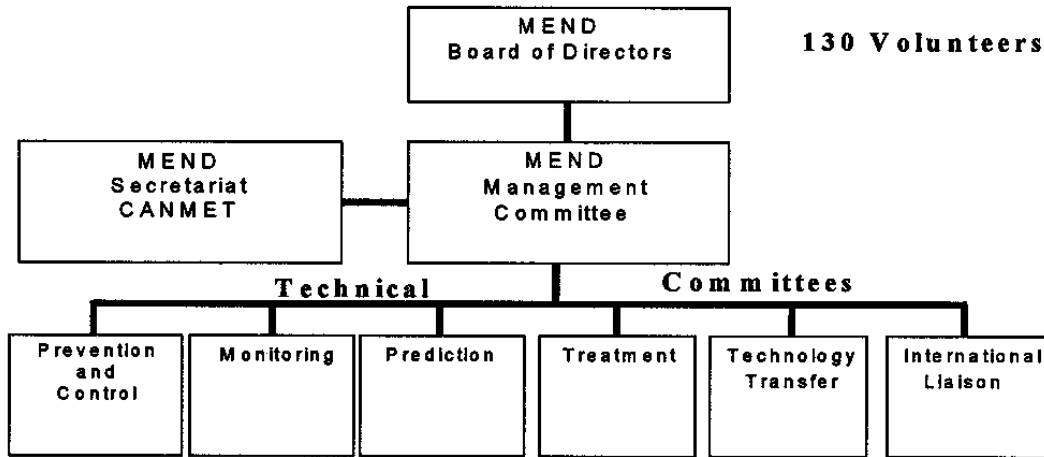
To ensure transparency of the program, it was also recommended that all research reports produced be made available to the partners and the public. Prior to their release the reports were critically reviewed and edited to enhance credibility and provide quality.

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.

Bryan, V. 1998. Personal Communication.

Gustafsson, H. 1997. *A Summary of Swedish AMD Experience*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 4, pp. 1895-1903.

Harries, J. 1997. *Estimating the Liability for Acid Mine/Rock Drainage in Australia*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 4, pp. 1905-1918.

Lewis, B.A. and Gallinger, R.D. 1999. *Poirier Site Reclamation Program*. In: Sudbury '99 – Mining and the Environment II Conference Proceedings. Sudbury, Ontario. 13 to 17 September. Vol 2, pp. 439-448.

Murray, G.S.C., Ferguson, K.D. and Brehaut, C.H. 1995. *Financial and Long Term Liability Associated with AMD*. In: Proceedings of the 2nd Australian Acid Mine Drainage Workshop. Charters Towers, Queensland. 28 to 31 March. pp. 165-177.

Price, B. 1995. *Defining the AMD Problem: II. An Operator's Perspective*. In: Proceedings of the 2nd Australian Acid Mine Drainage Workshop. Charters Towers, Queensland. 28 to 31 March. pp. 17-19.

Richmond, T.C. 1995. *Abandoned Mine Land Reclamation Costs in Wyoming*. In: Sudbury '95 – Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 3, pp. 1221-1230.

Skousen, J. 1995. *Prevention of Acid Mine Drainage*. In: Acid Mine Drainage Control and Treatment. (Eds. J.G. Skousen and P.F. Ziemkiewicz). West Virginia University and the National Mine Land Reclamation Center, Morgantown, West Virginia. pp. 13-14.

Zinck, J.M. and Aubé, B. 1999. *Optimization of Lime Treatment Processes*. In: Proceedings of the 31st Annual Meeting of the Canadian Mineral Processors. Ottawa, Ontario. 19 to 21 January. pp. 75-93.

TABLE OF CONTENTS

AUTHORS OF THE MEND MANUAL	i
Gilles Tremblay	ii
DISCLAIMER	iii
PREFACE	iv
5.0 TREATMENT	1
5.1 INTRODUCTION	1
5.2 ACTIVE TREATMENT.....	3
5.3 PASSIVE TREATMENT	46
5.0 TREATMENT	1
5.1 INTRODUCTION	1
5.2 ACTIVE TREATMENT	3
5.2.1 Chemical Treatment.....	3
I. Discussion of Theory	3
II. Discussion of MEND Research	6
III. Applications and Limitations.....	9
IV. Base Method	10
V. Variations.....	12
VI. Cost	15
VII. MEND and Relevant Publications.....	20
5.2.2 Metal Recovery/Recycling.....	21
I. Discussion of Theory	21
II. Discussion of MEND Research	22
III. Applications and Limitations.....	25
IV. Base Method	26
V. Variations.....	26
VI. Cost	27
VII. MEND and Relevant Publications.....	34
5.2.3 Treatment Byproducts.....	35
I. Discussion of Theory	35
II. Discussion of MEND Research	35
III. Applications and Limitations.....	44
IV. Base Method	44
V. Variations.....	45
VI. Cost	45
VII. MEND and Relevant Publications.....	45
5.3 PASSIVE TREATMENT	46
5.3.1 Discussion of Theory	46
5.3.1.1 Anoxic Limestone Drains (ALDs).....	46
5.3.1.2 Aerobic Wetland Treatment Systems	47
5.3.1.3 Passive Anaerobic Treatment Systems	50
5.3.1.4 Biosorption Treatment Methods	52
5.3.2. Discussion of MEND Research	53
5.3.3 Applications and Limitations.....	62

5.3.3.1	Anoxic Limestone Drains (ALDs).....	63
5.3.3.2	Aerobic Wetland Treatment Systems	64
5.3.3.3	Passive Anaerobic Treatment Systems	67
5.3.3.4	Biosorption Treatment Methods	71
5.3.4	Base Method	71
5.3.4.1	Anoxic Limestone Drains (ALDs).....	71
5.3.4.2	Aerobic Wetland Treatment Systems	73
5.3.4.3	Passive Anaerobic Treatment Systems	81
5.3.4.4	Biosorption Treatment Methods	84
5.3.5	Variations.....	85
5.3.5.1	Anoxic Limestone Drains (ALDs).....	85
5.3.5.2	Open Limestone Channels	86
5.3.5.3	Aerobic Wetland Treatment Systems	86
5.3.5.4	Passive Anaerobic Treatment Systems	87
5.3.5.5	Passive <i>In Situ</i> Treatment Methods.....	87
5.3.5.6	Hybrid Active/Passive Treatment Systems.....	90
5.3.6	Costs.....	96
5.3.6.1	Anoxic Limestone Drains (ALDs).....	97
5.3.6.2	Aerobic Wetland Treatment Systems	97
5.3.6.3	Passive Anaerobic Treatment Systems	97
5.3.6.4	Bioreactor Treatment Systems	98
5.3.6.5	Biosorption Treatment Systems.....	99
5.3.7	MEND and Relevant Publications.....	99

APPENDICES

- APPENDIX A – MEND Contractors
- APPENDIX B – Bibliography
- APPENDIX C – MEND Reports

LIST OF TABLES

Table 5.1-1	Treatment Projects	1
Table 5.2.1-1	Common Sulphide Minerals and Oxidation Products	4
Table 5.2.1-2	ARD Treatment Alkalis	4
Table 5.2.1-3	Estimated Annual Operating Costs for Conventional and HDS Treatment Plants	19
Table 5.2.2-1	Summary of AMD Treatment Options Considered for the Britannia Mine	31
Table 5.2.3-1	Leachate Extraction Procedure (Toxicity Test) for Two Neutralization Sludges.	36
Table 5.2.3-2	Chemical Composition of Sludge Solids	39
Table 5.2.3-3	Sludge Leaching Characteristics, Ontario LEP	42
Table 5.2.3-4	Sludge Leaching Characteristics, Modified Ontario LEP.....	43
Table 5.3-1	Guidelines and Case Studies Data for Wetland Areas.....	76

Table 5.3-2	Typical Cost Estimates for Constructed Wetlands	98
-------------	---	----

LIST OF FIGURES

Figure 5.2.1-1	Generalized Reaction Rates for Calcium and Magnesium Hydroxides and for Corresponding Limestones	7
Figure 5.2.1-2	Metal Hydroxide Solubilities	8
Figure 5.2.1-3	Process Flowsheet – Batch Treatment Process	11
Figure 5.2.1-4	Process Flowsheet – Conventional Treatment Process	13
Figure 5.2.1-5	Process Flowsheet – High Density Sludge Treatment Process	14
Figure 5.2.1-6	The Geco Process	16
Figure 5.2.1-7	Flow Rate versus Capital Cost for Conventional Treatment.....	17
Figure 5.2.1-8	Flow Rate versus Capital Cost for HDS Treatment	18
Figure 5.2.2-1	Simplified Flowsheet of a Proposed Process Comprising Lime Neutralization and Ion Exchange	23
Figure 5.2.2-2	Plan of Britannia Mine Site	29
Figure 5.2.2-3	Britannia Biosulphide Configuration	30
Figure 5.2.2-4	Temporary Minewater Treatment System.....	33
Figure 5.2.2-5	Preferred Active Treatment System – Block Diagram.....	33
Figure 5.3-1	Schematic of a Complete ALD Treatment System.....	48
Figure 5.3-2	Makela Test Cells	58
Figure 5.3-3	Design of the West Fork Passive Treatment System.....	72
Figure 5.3-4	Longitudinal-Section and Cross-Section of the Anoxic Limestone Drain	73
Figure 5.3-5	Decision Flowchart for Designing and Sizing Passive Mine Drainage Treatment Systems.....	77
Figure 5.3-6	Typical Stage, Aerobic Constructed Wetlands for Acid Minewater Purification	78
Figure 5.3-7	Examples of Staged, Aerobic Wetlands for Acid Minewater Purification.....	79
Figure 5.3-8	Simplified Flow Chart for Designing Staged, Aerobic Constructed Wetlands	80
Figure 5.3-9	Details and Sections of a Passive Acid Drainage Treatment System.....	82
Figure 5.3-10	Schematic of a Permeable Reactive Wall at a Mine-Tailings Site	89
Figure 5.3-11	Simplified Process Diagram Biological Metal and Sulphate Reducing Plant at Budelco	94
Figure 5.3-12	Upflow Anaerobic Sludge Blanket Reactor Schematic	95

5.0 TREATMENT

5.1 INTRODUCTION

MEND projects on the treatment of acidic drainage, also referred to as ARD and AMD, have added to the state of knowledge and expanded the understanding of technical and other issues that need to be taken into consideration in the responsible selection, operation and management, and decommissioning of treatment systems. The MEND program included expenditures in the order of \$1.5 million for projects on the active and passive treatment of acidic drainage.

MEND projects specifically carried out in the area of treatment are listed in Table 5.1-1.

**Table 5.1-1
Treatment Projects**

MEND Project	Title
3.11.1a-d	Treatment of Acidic Seepages Using Wetland Ecology and Microbiology
3.12.1a	Assessment of Existing Natural Wetlands Affected by Low pH, Metal Contaminated Seepages (Acid Mine Drainage)
3.12.2	Panel Wetlands - A Case History of Partially Submerged Pyritic Uranium Tailings Under Water
3.14.1	Review of Passive Systems for Treatment of Acid Mine Drainage
3.14.2*	Anoxic Drains to Separate AMD from Clean Runoff
3.21.1a	Study on Metals Recovery/Recycling from Acid Mine Drainage
3.21.1b	Metals Removal from Acid Mine Drainage by Ion Exchange
3.21.2a	Metals Removal from Acidic Drainage – Chemical Method
3.22.1	Canada-Wide Survey of Acid Mine Drainage Characteristics
3.32.1	Acid Mine Drainage – Status of Chemical Treatment and Sludge Management Practices
3.41.1a*	In Situ Treatment of AMD
3.41.2*	Biological Fixation of Sulphides
3.42.2a	Characterization and Stability of Acid Mine Drainage Treatment Sludges
3.42.2b	The Effect of Process Parameters and Aging on Lime Sludge Density and Stability
5.8.1	Economic Evaluation of Acid Mine Drainage Technologies
6.3	A Critique of Japanese Acid Mine Drainage Technology

* Open file report

The allowable concentrations for water quality parameters, such as metals in effluents from acidic drainage treatment systems, are defined under approvals and permits required by the Provinces as well as in standards in federal regulations. The limits are scientifically-based and put in place to protect the receiving environment including aquatic life and water use. The principal objectives in treating ARD are to neutralize free acidity and reduce the concentrations of contaminants of concern (i.e. metals, total dissolved solids) to very low levels so that the effluent quality is acceptable for recycle or release.

The active chemical treatment of acidic drainage is typically accomplished using lime-based processes which vary in application from the batch treatment of ponded acidic water to continuous treatment using a high density sludge type treatment plant. In these processes, lime is used to raise the pH of the acidic streams and remove dissolved metals through precipitation and coprecipitation. These processes result in the formation of a gypsum/metal hydroxide/carbonate sludge which requires disposal. Other alkalis are used for pH adjustment to a lesser degree (i.e. limestone, sodium hydroxide, and sodium carbonate) along with other metallic salts for the removal of specific contaminants (i.e. iron salts for arsenic removal and barium salts for radium removal).

At historic sites where acidic drainage prevention and control technologies cannot be effectively applied or would be too costly, the long-term active treatment may be the most cost-effective approach. At new sites, ARD prevention and control measures would be expected to eliminate or minimize acid generation. However, in some circumstances, treatment may still be required.

Treatment of acidic drainage at closed mines can represent a commitment to substantial expenditures. At mine properties where lime-based chemical treatment is required over the long term (e.g. one hundred years or more) the net present value (NPV) of capital and operating costs can be considerable.

Natural passive removal of metals and other contaminants from surface and ground water has long been observed. Pyrite occurrences in coal beds and bog iron ore (limonite) deposits are examples of natural passive systems. Contaminant reductions in nature can occur passively through a variety of abiotic (non-biological) and biologically mediated processes, including oxidation and reduction, biological alkalinity production, metals remineralization as hydroxides and sulphides, plant uptake, and filtering and sedimentation. Whether these natural reactions will occur depends on the site-specific conditions, such as topography, oxidation state (aerobic or anaerobic), and water chemistry.

Natural treatment processes can be imitated in man-made treatment systems, such as constructed wetlands, passive anaerobic treatment systems, and anoxic lime drains. The principal goal of a passive treatment system is the long term, sustainable neutralization of acid and immobilization of metals at low cost and with relatively minor labour, raw material, or energy inputs. The challenge facing the mining industry is to design passive treatment systems capable of consistently reducing contaminant concentrations in a time frame measured in hours or days, rather than centuries.

To date, Canadian experience indicates passive systems, alone, 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 in Canada. However, due in part to MEND's contributions, the quantum leap in knowledge and experience gained during the decade of the 1990s has resulted in a breakthrough in the applicability of passive AMD treatment methods.

Today, passive systems provide a wide variety of AMD treatment options, ranging from completely passive systems for treating small seeps, to treated effluent polishing systems, to integrated passive/active hybrid systems. Clearly, passive treatment is not applicable for all sites; however, it is now possible to base feasibility evaluations of passive AMD treatment on a far superior understanding of design principles and an ever broadening experience base.

The following sections further describe active treatment systems (Section 5.2) and passive treatment systems (Section 5.3) that are in use, as well as those that are under development.

5.2 ACTIVE TREATMENT

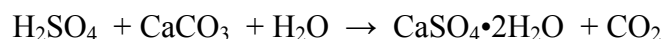
5.2.1 CHEMICAL TREATMENT

I. Discussion of Theory

MEND 3.22.1 characterized AMD in 72 untreated streams. The study showed that AMD streams typically have elevated sulphate and metal concentrations with low to near neutral pH. Near neutral pH AMD streams typically have elevated sulphate levels and may have metal concentrations in excess of objectives. Factors determining the quality and rate of release of AMD were indicated to be site specific and governed by chemical reactions and biological catalysis at the sulphide oxidation sites and along downstream flowpaths. AMD flowrates which often include local streams and runoff were shown to be typically higher in the spring and fall than in the summer and winter due to seasonal precipitation/runoff rate factors.

Sulphide oxidation leads to the solubilization of metals as shown in Table 5.2.1-1. Chemical treatment involves the addition of an alkali material to raise the pH of the AMD stream to levels that cause the solubilized metals to precipitate. Alkalis which can be used in the chemical treatment of AMD include: hydrated lime (calcium hydroxide), lime (calcium oxide), limestone (calcium carbonate), caustic soda (sodium hydroxide) and soda ash (sodium carbonate). A comparative listing of commonly used alkalis is provided in Table 5.2.1-2.

Most chemical treatment facilities use reagents derived from limestone. The reactivity of limestone is dependant on its CaCO_3 or CaO content and the presence of other materials such as SiO_2 and MgO . Commercially available high calcium limestone has a CaCO_3 content in excess of 90%. The reaction of CaCO_3 and sulphuric acid is as follows:



**Table 5.2.1-1
Common Sulphide Minerals and Oxidation Products**

Element	Mineral		Ionic Oxidation Products
Iron	FeS ₂	Pyrite/Marcasite	Fe ²⁺ , Fe ³⁺ , SO ₄ ²⁻ , H ⁺
	Fe _{1-x} S	Pyrrhotite	
Zinc	ZnS	Sphalerite	Zn ²⁺ , SO ₄ ²⁻
Copper	CuFeS ₂	Chalcopyrite	Cu ²⁺ , Fe ²⁺ , Fe ³⁺ , SO ₄ ²⁻ , H ⁺ Cu ²⁺ , SO ₄ ²⁻ , H ⁺ Cu ²⁺ , Fe ²⁺ , Fe ³⁺ , SO ₄ ²⁻ , H ⁺ Cu ²⁺ , SO ₄ ²⁻ , H ⁺
	CuS	Covellite	
	Cu ₅ FeS ₄	Bornite	
	Cu ₂ S	Chalcocite	
Arsenic	FeAs S	Arsenopyrite	Fe ²⁺ , Fe ³⁺ , AsO ₄ ³⁻ , SO ₄ ²⁻ , H ⁺ AsO ₄ ³⁻ , SO ₄ ²⁻ , H ⁺ AsO ₄ ³⁻ , SO ₄ ²⁻ , H ⁺
	As S	Realgar	
	As ₂ S ₃	Orpiment	
Lead	PbS	Galena	Pb ²⁺ , SO ₄ ²⁻
Nickel	NiAs	Niccolite	Ni ²⁺ , AsO ₄ ³⁻ , H ⁺ Fe ²⁺ , Fe ³⁺ , Ni ²⁺ , SO ₄ ²⁻ , H ⁺
	(Fe, Ni) ₉ S ₈	Pentlandite	
Mercury	HgS	Cinnabar	Hg ²⁺ , SO ₄ ²⁻ , H ⁺
Cobalt	CoAsS	Cobaltite	Co ²⁺ , AsO ₃ ²⁻ , AsO ₄ ³⁻ , SO ₄ ²⁻ , H ⁺

Source: Modified from SRK (1989)

**Table 5.2.1-2
ARD Treatment Alkalis**

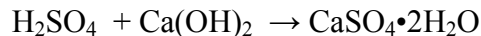
Reagent	Chemical Formula	Equivalent Basicity Factor ⁽¹⁾	Rounded Cost of Basicity ⁽²⁾
High calcium lime	CaO	1.00	1.0
High calcium hydrate	Ca(OH) ₂	1.33	1.6
Dolomitic lime	CaO·MgO	0.86	1.0
Dolomitic hydrate	Ca(OH) ₂ ·MgO	1.02	1.4
High calcium limestone	CaCO ₃	1.79	0.3
Dolomitic limestone	CaCO ₃ ·MgCO ₃	1.65	0.3
Sodium hydroxide (caustic soda)	NaOH	1.43	8.8
Soda ash	Na ₂ CO ₃	1.89	3.8
Magnesium oxide	MgO	0.72	3.4
Magnesium hydroxide	Mg(OH) ₂	1.04	4.9

Source: Modified from Stokowski *et al.* (1992)

Notes: (1) Relative weight of reagent in comparison to CaO
(2) Relative cost in comparison to CaO (transportation cost excluded)

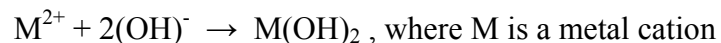
The reaction product gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) will be present in both soluble and precipitate form; the ratio depending on solution concentration. Supersaturation of gypsum leads to the scale formation seen at many chemical treatment plants. The above reaction occurs slowly due to the limited surface of the limestone and the coating of the limestone surfaces by reaction products. The reaction slows considerably as the pH is raised and approaches neutral. As such, limestone may be useful in applications where AMD flowrates are low (offering long residence times) and where acidic pH only needs to be raised to near neutral.

The AMD stream pH usually needs to be raised substantially above 6 to effectively precipitate metals. This can be accomplished using a second stage of alkaline addition, or by using calcined forms of limestone in place of crushed limestone. Calcined forms of limestone are collectively referred to as lime (i.e. quicklime, and hydrated lime). Quicklime is produced by burning calcium carbonate in a kiln at approximately 1000°C to drive off CO_2 gas. Quicklime is more effective in treating acidity if it is first slaked (reacted) with water to form a hydrated lime ($\text{Ca}(\text{OH})_2$) slurry. Quicklime presents several operational concerns including the risk of chemical burns to personnel and the need for dry storage. Hydrated lime is the most commonly used alkali. The neutralization reaction involving sulphuric acid and hydrated lime is as follows:



The neutralization effectiveness of lime is dependent upon its CaO content and reactivity. As indicated in Figure 5.2.1-1 the retention time required to neutralize sulphuric acid using a high calcium lime is short in comparison to the retention time required for lime with greater magnesium content.

The neutralization of AMD causes dissolved metals to precipitate from solution through the formation of metal hydroxide/carbonate precipitates which settle to form sludge. The characteristics of treatment sludge vary depending on the properties of the AMD, and the treatment process and neutralizing reagents used. The precipitation of heavy metals from solution can be expressed as follows:



Most metals precipitate as hydrated metal complexes $\text{M}(\text{OH})_2 \cdot n\text{H}_2\text{O}$. The solubilities of these metal hydroxides are related to the pH of the treated water as indicated by the theoretical solubility curves for metal hydroxides in single metal systems provided in Figure 5.2.1-2. In general, minimum solubilities of metal hydroxides occur in the range of pH 7 to 10. The minimum solubility values and corresponding pH's can vary considerably in complex systems such as acidic drainages.

Ferrous iron (Fe^{2+}) present in AMD can be oxidized to ferric iron (Fe^{3+}) through aeration of the AMD stream. This is beneficial as ferric oxy-hydroxide treatment sludges are more stable than ferrous hydroxide sludges. Moreover, coprecipitation phenomena associated with iron oxidation and precipitation reactions can have beneficial effects on metal concentrations produced by neutralization.

Lime-based metal precipitation technology is proven and has been shown to be effective in consistently providing acceptable effluent quality under normal operating conditions. Lime-based technology is applied in the following three forms: batch treatment of ponded water; continuous treatment using a conventional lime-based treatment plant; and continuous treatment using a high density sludge type treatment plant.

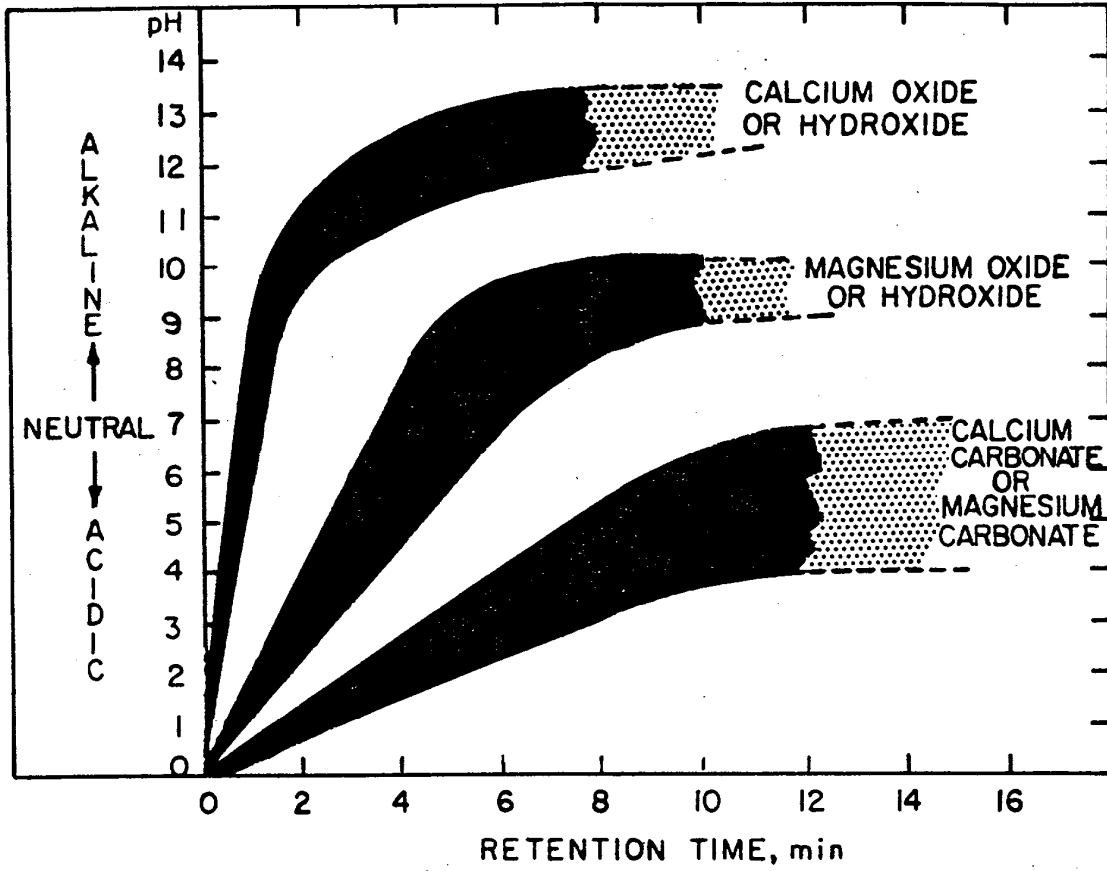
Batch treatment and conventional treatment processes involve lime addition and the settling of precipitates to produce a low density sludge. A high density sludge (HDS) type process also involves lime addition but includes the use of a clarifier for liquid-solid separation and the controlled recycling of a portion of the sludge to the treatment process to promote sludge densification. HDS-type processes represent the state-of-the-art for the active treatment of AMD.

Most jurisdictions provide upper and lower limits on effluent pH to protect aquatic communities from highly acidic or alkaline conditions. As such, the pH of the effluent from a lime-based AMD treatment process may need to be lowered prior to its release to the receiving environment. Sulphuric acid and carbonic acid are commonly used to adjust the pH of effluent prior to discharge. The required pH of final effluent typically needs to be in the range of 6 to 9.

II. Discussion of MEND Research

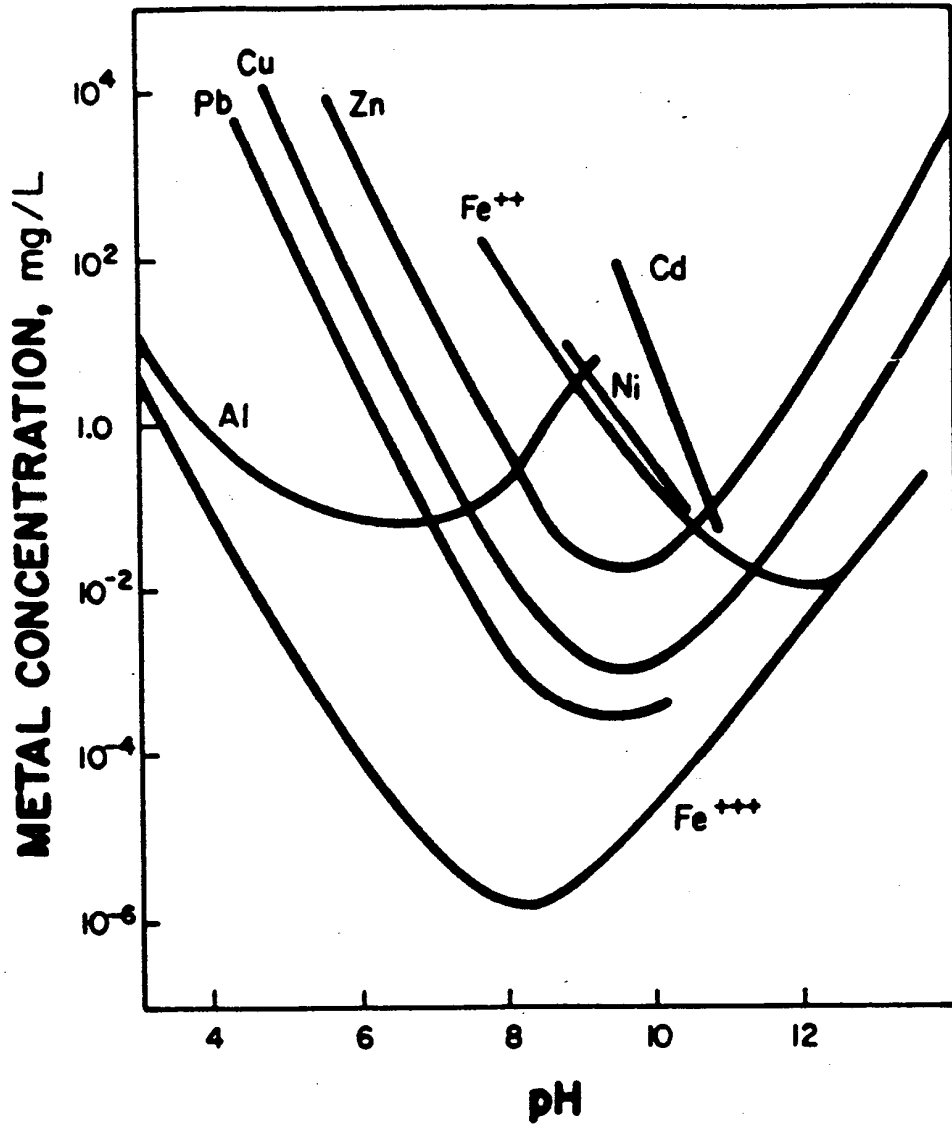
MEND 3.32.1 investigated the status of chemical treatment and sludge management practices and involved an intensive review of treatment methods and chemical treatment research. The objective was to investigate and review: the state-of-the-art of chemical treatment; the implications of long-term AMD treatment; capital and operating costs for chemical treatment facilities; and the direction of AMD chemical treatment research. The report is a useful reference regarding AMD chemical treatment processes including: the batch treatment of ponded acidic water; conventional lime treatment; the HDS-type lime-based treatment process; and an enhanced HDS lime-based treatment process. The latter was evaluated to assess the potential benefit of further dewatering sludge produced by an HDS-type process.

Figure 5.2.1-1 Generalized Reaction Rates for Calcium and Magnesium Hydroxides and for Corresponding Limestones



Source: MEND 3.32.1

Figure 5.2.1-2 Metal Hydroxide Solubilities



Source: MEND 3.32.1

III. Applications and Limitations

Considerable experience has been attained in the design, operation, and maintenance of chemical treatment systems which consist of four principal components: AMD collection, AMD treatment, treated water release or recycle, and treatment sludge disposal.

An AMD treatment system has to be compatible with site specific conditions including the AMD collection and storm water management system, and allowable limits on the timing and quality of treated discharge. The control of inflows to mechanical treatment plants is important as these facilities do not operate efficiently under low or extreme inflow conditions. The cost to develop a suitable water management system and undertake the required civil works (i.e. ditches, dams, pumps and pipelines) can be considerable at some mine properties. At active mine sites, the stream flow or ponded water that requires treatment often consists of a mixture of AMD and diverse flows such as mine water, process water, tailings area decant, seepage, and runoff. The cessation of mining or metallurgical activities typically reduces the volume of water to be treated and alters influent contaminant concentrations.

There are three types of lime-based treatment processes:

1. Batch treatment of ponded AMD by the addition of alkali material to the ponded water;
2. Conventional treatment of acidic water flows by continuous addition of lime; and
3. The high density sludge (HDS) type chemical treatment process.

These processes are used in Canada with the conventional treatment process being most common. The best application of these processes is site-specific, however, as a guide:

- Batch treatment is most suitable for the treatment of low flows of acidic water that can be collected, stored and treated on an infrequent basis (e.g. every three to six months);
- A conventional treatment plant is most suitable for continuous treatment where suitable conditions and sufficient space are available for the disposal of the low density sludge; and
- A HDS-type treatment plant is most suitable for continuous treatment and where sludge disposal space/conditions present a challenge. HDS plants produce significantly smaller volumes of sludge in comparison to conventional plants.

Concerns have been raised about the long-term chemical stability of treatment sludges and about potential liability arising from the dissolution of heavy metals contained in sludge. Studies to date largely indicate that sludge will remain stable if properly disposed and if geochemical conditions are maintained (MEND 3.42.2a; MEND 3.42.2b).

The volume of sludge requiring disposal can be large at some mine properties. In extreme conditions, the cumulative volume of sludge produced over the long term from the conventional lime-based chemical treatment of AMD from tailings can exceed the volume of the stored tailings. As part of chemical treatment system planning, provisions need to be made to provide for adequate and suitable sludge storage space, or consideration of methods to reduce sludge volume. Increasing the solids content of sludge can have a very significant impact. For instance, increasing the sludge solids content from 1% to 10% produces about one tenth the total sludge volume. An increase in solids content from 15% to 30% reduces sludge volume by roughly half. Conventional lime-based treatment plants produce a low density sludge typically in the range of <1 to 5% solids. These sludges tend to be fluffy and difficult to dewater. HDS treatment plants can produce treatment sludge with solids contents in excess of 25%.

The *Guidelines for Metal Leaching and Acid Rock Drainage at Minesites in British Columbia* by Price and Errington (1998) indicate that while long-term chemical treatment can be effective in protecting the off-site environment, its use can result in significant long-term environmental risk, liability and land alienation. As such, chemical treatment is acceptable if the following conditions are met and mitigative closure works are undertaken:

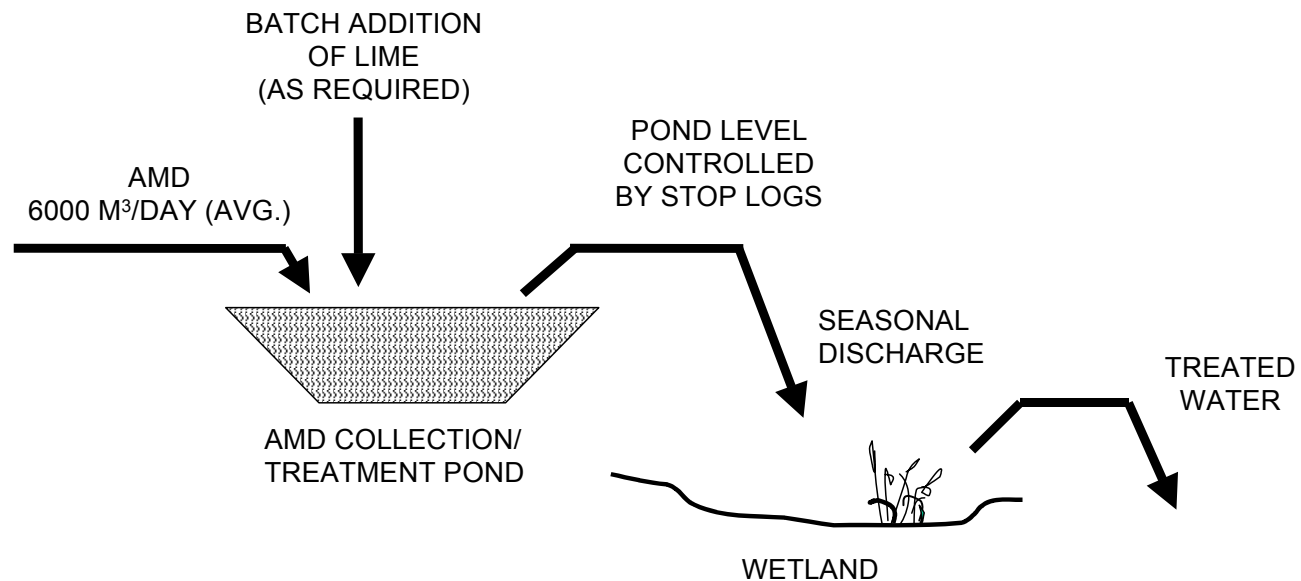
- If AMD prevention strategies such as underwater disposal are shown to have more environmental risk or shown to be uneconomic, unreliable or ineffective; or
- When chemical treatment is offered as a contingency measure where there is uncertainty regarding the long-term performance of the primary AMD mitigation strategies or in metal leaching and AMD prediction.

Price and Errington (1998) also indicate that supporting documentation to the mine review process regarding a treatment system should comprise detailed engineering, cost projections, consideration of relevant ecological factors and a comprehensive risk management plan.

IV. Base Method

Figure 5.2.1-3 provides a schematic flowchart representative of the batch treatment of ponded acidic water. As indicated, acidic flows are impounded and lime is added in batch to the pond. It is important that the lime be well distributed within the pond. Labour and equipment requirements for lime addition are normally minimal. Treatment sludge is allowed to settle in the pond, and excess water is decanted from the pond and released, possibly seasonally, to a wetland for passive treatment and polishing. Sludge can remain in the pond if there is sufficient capacity. If pond storage capacity is limited, the sludge would need to be relocated to a sludge management area. It is important that the precipitates be allowed to settle in the pond and not be transported out in the pond overflow - suspended treatment sludge particles from a treatment facility can be a source of elevated metal concentrations in the final treated effluent. Figure

Figure 5.2.1-3 Process Flowsheet – Batch Treatment Process



Source: MEND 3.32.1

5.2.1-4 provides a schematic flowsheet representative of a conventional lime-based treatment plant. As shown, the AMD stream is mixed with lime slurry in a neutralization tank. Single or two stage neutralization may be used depending upon the chemical nature of the drainage and the neutralization alkalis involved - the figure depicts a two stage neutralization circuit. Flocculant may be added to the settling pond to promote settling prior to discharge. Some of the overflow from the water pond can be recycled and used for reagent make-up water (e.g. in a slaker used to produce a lime slurry). However, in some instances this practice may increase maintenance requirements due to a build-up of calcium carbonate and calcium sulphate in the reclaim system - this can be overcome in many circumstances by avoiding excess lime addition and through the use of other scale control measures (e.g. chemical treatment).

V. Variations

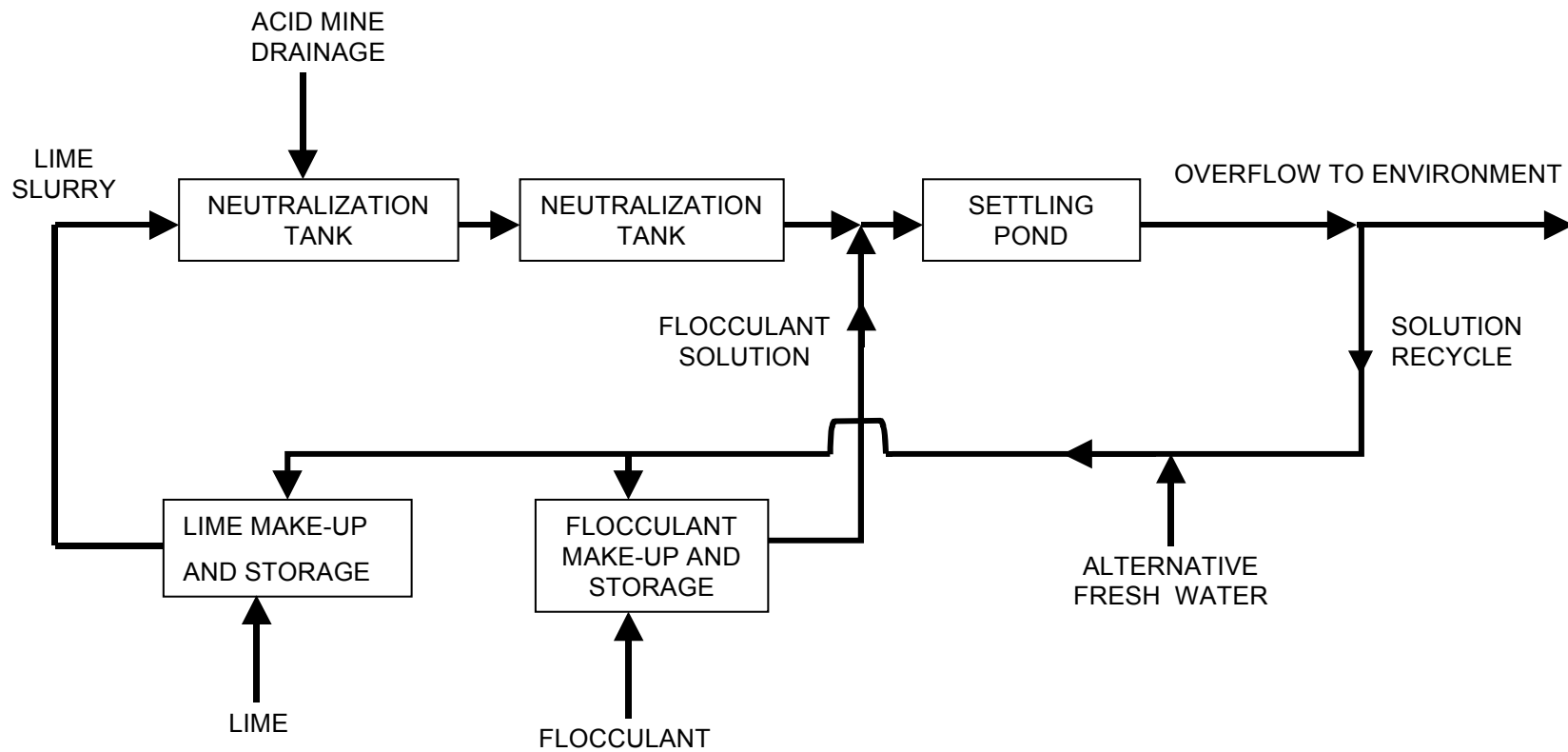
An HDS-type process involves the controlled recycle of sludge to improve the physical properties of the treatment sludge, in particular, its solids content. A flowsheet for a HDS-type process is provided in Figure 5.2.1-5. The process operates as follows. The AMD inflow stream is combined with lime/sludge slurry in the neutralization circuit and the overflow is discharged to a thickener. Flocculant is added to assist in the settlement of precipitates within the thickener. A controlled amount of the thickener underflow sludge is recycled back to the lime/sludge mix tank. A portion of the overflow from the HDS thickener may be recycled for reagent make-up. The remainder of the thickener overflow is discharged to a polishing pond and/or recycled.

The mixing of the thickener underflow sludge with lime slurry alters the physical nature of the sludge particles. HDS sludge particles may be larger than those from the conventional, low density sludge process. The sludge particles are more defined, rounded and smooth. As a result, HDS sludge is more dense and drains more readily to achieve a high solids content. Excess sludge (thickener underflow) is removed and disposed.

A well operated HDS process can also produce a better effluent quality than conventional treatment. This is a result of the superior physical properties of the sludge solids and good settling rates. Classification efficiency and responsiveness to flocculants are much better than with low density sludge (Kuit 1999).

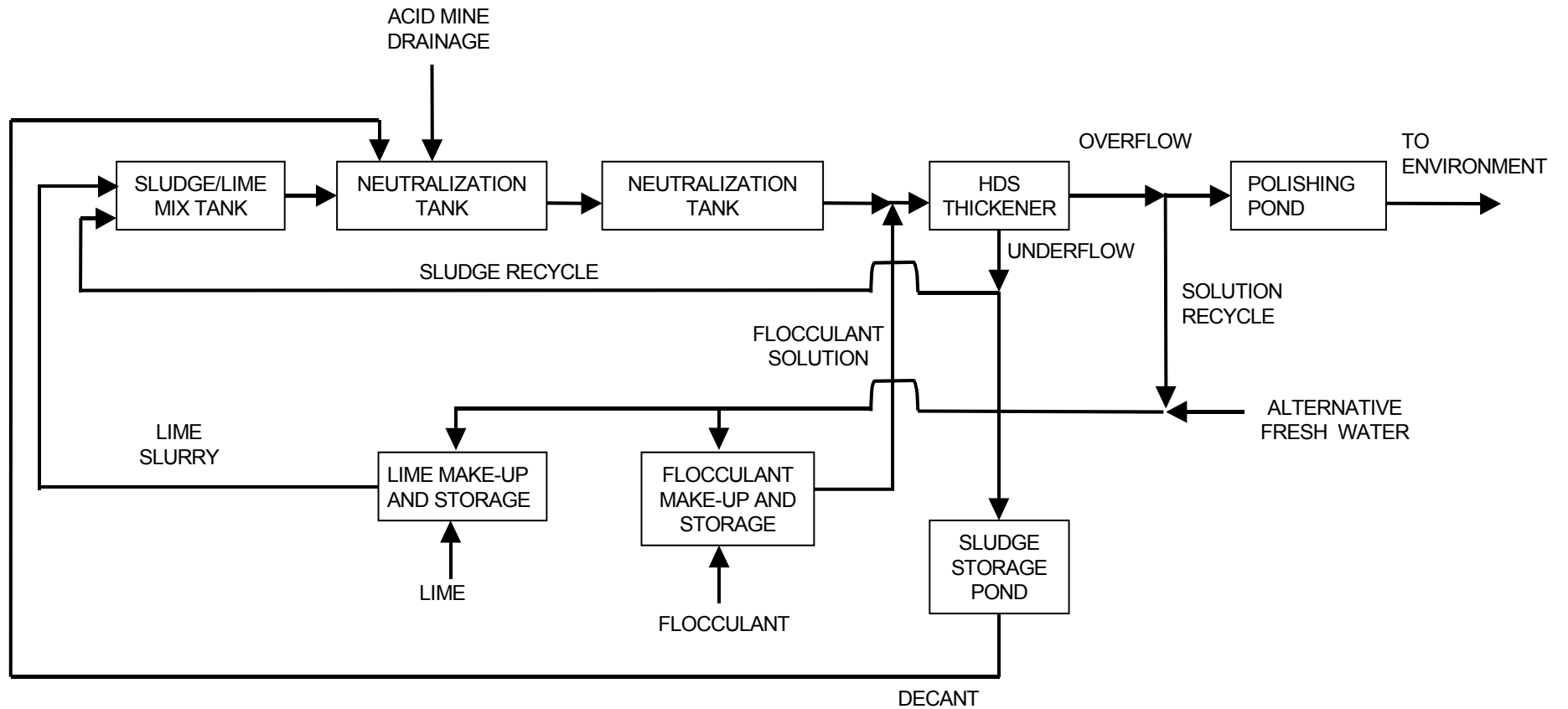
The Geco HDS process (Figure 5.2.1-6) uses two main reactors and a clarifier. AMD fed to the first reactor comes into contact with recycled sludge. The overflow from the first reactor is mixed with lime slurry and aerated in the second reactor. Precipitates are settled in the clarifier with a portion of the sludge recycled to the first reactor. The balance of the sludge is disposed. The conventional low-density sludge treatment plant at the Geco Mine in northern Ontario was replaced by the Geco HDS process in April 1995 - seven months prior to mine closure. Aubé and Payant (1997) report that the process has consistently produced low viscosity sludge with densities greater than 20% solids, and as high as 29% solids during some periods of operation.

Figure 5.2.1-4 Process Flowsheet – Conventional Treatment Process



Source: Modified from MEND 3.32.1

Figure 5.2.1-5 Process Flowsheet – High Density Sludge Treatment Process



Source: Modified from MEND 3.32.1

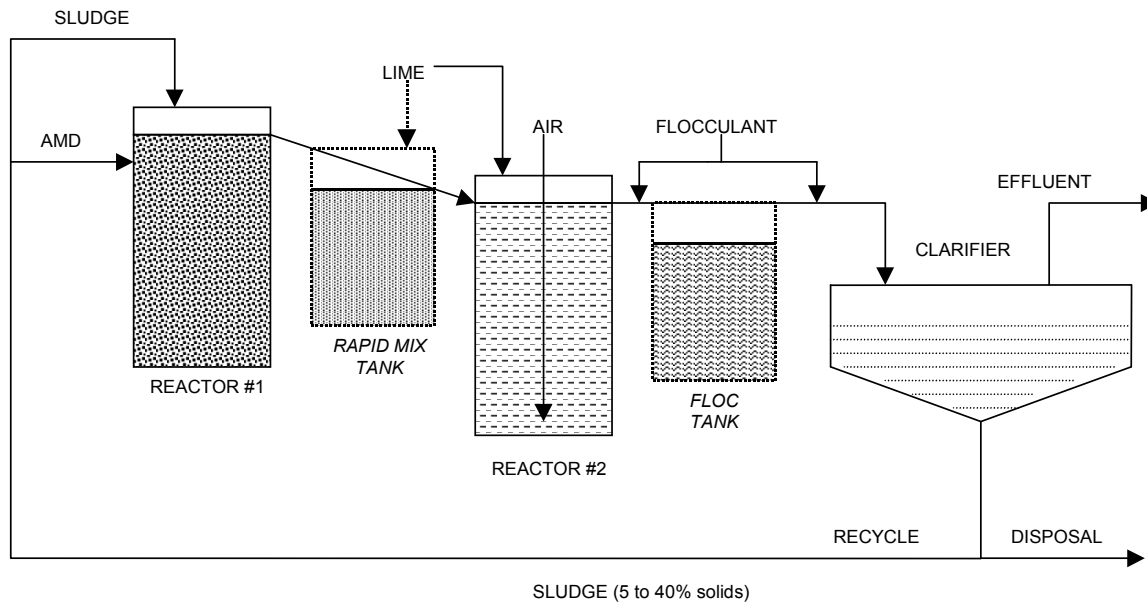
The Geco HDS process provides a good example of the application of a new scientific-based process to an existing treatment plant. The conventional treatment plant at the Geco Mine had operated for approximately 20 years before being replaced. The clarifier originally designed for the conventional treatment was modified so that it could handle heavier sludge from the HDS process. The low viscosity and reduced volume of sludge produced by the Geco HDS process are beneficial for sludge disposal which involves the pumping of the dense sludge to the tailings management area.

VI. Cost

MEND 3.32.1 provided a method to estimate the capital and annual operating costs of conventional and HDS treatment plants on an order-of-magnitude basis. Cost estimates were based on the application of conventional and HDS processes to AMD streams having average hourly AMD flowrates of 55, 190, and 820 m³/hr under net acidity concentrations of 50, 500 and 5,000 mg/L - where net acidity includes free and metal acidity. The estimated costs cannot account for site specific conditions and requirements and as such are meant to provide preliminary cost estimates. Site-specific requirements can add considerably to the estimated costs.

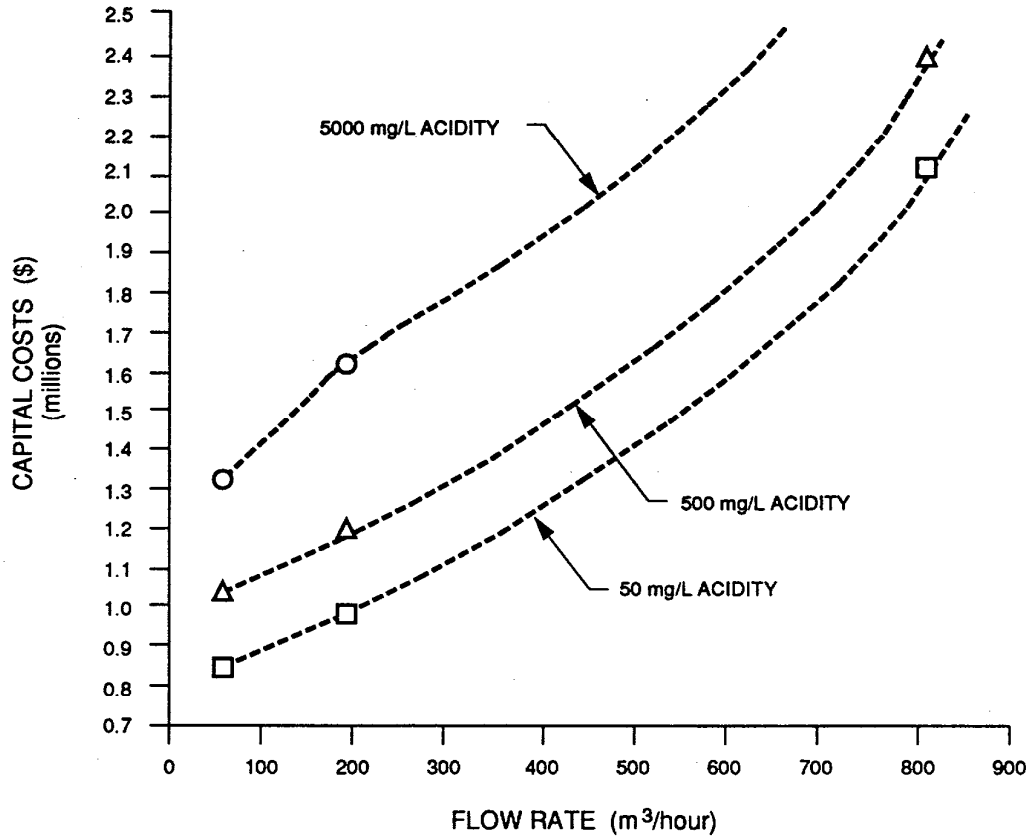
The capital cost estimating curves for conventional and HDS-type treatment plants presented in MEND 3.32.1 are reproduced in Figures 5.2.1-7 and 5.2.1-8. The horizontal axes of the capital cost curves represent the average hourly flowrate (m³/hr) of AMD to the treatment plant. The vertical axes of the curves represent the capital cost of the treatment plant. Capital costs are based on the construction of a new treatment plant including a building and foundations; AMD neutralization circuit equipment; solid/liquid separation equipment; treatment plant services; and allowances for a polishing pond, instrumentation and electrical components. The estimated construction costs include a 13% allowance for overheads, a 15% allowance for engineering, procurement, and project management, a 2% allowance for spare parts, and a contingency of 25%. Capital costs do not include the cost of developing a site (storm) water management and AMD collection system, site infrastructure including access, electrical power distribution to the treatment plant, associated investigative and permitting costs, the cost for a sludge management area and tertiary water treatment (e.g. CO₂ injection to adjust final effluent pH).

Figure 5.2.1-6 The Geco Process



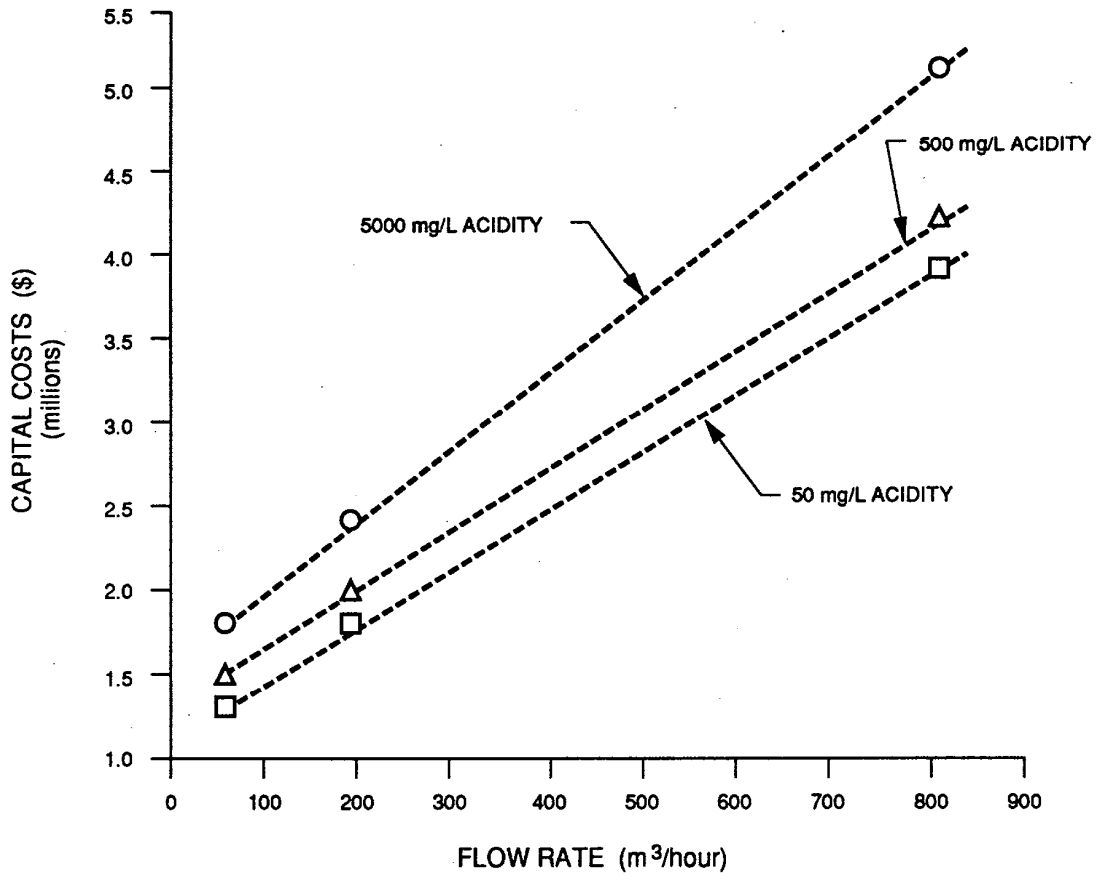
Source: Aubé and Payant (1997)

Figure 5.2.1-7 Flow Rate versus Capital Cost for Conventional Treatment



Source: MEND 3.32.1

Figure 5.2.1-8 Flow Rate versus Capital Cost for HDS Treatment



Source: MEND 3.32.1

The order-of-magnitude annual cost for treatment plant operation can be estimated by referring to the cost estimating tables and cost calculations included in Appendices C and D, respectively of MEND 3.32.1. For reference, selected treatment plant operating costs are presented in Table 5.2.1-3. The estimated operating costs account for the costs of reagents, flocculant, operating labour, maintenance labour and consumables, electrical power, a 10% indirect cost allowance, and a 10% contingency.

Table 5.2.1-3
Estimated Annual Operating Costs
for Conventional and HDS Treatment Plants

Average Flowrate of AMD to be Treated	Type of Lime Treatment Process	Annual Operating Cost (order-of-magnitude)		
		Net Acidity 50 mg/L	Net Acidity 500 mg/L	Net Acidity 5,000 mg/L
55 m ³ /hr (900 L/min)	Conventional	\$160,000	\$220,000	\$500,000
	HDS	\$190,000	\$250,000	\$530,000
190 m ³ /hr (3,200 L/min)	Conventional	\$220,000	\$390,000	\$1,100,000
	HDS	\$270,000	\$450,000	\$1,200,000
820 m ³ /hr (13,600 L/min)	Conventional	\$530,000	\$910,000	\$4,200,000
	HDS	\$640,000	\$1,000,000	\$4,300,000

MEND 3.32.1 also provides modelled capital and annual operating costs for an enhanced HDS process involving the use of additional mechanical dewatering equipment. Section 7.0 of the report examines the cost implications of long-term (perpetual) chemical treatment through the use of four case studies. The results of the case studies indicate that:

- The Net Present Value (NPV) of capital costs, and long-term operating and sludge disposal costs can be substantial. Sludge disposal costs may represent a significant portion of the total cost.
- The batch treatment of AMD is cost beneficial when conditions permit its use.

Readers comparing the costs of HDS and conventional treatment systems are reminded that the cost estimates included in this Volume, and in the MEND references are generic, order of magnitude type cost estimates. The capital and operating costs associated with treatment systems (which include all aspects from water management through the treatment process and facility, to sludge disposal) are highly dependent upon site-specific factors and the design/operating criteria selected. As such, decision-making regarding the use of a HDS type or conventional treatment system needs be based on detailed cost estimates which take into account a range of information from treatability tests using representative drainage samples from the site, sludge characteristics, other site-specific factors, to regulatory and corporate requirements. This is an area that requires multi-disciplinary input.

Key issues relevant to the evaluation of chemical treatment strategies, including the NPV of long-term costs, are further discussed in Orava *et al.* (1995).

VII. MEND and Relevant Publications

MEND 3.22.1 1994. Canada-Wide Survey of Acid Mine Drainage Characteristics. December.

MEND 3.32.1 1994. Acid Mine Drainage - Status of Chemical Treatment and Sludge Management Practices. June.

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

MEND 3.42.2b 1999. The Effect of Process Parameters and Aging on Lime Sludge Density and Stability. February.

Aubé, B. and Payant, S. 1997. *The Geco Process: A New High Density Sludge Treatment for Acid Mine Drainage*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 1, pp. 167-179.

Kuit, W. 1999. Cominco Ltd. Personal Communication. February.

Orava, D., Hallam, C.E. and Swider, R. 1995. *Evaluating Alternative Long-Term Strategies for Treatment of Acid Mine Drainage*. In: Sudbury '95 – Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 2, pp. 505-514.

Price, W.A. and Errington, J.C. 1998. Guidelines for Metal Leaching and Acid Rock Drainage at Minesites in British Columbia. Reclamation Section, Mines Branch. Ministry of Energy and Mines. British Columbia. August.

SENES Consultants Limited and Lakefield Research Limited 1998. Report on Technologies Applicable to the Management of Canadian Mining Effluents. Report prepared for Environment Canada, Environmental Protection Services, Minerals and Metal Division. December.

Steffen, Robertson and Kirsten (B.C.) Inc. (SRK), Norecol Environmental Consultants and Gormely Process Engineering 1989. Draft Acid Rock Drainage Technical Guide. Volume I. British Columbia AMD Task Force. August.

Stokowski, S., Shapiro, A. and Pincomb, A. 1992. *Industrial Minerals for Acid Neutralisation*. Industrial Minerals, November.

5.2.2 METAL RECOVERY/RECYCLING

I. Discussion of Theory

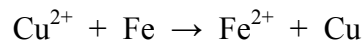
The recovery/recycling of metals from AMD streams is not currently undertaken to a great extent but offers potential benefits including the minimization or elimination of treatment waste byproducts, revenue from the sale of recovered metals which can be used to offset treatment costs, and improved effluent quality.

MEND studies regarding metal recovery/recycling from AMD have ranged from literature reviews to extensive laboratory testwork leading to the development of multi-step process flowsheets for the recovery of metals. The prospect of recovering and recycling useful metals from AMD is technically promising, however, the economic recovery of metals remains a challenge for most applications.

Processes that have been investigated to recover metals from AMD include: the modification of lime-based treatment processes with the objective of removing metals from an AMD stream prior to lime treatment; solvent extraction; ion exchange; biosorption; and electrowinning. Ion exchange and selective precipitation were identified as potentially useful techniques which require further research. In concept, these techniques could be used to selectively remove metals and sulphate before neutralization, and remove soluble metals remaining in solution after neutralization.

Modified chemical treatment processes have been studied and include: copper cementation with iron; selective iron removal; and selective metal recovery (i.e. Ni, Zn). MEND 3.21.1a indicated that copper removal from AMD by cementation is technically feasible, however, uncertainty remains respecting the lowest residual copper concentration in the treated effluent that can be achieved in a cost efficient manner.

The selective process of copper cementation on iron involves the electrochemical precipitation of copper from solution as follows:



Other reactions occur simultaneously and cause considerable amounts of iron to be consumed. The efficiency of the copper cementation process can be problematic due to a high consumption of iron, a slow reaction rate, poor quality of cemented copper, and insufficient removal of copper from solution.

Selective iron removal is of interest as iron is a common contaminant in AMD and may be present in concentrations exceeding 1,000 mg/L. Iron removal from AMD is reasonable and can

be effective. Research has been suggested to improve iron removal parameters including: the rate of ferrous iron oxidation; the final solution pH; the rate of lime addition; flocculant use; and seeding materials (used to initiate particle agglomeration). Selective metal recovery could be based, in concept, on the initial removal of iron from solution to produce a residual solution with other metals such as Ni and Zn. It has been suggested that if the concentrations of these residual metals were sufficient, lime-based treatment processes could be used to create a metal hydroxide sludge that could be economically recycled to a smelter.

Ion exchange is extensively used in metallurgical applications and MEND has assessed the extracting capabilities of ion exchangers and the feasibility of improving the economic and environmental aspects of lime neutralization through its use. There are two main groups of ion exchangers: organic (resins); and inorganic (zeolite). Ion exchangers are typically classified into three main groups: anionic, cationic and chelating. Anionic resins have amine groups useful for extracting amphoteric elements or metals that have anionic complexes. Cationic resins have either sulphonic or carboxylic groups and can be used to extract polyvalent cations. Chelating resins have organic groups which can form bonds with specific metals and as such offer selectivity. Zeolite are cationic exchangers which offer some selectivity as a result of the regular size of molecular spaces with their structures. They are capable of exchanging heavy metals for alkali elements such as Ca, Na, and Mg. MEND Project 3.21.1a indicated that chemical precipitation and selective ion exchange offer the potential of recovery of metals from AMD.

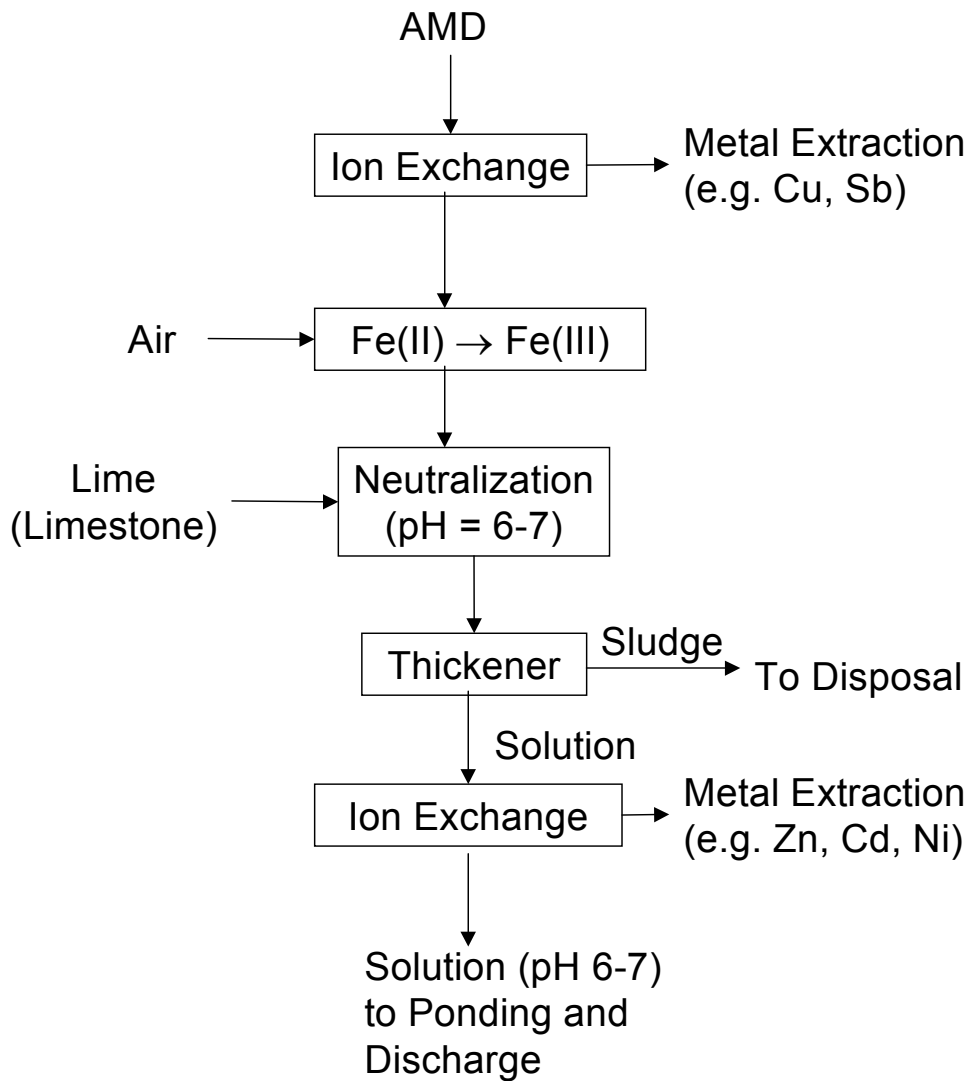
The biosorption of metals has been identified as one of the areas that might be applied in treating AMD by making use of the ability of some microorganisms and aquatic and terrestrial plants to accumulate metals to levels that exceed normal background concentrations. This accumulation can occur through three distinct mechanisms: bioaccumulation, physical entrapment, and biosorption. These mechanisms are applied in passive treatment systems.

Electrowinning technology has been applied to the recovery of metals from metal finishing operations, and has been investigated for possible use in recovering metals from AMD. The application of this technology holds promise, but high cost remains a drawback.

II. Discussion of MEND Research

MEND 3.21.1a investigated alternative technologies, which can in concept facilitate the recovery of metals from AMD. The study involved a review of literature concerning the biosorption of metals, chemical treatment, electrowinning, and ion exchange and solvent extraction. MEND 3.21.1b focused on the removal of metals from AMD through the use of ion exchange technology in combination with lime-based chemical treatment. A simplified flowsheet of a proposed lime neutralization/ion exchange process is provided in Figure 5.2.2-1. Testwork involved batch and column tests of cationic and chelating type resins, and zeolites, and AMD

Figure 5.2.2-1 Simplified Flowsheet of a Proposed Process Comprising Lime Neutralization and Ion Exchange



Source: MEND 3.21.1b

samples from three mine sites. Tests were carried out to assess the selective extraction of Cu, Sb, Cd, Zn, and Ni, and the bulk extraction of Cd, Ni, and Zn from AMD. It was determined that most commercial ion exchangers do not exhibit a marked selectivity for Cu, Sb, Cd, Ni, and Zn.

Testwork, however, showed that the extraction of Cd, Ni, and Zn can be accomplished at neutral pH using either a chelating resin or synthetic zeolite. This approach could, in principle, reduce lime consumption. A preliminary cost comparison was used to assess whether or not cost savings in lime consumption could be offset by the cost of operating an ion exchange process. The estimated annual reagent costs for AMD treatment by lime neutralization to pH 6 and adsorption on a resin, and lime neutralization to pH 6 and adsorption on a zeolite were estimated to be 92% and 80% respectively of the annual reagent cost for lime neutralization to pH 11. The preliminary cost comparison suggests that lime treatment reagent costs may be lower with a combined lime treatment/ion exchange process as compared to full lime neutralization process.

In MEND 3.21.2a several chemical methods were evaluated to selectively precipitate and recover metal ions from AMD. A conceptual flowsheet consisting of a three-step precipitation process was developed. The process consisted of oxidizing Fe^{2+} to Fe^{3+} with H_2O_2 and precipitating ferric hydroxide sludge in the first step, then recovering/recycling Zn and Cu as sulphide precipitates in the second step. In the third step, residual metal ions remaining in the water were removed via lime neutralization to obtain a final water quality in compliance with the regulated standards. Further bench scale investigations were carried out to optimize the initial flowsheet of separating iron as the hydroxide using lime and a dodecylamine surfactant (DDA), which could reduce coprecipitation of other metal ions. Copper and zinc were removed as the sulphide, and techniques were tried to produce a precipitate that could be recycled to a zinc production circuit (smelter - refinery).

The results show that more than 90% zinc recovery and greater than 50% Zn grade can be obtained with the three-step method. A preliminary economic analysis was performed to compare the various options in terms of available reagents for precipitation and methods of oxidation. Based on the preliminary economic analysis, the feasibility of the proposed value recovery process would be dependent on the costs associated with chemical reagents and solid/liquid separation. A significant issue that was not researched by MEND is the potential toxicity of effluents from a metals recovery plant - DDA and residual sulphides are known to exhibit toxicity.

MEND 6.3 involved a review of Japanese AMD technology under development or being introduced. Technologies identified as being at the development stage were: ion exchange, membranes, sulphur reducing bacteria, sulphur oxidizing bacteria, metal absorbing organisms, and the flotation recovery of metals from AMD. Recently introduced technologies include the bacterial oxidation of ferrous iron at the Matsuo Mine drainage plant, and the planned use of the

recovered iron in ferrite and iron powder production processes. Processes for the recovery of ferrite and hematite from ferric oxide sludge at the Matsuo Mine were fully researched and developed but the cost of production was comparable to, or higher than, prevailing product prices so production never started.

III. Applications and Limitations

Principal incentives for the recovery of metals from AMD are improved effluent quality, improved treatment waste byproduct characteristics, and revenue to offset treatment cost. Metals are currently being recovered from AMD albeit on a limited scale. Applications include copper cementation on scrap steel, and the recovery of metals through the smelting of lime treatment sludge.

Recycling of hydroxide sludges to smelters is carried out at a few sites as it eliminates concerns over sludge stability and may provide revenue to partially offset treatment costs. The recycling of sludge requires that the sludge be physically and chemically suited to the smelter, and that the sludge meet the feed requirements including allowable limits on contaminants (i.e. arsenic, antimony). Transportation costs may make sludge recycle to smelter unattractive, however, at mine properties where sludge disposal presents a significant challenge, sludge disposal to smelter may ultimately be better than alternate methods of disposal.

MEND 3.32.1 included a preliminary evaluation of the costs to treat a hydroxide sludge containing 60% moisture and a 5% Cu content (wet basis equivalent to 12.5% on a dry basis). The calculation indicated that revenue from the recovered copper would be less than the smelter costs.

Sludge Recycle to Smelter Preliminary Sludge Revenue and Treatment Cost Estimate

Revenue:	166 lb. Cu/t wet sludge @ CDN \$1.15/lb.(1994) =	\$190/t
Costs:	Transportation allowance	(\$40/t)
	Smelter treatment allowance	(\$100/t)
	Moisture penalty (60%)	(\$70/t)

	Net cost: (loss)	(\$20/t)

Key drawbacks to the implementation of technologies to recover valuable metals from AMD streams are the need for more research to develop site-specific metal recovery processes, and high costs.

IV. Base Method

Metal recovery/recycle is principally carried out through the recycling of lime treatment waste products.

V. Variations

Metal recovery/recycle continues to be a topic of discussion, and it is expected that further research will be carried out in this area. At present, variations to metal recovery/recycling from AMD are for applied purposes, limited to the recovery of metals through copper cementation on scrap steel.

The potential recovery of metals from AMD at the historic Britannia Mine, located approximately 48 km north of Vancouver, B.C., has been investigated by a number of research groups. Rowley *et al.* (1997) reports that AMD from the Britannia Mine discharges from a number of locations and primarily from a concrete bulkhead on the 4100 level where the flow averages about 12,000 m³/day and ranges seasonally from 4,000 to 40,000 m³/day. The concentrations of copper and zinc range from 12 to 28 mg/L, cadmium levels are about 0.1 mg/L, and the pH is typically 3 to 4. Flow from the 4100 level flow is piped and discharged at depth in Howe Sound. Acidic drainage from the 2200 level adit flows to Britannia Creek (Figure 5.2.2-2). Copper and zinc concentrations in the 2200 level adit stream range from 0.3 to 115 mg/L and 3 to 48 mg/L, respectively, with cadmium levels of about 0.1 mg/L, and a pH in the range of 2.4 to 4.6. The Britannia Mine, which at one time had been one of the largest copper producers in North America, ceased operations in 1974.

The use of zeolite to treat AMD from the Britannia Mine was investigated by the British Columbia Research Corporation in 1992. Perceived benefits included:

1. Elimination of the need for a lime-based treatment plant;
2. Elimination of treatment sludge production and disposal; and
3. Generation of revenue through metal recovery.

The performance of a number of zeolite samples were assessed through shake flask and column loading and elution tests. Of the zeolites tested, Pine Valley phillipsite had the greatest affinity for copper. Column and elution tests indicated that copper could be eluted with sea water. The quantity of zeolite required to treat the Britannia Mine was estimated based on the laboratory data and an average annual AMD flowrate of 518 m³/hr at an average copper concentration of 18 mg/L. It was estimated that 311 tonnes of Pine Valley phillipsite would be required - equivalent to 464 m³ of tank volume. Surge capacity would be additional, and required to deal with greater than average AMD flowrates and copper levels.

The envisaged process would involve a series of zeolite chambers. AMD would first be filtered to remove iron precipitates and avoid zeolite plugging. The process would be fully automated. Once the first zeolite chamber became loaded with copper, it would be disconnected from the circuit and eluted using sea water. The sea water eluant would in turn be recycled until a maximum copper level was attained at which point the eluant would be sent to the copper cementation plant. Based on initial bench-scale testing, it was expected that the zeolite/copper cementation plant would result in a copper recovery in the range of 90 to 95%, and that the cost of the treatment plant operation and maintenance could be offset by the copper recovered. Further research was recommended to address: maximum inflow rates; the maximum copper concentration in the eluant; temperature effects; and the effect of repeated zeolite loadings and elution. At the completion of the project, it was recognized that although copper removal was close to acceptable, zinc and acidity levels in the effluent remained above discharge criteria (Vos 1998). Acidity and zinc levels could have been reduced to acceptable levels through the addition of a lime-based effluent treatment circuit.

Rowley *et al.* (1997) investigated the application of NTBC Research's patented Biosulphide treatment process at the Britannia Mine. The Britannia Mine Biosulphide pilot configuration shown in Figure 5.2.2-3 included chemical and biological steps. Raw water entering the chemical storage tank contacts hydrogen sulphide from the biological circuit. A fraction of the AMD is fed to the biological circuit as the sulphate source. Selective metal sulphide precipitation is achieved by pH and sulphide control. A key potential benefit from the application of the Biosulphide process was the recovery of metal from the drainage. The results of an on-site pilot project carried out from July 1995 to October 1996 demonstrated that the Biosulphide process was highly effective at removing zinc, copper and cadmium to levels as low as <0.1, <0.001 and <0.001 mg/L. Rowley *et al.* (1997) reported that the grades of copper and zinc sulphide products reached levels that could allow for metal recovery. The capital cost of a full scale Biosulphide process-based treatment plant at the Britannia Mine was estimated to be \$2.2 million. Based on the sale of the sulphide concentrates, and assuming a 65% net smelter return (NSR) on the CuS product and a 50% NSR on ZnS, it was estimated that there would be a net operating profit of \$130,000/a. In comparison, the capital cost for a lime-based treatment plant at the mine had previously been estimated to be \$3.5 million, with an annual operating cost in excess of \$900,000/a excluding the cost of sludge disposal. Rowley *et al.* (1997) indicate that the next stage in the development of the process would be further scale-up and the introduction of process control to allow for continuous automated operation with routine maintenance. This process, like a number of others, remains under development and in the yet-to-be-proven category.

VI. Cost

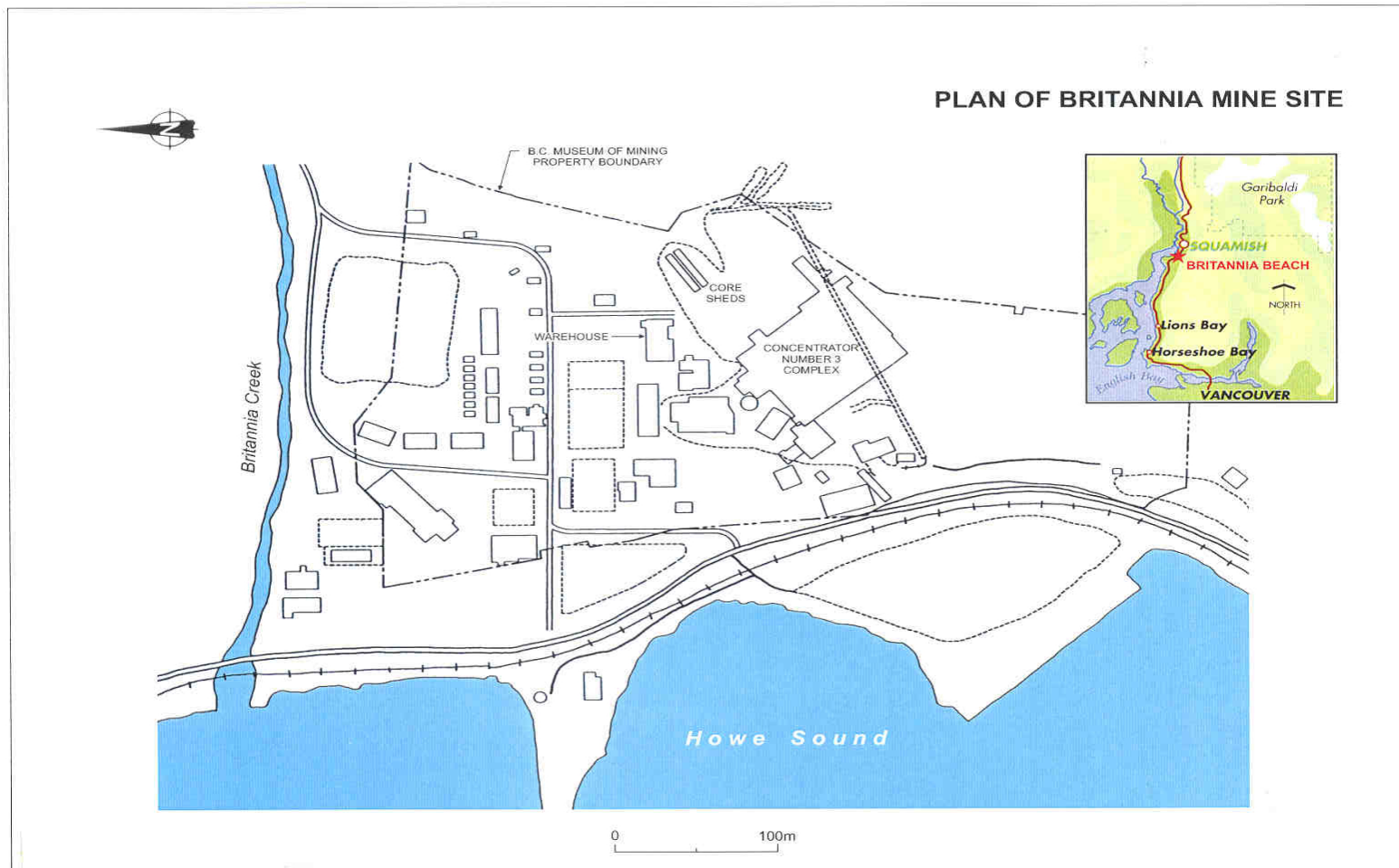
MEND 5.8.1 evaluated the costs of currently applied, or perceived feasible, AMD technologies. The study provides a framework that can be used to develop a cost model for selected AMD

technologies and site specific conditions. The study involved a comparison of costs associated with the application of a soil cover, a self-sustaining water cover, a maintained water cover, a plastic liner cover, a simple soil cover, waste removal, and AMD collection and treatment. The findings of the cost comparison indicated that the application of a self-sustained water cover, and AMD collection and treatment may represent the best option from the perspective of lower implementation costs.

More recently, Environment Canada with the support of the British Columbia Ministry of Environment, Lands and Parks retained H.A. Simons Ltd. to prepare prefeasibility designs and cost estimates for an AMD treatment system at the Britannia Mine. The report by H.A. Simons (1998) provides a good example of the range of options presently being considered for the treatment of AMD. The treatment options considered for the Britannia Mine are summarized in Table 5.2.2-1. A lime-based HDS type process was ultimately selected as the most appropriate for the Britannia site based on capital cost, operating cost and operating complexity considerations. It was proposed that contaminated water from the underground workings of the Britannia Mine would be collected and fed to the new HDS plant. It was additionally proposed that the treated effluent would be discharged to Howe Sound and that the thickened sludge would be removed from the treatment system on a batch basis and transported by truck to a sludge management facility.

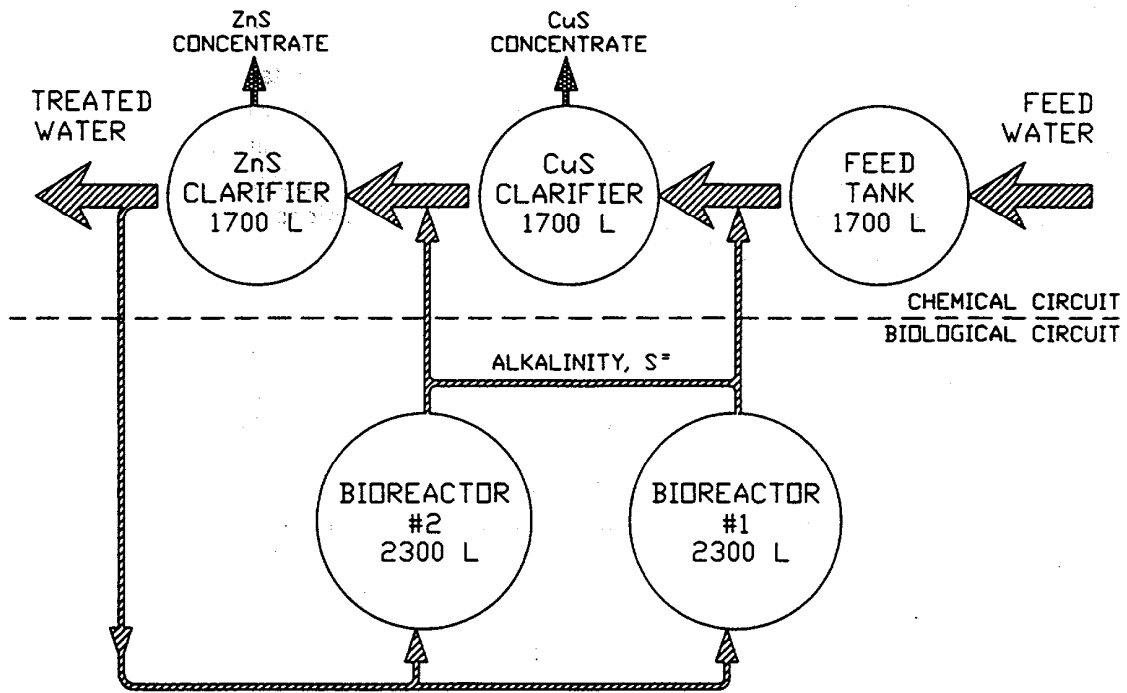
The potential saleability of metal concentrates produced by selective metal removal from AMD was also a major consideration in the assessment of options for the long-term treatment of acidic drainage from the Wheal Jane, Cornish Tin Mine in the U.K.

Figure 5.2.2-2 Plan of Britannia Mine Site



Source: Adapted from H.A. Simmons (1998)

Figure 5.2.2-3 Britannia Biosulphide Configuration



Source: Rowley *et al.* (1997)

**Table 5.2.2-1
Summary of AMD Treatment Options Considered for the Britannia Mine**

Process	Description	Assessment and Comments
Lime Neutralization Low and High Density	Lime is added to neutralize acid and precipitate metals. Process is carried out in agitated tanks. Solids removed in clarifier can be recycled to improve performance and increase sludge density.	Conventional proven technology for medium to high flows. Can produce high quality effluent and high density sludges.
Iron/Alum Coagulation	Iron or alum can be added in some situations to improve performance by coprecipitating metals and generating sludge to enhance high density sludge process.	Britannia drainage contains sufficient iron to remove metals via coprecipitation and generate sludge. Testwork did not demonstrate significant advantage to warrant further consideration.
Neutralization – Alternative Reagents	Alternative reagents such as soda ash, caustic soda and limestone can be considered to achieve neutralization.	None of the alternative reagents demonstrated an advantage over lime. Some may have some applications in combination with lime.
Sulphide Precipitation using either Chemical Reagent or Biologically Produced Hydrogen Sulphide	Metals can be removed by precipitation with sulphide using NaHS. Process requires excess of sulphide to be effective for zinc and iron. Sulphide precipitates difficult to settle. Sulphide commonly used to remove Cd and Pb as part of lime treatment.	Reagent costs high relative to lime, since separate neutralization step still required, use of NaHS has no process advantage over lime. Cost of biologically-generated sulphide can be as high as chemical reagents. The need for an organic reductant adds additional cost to the biological system. Not applicable at Britannia due to insufficient cost recovery from metals.
Sea Water Dilution	ARD would be diluted and neutralized by seawater and then settled in a large clarifier to remove precipitates.	Capital costs for clarifier would be very high. Unproven concept. Precipitate could be difficult to settle and thicken. Space requirements would be high. Not applicable to Britannia.
Ion Exchange	Resins exchange H ⁺ , OH ⁻ , or other ions for contaminant ions. Resin regeneration removes the contaminant ions into a concentrated waste stream.	Resins subject to fouling by suspended solids or organic compounds. Concentrated waste regenerant stream still requires extensive additional treatment to generate dry product for disposal. Complex system with high capital and operating costs. Potential for high purity products but no significant process advantage over lime treatment.
Activated Carbon Adsorption	Carbon used to adsorb heavy metals, acts as catalyst to oxidize reduced species such as ferrous iron.	Carbon does not have affinity for some metals. Could require extensive pre-treatment. Costs for replacement of carbon would be high. Not widely practised for primary removal of metals.
Reverse Osmosis	Water flows across semipermeable membrane under pressure in excess of osmotic pressure; contaminants remain behind. Currently used for small flows and desalination.	Subject to gypsum and suspended solids fouling, may require pre-treatment. Complex system with high pressures required. Membrane replacement costs could be high. Concentrated waste solution requires additional treatment, does not produce a dry product.
SX/EW Solvent Extraction in Combination with Electrowinning and Direct Electrowinning	Certain contaminants transferred from aqueous solution to immiscible organic solvent. Solvent regeneration gives concentrated contaminant stream that can be treated via electrowinning.	Potential for selective recovery of valuable contaminants (e.g. copper by electrowinning). Highly complex with high capital and operating costs. Solvent losses costly for low strength feed. May not be effective for zinc and iron, not practical at Britannia at low copper concentrations insufficient cost recovery from metals to cover additional costs.

Source: H.A. Simmons (1998), Table 7-1

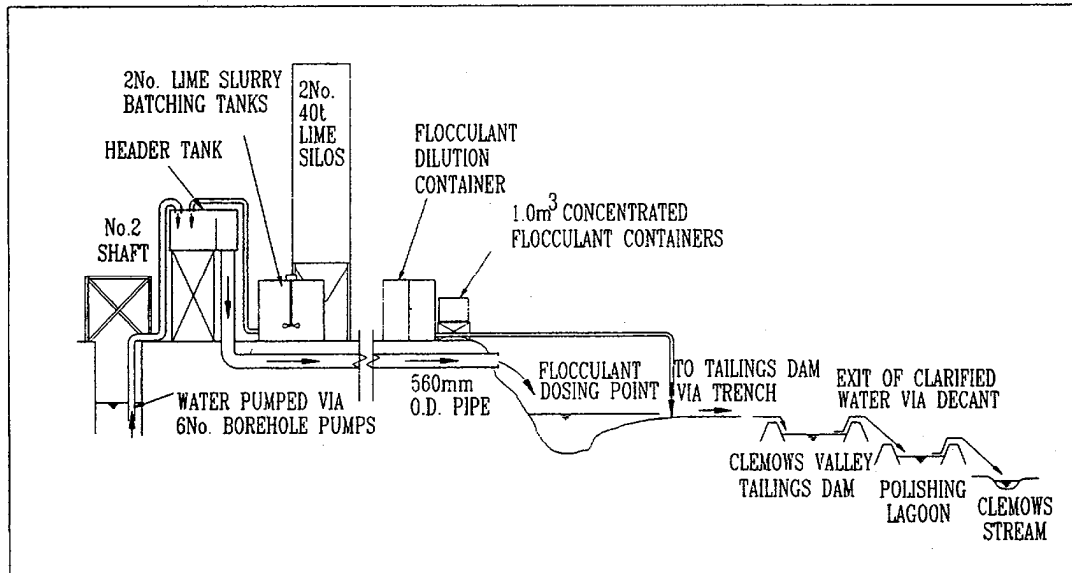
Cambridge (1997) reports that the Wheal Jane Mine closed in March 1991. In 1992, the flooding of the mine coupled with the failure of an adit plug, led to the release of an estimated 25,000 to 30,000 m³ of acidic water into the adjacent river and estuary system. A temporary conventional lime-based treatment system was installed to treat the mine water (Figure 5.2.2-4) and restore water quality in the adjacent river to pre-mine closure conditions. Treatment sludge was disposed of in an existing tailings basin. Both passive and active treatment technologies were considered for long-term treatment. The active treatment process assessed included four stages. Technical aspects considered for each of the treatment process stages are given below:

1. Metal Precipitation
 - Hydroxide and sulphide precipitation.
 - Selective metal precipitation to obtain an economic metal concentrate.
2. Solids/Water Separation
 - Conventional high density thickening.
 - Hydrocycloning.
 - Magnetic-separation.
 - Flotation.
3. Sludge Dewatering
 - Rotating and horizontal vacuum filters.
 - Pressure belt filters/presses.
 - Centrifuge or frame and plate processes.
4. Tertiary Treatment
 - Sand filtration.
 - Chemical polishing.

The selective recovery of zinc was investigated, however, impurities in the concentrate reduced its value. Cambridge (1997) reports that discounted cash flow analyses indicated a break-even period of more than 15 years which had to be assessed in light of the potential decline of the zinc concentration in the treatment plant influent over time. The preferred active treatment process is shown in Figure 5.2.2-5 and involves the use of an HDS-type process and the disposal of thickened dewatered sludge in the tailings basin or off-site at licensed waste management facilities. Present plans are to replace the existing conventional mine water treatment system by the year 2000.

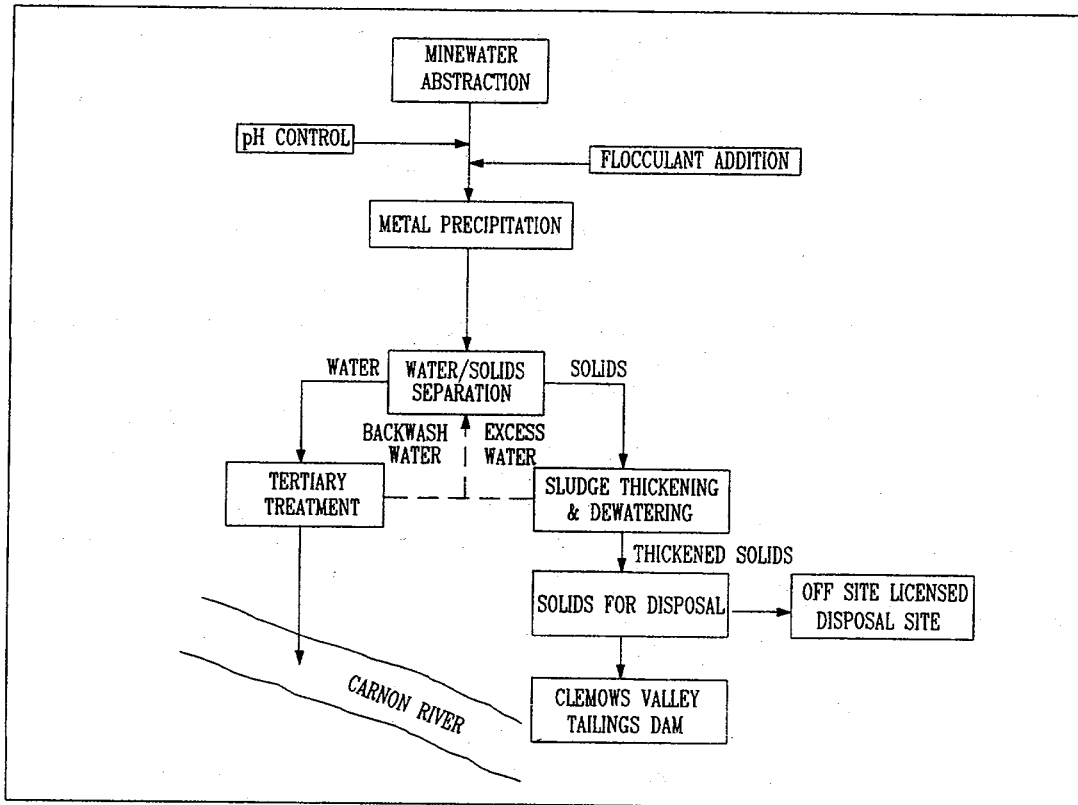
Wheal Jane was also the site of an extensive passive treatment pilot plant test. Recent results are discussed in Section 5.3.

Figure 5.2.2-4 Temporary Minewater Treatment System



Source: Cambridge (1997)

Figure 5.2.2-5 Preferred Active Treatment System – Block Diagram



Source: Cambridge (1997)

VII. MEND and Relevant Publications

- MEND 3.21.1a 1991. Study on Metals Recovery/Recycling from Acid Mine Drainage. July.
- MEND 3.21.1b 1995. Metals Removal from Acid Mine Drainage by Ion Exchange. June.
- MEND 3.21.2a 1996. Metals Removal from Acidic Drainage - Chemical Method. March.
- MEND 3.32.1 1994. Acid Mine Drainage - Status of Chemical Treatment and Sludge Management Practices. June.
- MEND 5.8.1 1995. Economic Evaluation of Acid Mine Drainage Technologies. January.
- MEND 6.3 1994. A Critique of Japanese Acid Mine Drainage Technology. April.
- Cambridge M. 1997. *Wheal Jane - The Long-Term Treatment of Acid Mine Drainage*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 3, pp. 1125-1144.
- H.A. Simons Ltd. 1998. Treatment of Acid Drainage at the Britannia Mine, Britannia Beach, British Columbia. Report P. B257B prepared for Environment Canada and the British Columbia Ministry of Environment, Lands and Parks. March.
- Rowley, M.V., Warkentin, D.D. and Sicotte, V. 1997. *Site Demonstration of the Biosulphide Process at the Former Britannia Mine*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 4, pp. 1531-1547.
- Vos, R. 1998. B.C. Research Inc. Personal Communication. August.

5.2.3 TREATMENT BYPRODUCTS

I. Discussion of Theory

The characteristics of the sludge byproduct of the chemical treatment of AMD are dependant upon the properties of the AMD, the treatment process, and the neutralizing reagent used. Limestone neutralization of AMD produces a dense, granular sludge which settles and compacts well. The volume of sludge produced when limestone is used is often less than that produced when other alkaline reagents are used provided good reagent efficiency is obtained. However, as indicated in Section 5.2.1 the usefulness of limestone is limited as it is only effective up to a pH in the range of 6. Hydrated lime is widely used in conventional and HDS processes and produces a carbonate/gypsum/metal hydroxide sludge. The sludge produced by the conventional treatment process typically has a low solids content (e.g. <1 to 5% solids). The low solids content is due to the fine and amorphous nature of the precipitates, and water chemically bonded to the particles. As such, conventional treatment sludge tends to be resistant to compaction and dewatering. The HDS process, however, involves the controlled recycling of sludge within the treatment circuit and the withdrawal of excess sludge from a thickener. HDS process sludge has a greater percent solids (e.g. in excess of 20% solids) with larger and more rounded particles.

Treatment sludge management has recently received increased attention due to the volume of sludge produced at some sites; concerns over sludge stability; and the cost of sludge disposal. These aspects are discussed below.

II. Discussion of MEND Research

MEND 3.32.1 recommended that investigations were needed on the stabilization of lime treatment sludges. This recommendation had been reinforced by participants from industry and government at chemical treatment workshops across Canada.

Sludge production from some AMD sources can be considerable. MEND 3.32.1 provides an example calculation of sludge production from base metal tailings with a 35% FeS₂ (equivalent) content. At 1.7 t/m³, one cubic metre of the tailings would contain 0.6 t of pyrite. The oxidation of the pyrite contained in 1 m³ of these tailings would produce 2.3 t of sludge solids assuming all sulphate produced is precipitated as gypsum. In reality, due to dilution more than 90% of sulphate may be released with the effluent. In this case, the treatment of AMD from 1 m³ of tailings would lead to the production of about 46 m³ of sludge (at 5% solids), or about 3.4 m³ of sludge (at 40% solids).

The concern over metal leaching from sludge arises from the fact that sludge includes metal oxides and metals in other forms which can mobilize in water under certain conditions (e.g. under low pH conditions). The mobility of metals is dependant upon the metals present and the

physiochemical properties of the sludge. Key factors affecting sludge stability include excess buffering capacity, iron content and state, gypsum saturation, crystallinity and age of the sludge, acidity, and the alkali used.

MEND 3.21.1b assessed the toxicity of lime treatment sludge and examined metals removal from AMD using ion exchange technology. Two samples of sludge were subject to the toxicity test (leachate extraction) procedure referred to in Regulation 347 of the Environmental Protection Act of Ontario. The regulation notes that if a waste produces a leachate with contaminant concentrations in excess of 100 times those listed in Schedule 4 of the Act, the leachate is classified as leachate toxic waste, or hazardous waste, and regulated accordingly. Test results are presented in Table 5.2.3-1 and indicate that the concentrations of As, Cd, Pb, and Hg are below Schedule 4 leachate quality criteria. However, the sludge is not deemed hazardous mainly because metals such as Cu and Zn are not included in Schedule 4. The report indicates that sludge could become an environmental liability should additional metals be included in future regulations. The leachate tests do not apply to treatment sludges as they are considered mining wastes.

**Table 5.2.3-1
Leachate Extraction Procedure (Toxicity Test)
for Two Neutralization Sludges**

Element	Lime Neutralization to pH 10.5		Lime Neutralization to pH 4.5		Leachate Quality Criteria ⁽³⁾ (ppb)
	Composition of Dry Solids ⁽¹⁾ (%)	Leachate Composition ⁽²⁾ (ppb)	Composition of Dry Solids ⁽¹⁾ (%)	Leachate Composition ⁽²⁾ (ppb)	
Aluminum	0.14	28	0.18	10	NL
Arsenic	---	<2.0	---	<2.0	50
Calcium	18.45	---	20.46	---	NL
Cadmium	---	413	---	36	5
Copper	0.80	63,000	0.64	14,200	NL
Iron	7.29	---	10.28	---	NL
Mercury	---	<2.0	---	<2	1
Magnesium	0.85	---	0.07	---	NL
Lead	0.01	<1	0.02	4	50
Antimony	0.06	24	0.08	3	NL
Zinc	2.89	906,000	0.41	122,000	NL

Source: MEND Project 3.21.1b

Notes: (1) Solids were dried at 110°C for 24 hours

(2) Determined by CANMET according to Regulation 347 of the Ontario Environmental Protection Act

(3) From Schedule No. 4, Regulation 347 of the Ontario Environmental Protection Act

NL Not Listed

Poirier and Roy (1997) report that approximately 45,000 m³ of high density sludge averaging 20% solids are produced annually at La Mine Doyon (Québec) and disposed of in a storage

pond. The sludge is typically composed of 52% gypsum, 24% ferric hydroxides, 12% aluminum hydroxides and 6% magnesium hydroxides. The results of conventional solid waste leachate tests (using acetic acid) and modified leachate tests (using 60% H₂SO₄/40% HNO₃) on the sludge show that the leachates meet provincial solid waste requirements. In addition, leachate testing at a pH above 5.0 produced very low (often below detection limits) metal concentrations in the leachate. Poirier and Roy also indicated that the high density sludge was shown to have a low neutralization potential indicative of a low level of residual lime and hence good treatment plant efficiency.

More recently, MEND 3.42.2a characterized and assessed the stability of AMD treatment sludges from 11 mine sites (7 base metal, 2 uranium, 1 gold, and 1 coal site). The AMD treatment processes used at the sites are as follows:

- 3 sites use lime-based HDS treatment processes;
- 3 sites use lime-based conventional treatment processes; and
- 5 sites use a basic process where lime slurry is added to an AMD stream.

In addition, the uranium sites use barium chloride to precipitate radium. The report provides useful information respecting sludge sampling techniques, the sludge characterization data, an assessment of leachate protocols (none of which are specific for the evaluation of AMD treatment sludge), and the leachate test data and an assessment of the results. Selected aspects of the report are summarized below.

Composite sludge samples were collected from the 11 sites between December 1995 and March 1996. Samples used for mineralogical, chemical and thermal analyses were freeze-dried while wet samples were used in leachate extraction testing and physical analysis. The solids content of the sludges ranged from 2.4% to 32.8% with the denser sludges produced by the HDS-type processes. Sludge aging was shown to have a beneficial effect on the percent solids - the percent solids in aged sludge was generally 25% higher than that of fresh sludge. The degree of densification did not appear to be significantly influenced by the aging duration or by the presence of a water cover over the sludge. The greatest densification due to aging was for an aged coal mine sludge which exhibited a 250% increase in density. With the exception of one sample, sludge particle size increased with aging suggesting that sludge particle growth and aggregation can occur as a result of sludge aging and particle dissolution and recrystallation.

Mineralogical analyses of the sludge samples showed that readily leachable metal species such as zinc were commonly present in an amorphous phase. Metal species (i.e. Al, Cu, Fe, Mg, Na, Ni, Zn) appear to be effectively scavenged during precipitation.

Chemical analysis data for the sludges is presented in Table 5.2.3-2. The key points are:

- Arsenic, boron, cadmium, mercury, lead, and selenium occur in trace amounts. The concentration of barium is typically less than 0.01% except for one site;
- Iron concentrations range from 1.5% to 28.1% with iron largely in the ferric state;
- Copper concentrations are low and less than 1% except for a sample from one site. Nickel concentrations were less than 1%;
- Zinc concentrations range from 0.019% to 14.4%; and
- Metals contained in sludge can be viewed as a source of leachable metals or a potential asset for metal recovery. The researchers indicated that for the sludges tested, zinc recovery may be possible for sludges containing >14% Zn.

The Neutralization Potential (NP) of the sludge ranged from 108 to 725 t CaCO₃ per 1,000 t sludge. Higher NPs are beneficial to long-term sludge stability while low NPs are attractive as they indicate the efficiency of the treatment process.

**Table 5.2.3-2
Chemical Composition of Sludge Solids**

Site Code	Sample	Chemical Composition (%)												
		Al	Ag ⁽¹⁾	As	Ba	B	C	Cd	Ca	Cr	Cu	CO ₃	Fe ₁	Hg
D-1	Fresh	0.1		<0.0016	0.012	0.0051	7.11	0.0002	26.6	<0.054	0.05	25.9	4.8	<0.0008
	Aged	0.5	1.5	0.0023	0.005	<0.002	6.57	0.0009	22.9	<0.054	0.021	23.4	7.1	<0.0008
Q-2	Fresh	1.0	10.40	0.011	0.004	0.009		0.059	6.9	<0.060	0.041	6.45	2.9	0.00011
	Aged	1.8	6.6	0.0978	0.05	<0.002	3.29	0.0825	9.6	<0.054	0.25	11.6	12.3	<0.0008
M-3	Fresh	1.5	19.5	0.0105	0.014	<0.002	1.97	0.0094	6.0	<0.054	0.27	6.45	14.7	<0.0008
R-4	Fresh	2.8	1.0	<0.0016	0.020	<0.002	1.75	0.0029	8.3	<0.054	0.33	5.22	10.8	<0.0008
	Aged	3.3	1.2	0.0025	0.005	0.0017	2.42	0.0025	7.4	<0.054	0.27	8.20	26.1	<0.0008
F-5	Fresh	7.7	1.1	0.0018	0.005	0.29	1.34	0.0004	14.0	<0.052	0.0029	4.80	1.5	<0.0008
	Aged	11.2	1.2	0.0020	0.005	0.16	0.98	0.0005	9.9	<0.052	0.010	3.41	6.2	<0.0008
S-6	Fresh	1.3	7.3	0.0056	0.010	<0.002	4.57	0.0674	17.2	<0.052	0.15	16.1	2.3	<0.0008
	Aged	0.6		0.0051	0.011	<0.002	2.40	0.1390	10.0	<0.054	0.20	8.66	3.0	<0.0008
J-7	Fresh	4.3	4.7	<0.0016	0.005	0.0066	0.54	0.0002	13.0	<0.055	0.077	1.87	12.8	<0.0008
	Aged	3.4	0.9	<0.0016	0.003	0.0049	0.30	0.0001	14.2	<0.055	0.054	0.95	13.4	<0.0008
W-8 ⁽²⁾	Fresh	3.9	13.7	0.0248	0.014	0.0041	0.55	0.0137	3.8	<0.054	0.12	1.76	15.0	<0.0008
	Aged	1.8	15.2	0.0487	0.022	<0.002	1.36	0.0057	11.6	<0.054	0.05	4.76	10.9	<0.0008
N-9	Aged	4.9	1.1	0.0021	7.8	0.22	1.86	0.0014	5.0	<0.055	0.029	5.44	7.7	<0.0008
B-10	Fresh	3.6	4.1	<0.0016	0.005	<0.002	2.52	0.0058	4.6	<0.054	1.48	7.73	22.2	<0.0008
T-11	Fresh	0.6	1.8	<0.0016	0.011	<0.002	1.35	<0.0001	10.2	<0.055	0.001	4.80	28.1	<0.0008

**Table 5.2.3-2
Chemical Composition of Sludge Solids, Continued**

Site Code	Sample	Chemical Composition (%)															
		Mg	Mn	Na	Ni	Pb	Se	Si	S	U	Zn	SO ₄	NNP ⁽³⁾	AP ⁽³⁾	NP ⁽³⁾	LOM ⁽⁴⁾	LOI ⁽⁵⁾
D1	Fresh	5.8	-	0.17	0.26	<0.43	<0.0009	1.1	1.43	-	0.067	3.70	NA	6	NA	3.69	38.3
	Aged	6.3	-	0.07	1.06	<0.43	<0.0009	2.0	1.10	-	0.021	3.60	725	-	725	4.48	35.5
Q-2	Fresh	18.1		0.24	0.005	<0.20		2.8	1.75	-	7.5	3.01	796	23	819	8.09	27.9
	Aged	7.9	-	0.21	<0.11	<0.43	0.0296	5.2	3.18	-	5.9	3.22	359	66	425	6.19	21.8
M-3	Fresh	7.3	-	0.21	4.19	<0.43	0.0148	4.5	3.00	-	0.98	5.95	293	32	325	14.5	23.0
R-4	Fresh	5.5	-	0.04		<0.43	<0.0009	7.2	1.85	-	1.4	5.20	315	4	319	5.93	24.2
	Aged	2.6	-	0.06	<0.11	<0.43	<0.0009	4.4	1.34	-	1.1	3.77	207	3	210	9.62	21.1
F-5	Fresh	6.0	3.6	0.11	0.059	<0.43	<0.0009	1.7	7.46	-	0.14	18.80	335	38	372	6.85	23.7
	Aged	1.2	2.1	0.07	0.059	<0.43	<0.0009	2.7	7.24	-	0.15	18.98	94	29	123	15.3	21.3
S-6	Fresh	5.7	-	0.31	0.13	<0.42	0.0159	4.8	2.92	-	8.5	6.90	452	19	471	6.83	25.9
	Aged	7.8	-	0.21	0.20	<0.43	0.0169	2.3	4.58	-	14.4	11.29	497	26	523	8.33	23.2
J-7	Fresh	2.2	0.47	0.03	<0.03	<0.44	<0.0009	1.2	9.97	-	0.0031	26.71	84	34	118	14.1	16.1
	Aged	1.7	0.24	0.03	<0.03	<0.44	<0.0009	0.8	11.3	-	0.019	30.71	74	34	108	12.8	14.1
W-8 ⁽²⁾	Fresh	3.13	-	0.08	<0.11	<0.43	<0.0009	1.28	4.14	-	14.2	11.80	135	7	142	9.73	20.1
	Aged	6.3	-	0.28	<0.11	<0.43	<0.0009	2.0	5.75	-	4.6	14.2	346	32	378	10.5	21.9
N-9	Aged	3.8	1.1	0.15	<0.11	<0.45	0.0039	3.0	5.34	0.605	0.270	11.2	154	50	204	7.81	18.1
B-10	Fresh	7.4	-	0.24	<0.11	<0.43	<0.0009	4.9	1.77	-	0.17	4.55	345	8	353	6.02	24.5
T-11	Fresh	2.6	0.21	0.03	<0.11	<0.45	<0.0009	1.2	6.56	0.011	0.029	18.61	167	11	178	11.3	15.2

- Notes: (1) ppm.
(2) Fresh sludge from HDS process; aged sludge from conventional process
(3) t CaCO₃ eq/1000 t sludge
(4) LOM = Loss of Moisture
(5) LOI = Loss of Ignition

Source: MEND 3.42.2a, Tables 8A and 8B

Although numerous protocols have been developed for the leachate extraction testing of solid wastes, none have specifically been developed for evaluating the leachability of AMD treatment sludge. Based on a review of protocols, the researchers selected to use the Ontario Leachate Extraction Procedure (LEP) which uses an acetic acid leachate solution, and a Modified LEP where the acetic acid is replaced by a synthetic acid rain. The concentrations of metals in the leachates from the Ontario LEP and Modified LEP testing are shown in Tables 5.2.3-3 and 5.2.3-4.

The leachate concentrations of metals from the leachate extraction tests were compared to regulated limits governing the classification of hazardous waste material under the Transportation of Dangerous Goods Regulations, and regulations applicable to hazardous waste classification in British Columbia, Alberta, Manitoba, Ontario and Québec. The key findings were as follows:

- All but two of the sludge samples subjected to Ontario LEP testing passed the test. Metal concentrations in leachates were generally at least five times lower than the most stringent regulatory limits. The two sludges that failed the Ontario LEP test included: a base metal mine sludge which produced a leachate with a zinc concentration of 27.2 mg/L and a uranium mine sludge which produced a leachate with a uranium concentration of 5.02 mg/L;
- All of the sludges submitted for Modified LEP testing passed that test; and
- The leach data indicate that aged sludges have increased stability relative to fresh sludge.

MEND 3.42.2a additionally indicated that while sludge stability is an issue, greater emphasis should be placed on reducing the volume of sludge produced, and on sludge disposal.

MEND 3.42.2b assessed the effect of treatment process parameters and sludge aging on sludge metal leachability and sludge density. The testwork involved the operation of a bench-scale HDS type pilot plant at a flow rate of 200 mL/min and the sampling of process flows, clarifier overflow and sludge. The process was monitored to assess the effects of alterations made to treatment process parameters including: reactor agitation rates, flocculant usage, the rate of sludge recycle, and the $\text{Fe}^{3+}:\text{Fe}^{2+}$ (ferric-ferrous iron) ratio. It was found that a number of treatment parameters significantly influence sludge production and the geochemical stability of lime treatment sludge, and that a dense stable sludge can be produced by optimizing treatment conditions. In particular, particle abrasion needs to be discouraged through the selection of proper agitation rates and impeller designs for continuous stirred tank reactors. In addition, the recycling of sludge needs to be optimized to suit the site specific composition of the AMD and the treatment plant configuration; and, staged neutralization can be used to increase particle settling rates and promote efficient lime use.

**Table 5.2.3-3
Sludge Leaching Characteristics, Ontario LEP**

Site Code	Sample	Leachate Composition (µg/L)												
		Ag	As	Ba	B ⁽¹⁾	Cd	Cr	Cu	Fe _t ⁽¹⁾	Hg	Ni	Pb	Se	Zn ⁽¹⁾
D-1	Fresh	<2	<5	9.4	124.2	<1	<7	<13	<40	<4	4.9	<2	<24	<50
	Aged	<2	<5	38.8	397.6	<1	<7	73.3	<40	<4	769.3	<2	<24	<50
Q-2	Fresh	<4	<5	109.0	120	35.7	<24	<196	<40	-	<91	<0.7	144.8	0.16
	Aged	<6	<6	104.3	149.8	43.0	<34	<235	<40	<27	8.0	<10	153.2	140
M-3	Fresh	<6	<6	86.8	293.7	<4	<34	<235	<40	<27	942.6	<10	<97	<60
R-4	Fresh	<6	<6	30.0	68.1	<4	<34	<235	<40	<27	32.8	<10	<97	330
	Aged	<6	<6	22.4	<62	<4	<34	<235	<40	<27	11.8	<10	<97	160
F-5	Fresh	<6	<6	23.1	<77	<3	<8	<28	<40	<40	<6	<5	<35	<60
	Aged	<6	<6	65.5	<77	<3	<8	<28	<40	<40	413.0	<5	<35	300
S-6	Fresh	<4	<6	60.2	79	47.8	<24	<196	<50	<30	<112	<1	132.4	480
	Aged	<2	<5	29.4	150.0	3.7	<7	<13	<40	<4	8.2	<2	186.3	<50
J-7	Fresh	<2	<5	219.2	927.1	<1	<7	<13	<40	<4	25.2	<2	<24	<50
	Aged	<2	<5	53.3	278.6	<1	<17	<12	<40	<4	60.1	<2	<24	<50
W-8	Fresh	25.7	<6	117.7	228	375.5	<24	<196	<40	<40	<91	<5	<35	27,200
	Aged	<6	<6	64.9	<77	<3	<8	<28	<40	<40	24.9	<5	<35	80
N-9 ⁽²⁾	Aged	<6	<6	49.0	1719.4	3.2	<24	<196	<40	<40	391.7	<5	<35	270
B-10	Fresh	<6	<6	40.8	<62	<4	<34	<235	<40	<27	<7	<10	<97	<60
T-11 ⁽³⁾	Fresh	<6	<6	16.4	124.5	<3	<8	<28	<40	<40	<6	<5	<35	<60
Most Stringent of Cdn. Regulated Limits Referenced ⁽⁴⁾		5,000	5,000	100,000	500,000	500	5,000	10,000	1x10 ⁶	100	5,000	5,000	1,000	10,000

Notes: (1) Trailing zeros may not be significant since analytical results were originally in mg/L.

(2) U = 5,015 µg/L.

(3) U < 11µg/L

(4) U limit is 2,000 µg/L

Source: MEND 3.42.2a, modified from Table 14

**Table 5.2.3-4
Sludge Leaching Characteristics, Modified Ontario LEP**

Site Code	Sample	Leachate Composition (µg/L)												
		Ag	As	Ba	B ⁽¹⁾	Cd	Cr	Cu	Fe _t ⁽¹⁾	Hg	Ni	Pb	Se	Zn ⁽¹⁾
D1	Fresh	<2	<5	9.8	131.8	<1	<7	<13	<40	<4	5.2	<2	<24	<50
	Aged	<2	<5	16.9	74.2	<1	<7	28.3	<40	<4	26.5	<2	<24	<50
Q-2	Fresh	<4	<5	48.4	200	<0.7	<24	<196	<40	-	<91	1.0	141.4	40
	Aged	<6	<6	48.8	95.0	4.4	<34	<235	<40	<27	<7	<10	115.7	<60
M-3	Fresh	<6	<6	38.3	111.6	<4	<34	<235	<40	<27	187.0	<10	<97	<60
R-4	Fresh	<6	<6	<5	<62	<4	<34	<235	<40	<27	<7	<10	<97	<60
	Aged	<6	<6	<5	<62	<4	<34	<235	<40	<27	<7	<10	<97	<60
F-5	Fresh	<6	<6	23.5	<77	<3	<8	<28	<40	<40	<6	<5	<35	<60
	Aged	<6	<6	13.8	<77	<3	<8	<28	<40	<40	<6	<5	<35	<60
S-6	Fresh	<3	<3	23.1	<49	9.7	<9	<94	<40	<30	19.9	<9	89.8	5200
	Aged	<2	<5	28.2	147.8	3.5	<7	<13	<40	<4	7.2	<2	177.5	<50
J-7	Fresh	<2	<5	47.9	317.8	<1	<7	<13	<40	<4	4.6	<2	<24	<50
	Aged	<2	<5	7.3	66.1	<1	<7	<13	<40	<4	5.3	<2	<24	<50
W-8	Fresh	<6	<6	32.3	<77	<3	<8	<28	<40	<40	<6	<5	<35	<60
	Aged	<6	<6	24.4	<77	<3	<8	<28	<40	<40	24.8	<5	<35	<60
N-9 ⁽²⁾	Aged	<6	<6	24.9	762.4	<3	<8	<28	<40	<40	<24.2	<5	<35	<60
B-10	Fresh	<6	<6	40.7	<62	<4	<34	<235	<40	<27	<7	<10	<97	<60
T-11 ⁽³⁾	Fresh	<6	<6	16.3	117.0	<3	<8	<28	<40	<40	<6	<5	<35	<60
Most Stringent of Cdn. Regulated Limits Referenced ⁽⁴⁾		5,000	5,000	100,000	500,000	500	5,000	10,000	1x10 ⁶	100	5,000	5,000	1,000	10,000

Notes: (1) Trailing zeros may not be significant since analytical results were originally in mg/L

(2) U = 405 µg/L

(3) U < 11 µg/L

(4) U limit is 2,000 µg/L

Source: MEND 3.42.2a, modified from Table 15

Increased sulphate levels in the pilot plant influent produced higher sludge densities largely due to the formation of gypsum, while sludge settleability decreased linearly with increased sulphate concentrations. The addition of a flocculant facilitated particle agglomeration at high sulphate levels (e.g. 30 g/L range). The metal leachability of sludge appeared to be significantly influenced by the AMD sulphate level, with zinc and aluminum most mobile in sludge produced from high sulphate influent. The addition of excess lime to the sludges was not beneficial to the sludge properties or the sludge metal leachability as determined by Ontario LEP 347 testing. High concentrations of excess lime increased the leachability of aluminum from the sludge and increased the sludge volume. The degree of metal mobility from sludge was shown to decline with aging. There was a significant reduction in leachate concentrations after one year of laboratory aging under a range of temperature conditions. The effect of aging was particularly apparent for zinc mobility which declined by several orders of magnitude after one year of aging.

III. Applications and Limitations

The classification of AMD treatment sludges has been a recent area of study in Canada. This is an important issue as classification determines what disposal methods are suitable, and hence has an influence on disposal costs. Key questions are: What tests are applicable to classifying the stability of a sludge?, What is the long-term stability of the sludge? Research to date suggests that sludge will remain stable over the long term provided its geochemical environment is maintained. Operators would be prudent to:

- Characterize their treatment sludge; and
- Provide a geochemical environment that will remain stable over the long term.

IV. Base Method

Sludge disposal practices at 40 Canadian sites, as reported in MEND 3.32.1, include disposal to tailings ponds, settling ponds, recycle to smelter, landfill, natural basin, and a mined out open pit. The recycling of hydroxide sludges to smelters continues to be investigated, as, in concept, sludge recycling is beneficial as it reduces storage volume requirements, eliminates concerns over sludge stability, and provides some revenue to offset costs. In practice, the recycling of sludge presents a number of problems such as the acceptability of the sludge to the smelter, keeping in mind that smelters are licensed metal processing facilities and not waste disposal facilities, as well as the smelter charges, and the sludge drying, handling and transportation requirements. Nevertheless, at mine properties where sludge disposal presents a significant challenge, sludge disposal to a smelter may be preferable to alternate methods of disposal.

V. Variations

Alternate methods of sludge disposal including metal recovery are increasingly being assessed. The recycling of sludge to a smelter (Section 5.2.2) is one such method which is interesting but likely to be uneconomic.

VI. Cost

Sludge disposal costs range from low (e.g. permanent disposal in a settling pond) to very high as a result of sludge rehandling and disposal site costs or in some instances sludge processing costs.

VII. MEND and Relevant Publications

MEND 3.21.1b 1995. Metals Removal from Acid Mine Drainage by Ion Exchange. June.

MEND 3.32.1 1994. Acid Mine Drainage - Status of Chemical Treatment and Sludge Management Practices. June.

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

MEND 3.42.2b 1999. The Effect of Process Parameters and Aging on Lime Sludge Density and Stability. February.

Ford , R.C., Clapper, J.L. and Romig, B.R. 1998a. *Stability of Water Treatment Sludge, Climax Mine, Colorado. Part I: Chemical and Mineralogical Properties*. In: Proceedings of the 5th International Conference on Tailings and Mine Waste '98. Fort Collins, Colorado. 26 to 28 January. pp. 645-656.

Ford , R.C., Clapper, J.L. and Romig, B.R. 1998b. *Stability of Water Treatment Sludge, Climax Mine, Colorado. Part II: Leaching Characteristics*. In: Proceedings of the 5th International Conference on Tailings and Mine Waste '98. Fort Collins, Colorado. 26 to 28 January. pp. 657-667.

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

5.3 PASSIVE TREATMENT

This section summarizes MEND's contributions to the current understanding and application of passive AMD treatment methods. By definition, passive treatment includes methods of neutralizing AMD and removing metal contaminants that require minimal inputs of labour, energy, or raw materials following the initial capital construction phase. Passive treatment technologies include both physical/chemical and biological treatment methods. The passive technologies discussed in this section include anoxic limestone drains, aerobic wetland treatment systems, passive anaerobic treatment systems, and biosorbents. Variations on these basic passive treatment methods are also discussed, including open limestone channels, passive *in situ* treatment techniques, and hybrid active/passive treatment technologies.

The following discussion of MEND-sponsored research is supplemented by an overview of recent findings by governmental organizations, the mining industry, academic institutions, and consultants that have advanced the knowledge and applicability of passive AMD treatment technologies.

5.3.1 DISCUSSION OF THEORY

This section describes the theoretical basis for passive physical/chemical and biological AMD treatment systems.

5.3.1.1 Anoxic Limestone Drains (ALDs)

ALDs consist of limestone rock filters designed and constructed to gradually release alkalinity through dissolution of the limestone as acidic water flows through the drain. ALDs are truly passive treatment methods because the AMD flows through the limestone by gravity. Further, the rate of dissolution is controlled only by the flow rate through the drain and the size and quality of the limestone used. The maximum alkalinity achievable in ALD effluent is reported to be approximately 300 mg/L as CaCO₃ and cannot be increased significantly beyond this level by increasing the hydraulic retention time (MEND 3.14.1; Nairn *et al.* 1992).

ALDs are designed to exclude oxygen, as indicated by the term "anoxic" in their name. Excluding oxygen prevents iron oxidation and subsequent precipitation of ferric hydroxides within the drain. Also, the anoxic character of ALDs allows high CO₂ partial pressures to develop resulting in alkalinity additions greater than those possible in systems open to the atmosphere. Hence, anoxic conditions are critical to achieving effective treatment through the use of ALDs.

Effective ALDs are reportedly capable of neutralizing acidity resulting in the subsequent removal of metals, including aluminum, iron, and manganese (MEND 3.14.1). Metal removal occurs in an

aerobic pond or wetland downstream of the ALD rather than within the ALD. Therefore, oxidative ponds or wetlands are typically installed in conjunction with and downstream of ALDs. Figure 5.3-1 illustrates a schematic of a complete ALD system for treating coal mine drainage designed by Nairn *et al.* (1992), including settling ponds and aerobic wetlands downstream of an ALD.

5.3.1.2 Aerobic Wetland Treatment Systems

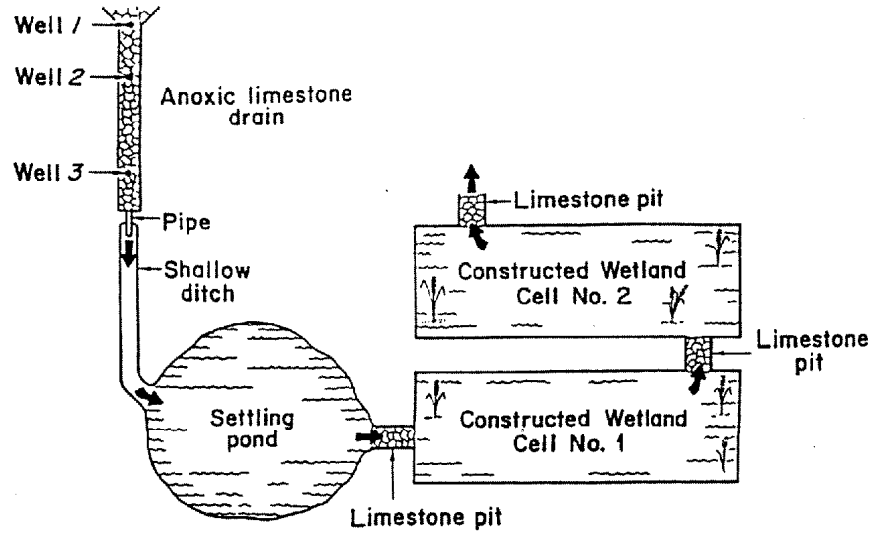
Aerobic wetlands are capable of facilitating a wide variety of abiotic chemical reactions and biologically mediated treatment processes for removing metal contaminants from aquatic environments. The key to successful treatment of AMD in constructed, aerobic wetland systems involves providing the proper combination of environments in the correct sequence required to facilitate the appropriate, site-specific removal processes.

Numerous examples of metal removal occurring in natural and constructed aerobic wetlands have been documented in Canada, Australia, the United Kingdom (UK), and the United States (U.S.). Several MEND reports describing pilot- and full-scale wetland treatment systems at metal mining sites are available, including MEND 3.14.1, 3.11.1, and 3.13.1a. However, Canadian experience to date indicates aerobic wetlands may only be applicable for mitigating small, marginally contaminated drainages or for use in polishing effluent from active treatment plants. Price and Errington (1998) cite the unreliability of passive treatment systems for consistently achieving compliance with low metals discharge limits in Canada due to the high influent metals concentrations, low temperatures during Canadian winters, and high metal loadings during the spring freshet.

Chemical and physical processes occurring in aerobic wetlands include oxidation, hydrolysis, chelation, adsorption, complexation, sedimentation, and filtration (MEND 3.14.1; MEND 3.11.1; Sobolewski 1997; Skousen *et al.* 1996). In his *Handbook for Constructed Wetlands Receiving Acid Mine Drainage*, Wildeman (1991) describes the abiotic removal processes occurring in passive wetland treatment systems. These processes include the exchange of metals onto naturally occurring organic matter, oxidation and oxyhydroxide precipitation, coprecipitation, and adsorption.

Aerobic wetlands are frequently constructed to act as sedimentation basins aided by various plant-mediated filtering mechanisms. Concentrations of metals such as aluminum, copper, and iron can be significantly decreased through abiotic processes as AMD flows through an aerobic wetland. Further, oxyhydroxide precipitates of ferric iron and aluminum are capable of scavenging other metal ions and removing them from solution by adsorption and coprecipitation reactions. For example, arsenic is readily removed from solution by coprecipitation with ferric hydroxide.

Figure 5.3-1 Schematic of a Complete ALD Treatment System



Source: Nairn *et al.* (1992)

Oxidation of iron from ferrous (Fe^{2+}) to ferric (Fe^{3+}) is dominated by abiotic processes at pH greater than about 4.5. The subsequent hydrolysis reactions leading to precipitation occur abiotically in the presence of oxygen, i.e. the reactions are not catalyzed by microorganisms (Hedin *et al.* 1994). However, the rate of iron oxidation is highly pH dependent. Ackman *et al.* (1984) indicate the relationship between pH and the time required to oxidize 97% of the ferrous iron in Pennsylvania coal mine drainage under oxygen saturation conditions was exponential. At a pH of 7, oxidation occurred in less than an hour, whereas at a pH of 6.0, 35 hours were required. At a pH of 5.5, more than 350 hours are required to oxidize 97% of the ferrous iron.

Ferric iron hydrolysis and precipitation reactions tend to proceed rapidly at pH greater than 3, but occur very slowly at pH less than 2.5. Provided oxygen and pH are not limiting and given the appropriate retention time, iron oxidation, hydrolysis, and precipitation occurs passively in oxidized portions of wetland environments. Oxidizing conditions needed to facilitate iron removal can be promoted in constructed wetlands in the following ways:

- By maintaining a shallow water depth, thereby by providing a large surface area for diffusion of atmospheric oxygen into the water;
- By planting aquatic plant species that oxygenate their root zones; and
- By providing mechanical aeration through construction of artificial riffles, such as small man-made cascades or drop structures.

Aerobic wetlands facilitate a wide variety of biologically-mediated chemical reactions and treatment processes capable of removing metal contaminants from aquatic environments. Biologically-mediated processes occurring in aerobic wetland systems include biological oxidation and plant uptake. Constructed aerobic wetlands are typically designed to mimic conditions in natural wetlands. Hence, an understanding of the biological processes occurring in aerobic wetlands is key to designing effective passive treatment systems. Metals are mainly removed by precipitation and exchange reactions while plant uptake and other processes are responsible for removal of a portion of the dissolved metals. Plants, especially the plant rhizosphere, provide large surface areas for oxygen exchange and also act as hydraulic baffles, thereby increasing the mass transfer of oxygen into the AMD. Plant growth and decay provide a constant supply of degradable organic matter. The organic matter provides sorption (adsorption and absorption) sites and stimulates bacterial activity.

Metals can also be removed by algae. For example, filamentous algae of the genus *Leptothrix* are capable of oxidizing manganese at relatively low pH and are a key component of aerobic rock filters being incorporated in passive wetland designs for AMD treatment. However, the total metal removal due to algae, other than *Leptothrix*, in wetlands is relatively low. Commonly used plant species in the wetlands can also transfer up to 45 grams of oxygen/m²/day (g/m²/d) to the rhizomes creating an aerobic environment for oxidation and precipitation reactions (MEND 3.14.1). Constructed wetland treatment systems have proven to be reliable and accepted mitigation

alternatives for treating net-alkaline AMD containing iron, aluminum and manganese (Jablonowski 1995).

5.3.1.3 Passive Anaerobic Treatment Systems

Studies conducted in Canada and the U.S. have documented substantial decreases in metals and sulphate concentrations and increases in the pH of AMD flowing through natural wetlands. MEND 3.12.2, *Panel Wetlands: A Case History of Partially Submerged Pyritic Uranium Tailings Under Water*, documents the findings of an extensive Canadian study of the processes controlling acid generation and metal mobility in a natural wetland. The Panel wetland area of Elliot Lake, Ontario, was affected by an accidental tailings release in the late 1950s. The natural wetland that developed behind a beaver dam at the downstream end of the basin contains both aerobic and anaerobic areas exhibiting different effects on water quality. The wetland had a surface area of approximately 15 hectares. Although pyrite oxidation and AMD generation continue in the unsaturated and shallow submerged tailings, the study demonstrated a significant increase in pH of the ponded water (from as low as 3.5 to as high as 9.8) and estimated approximately 96% of the oxidized iron was retained in the wetland system. The study observed no strong seasonal dependence on surface water quality, despite the harsh winter conditions at the site (MEND 3.12.2).

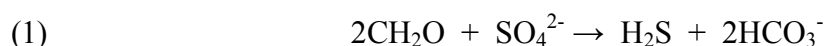
In contrast to Panel, MEND 3.12.1, *Assessment of Existing Natural Wetlands Affected by Low pH, Metal Contaminated Seepages*, documented the limitations of using natural wetlands for treating AMD. This project investigated six natural wetlands receiving AMD from metal mines in eastern Canada. The study concluded that all six natural wetlands were ineffective in treating AMD. Due to hydraulic channeling, metal-laden acidic water in natural wetlands tends to short-circuit the treatment processes by flowing mainly across the oxidized, vegetated surfaces. Although oxidation is an important process for removing iron, aluminum, and manganese, contact with the anaerobic sediments and anoxic deep water zones is needed for heavy metals removal and alkalinity production. It is well recognized that natural wetlands often do not facilitate adequate contact with the anaerobic sediments (MEND 3.12.1).

Passive anaerobic treatment systems are engineered ecological systems. In some respects, these system may appear to be similar to wetlands, but are designed to optimize the natural microbially-catalyzed chemical processes resulting in AMD treatment. Whereas aerobic systems may be adequate for removing iron, aluminum, and manganese from sources of net alkaline AMD, anaerobic systems are needed to remove the heavy metals and acidity typical of metal mining sites. In an anaerobic system designed to treat AMD, microbiological and chemical processes are responsible for most of the neutralization and heavy metal removal. Metals removal and acid neutralization are achieved by the activity of sulphate reducing bacteria (SRB). Typically, degradable low-cost agricultural wastes are used as the organic substrate for a consortium of bacteria to generate free sugars and other metabolites. Anaerobic microorganisms utilize these free

sugars to produce short chain organic acids that are further utilized as the carbon source for SRB (MEND 3.14.1). SRB derive energy by reducing sulphate ions to sulphide. This bacterial sulphate reduction reaction produces bicarbonate alkalinity and hydrogen sulphide (H₂S). The H₂S reacts with metals to form insoluble metal sulphides and the bicarbonate alkalinity neutralizes the AMD.

Conditions needed to promote biological alkalinity generation and sulphide precipitation include a highly reduced environment characterized by a low oxidation reduction potential (ORP) in the range of -100 to -300 millivolts (mV) and an abundance of degradable organic carbon. The organic carbon source is designed to be site-specific and waste-specific to provide a long-term food source for heterotrophic bacteria. The organic carbon source also exerts the biochemical oxygen demand (BOD) needed to create the highly reduced conditions.

Passive anaerobic treatment systems are living systems designed to optimize conditions for the growth of the SRB consortium. As represented in Equation 1, the SRB consortium mineralizes degradable organic matter (CH₂O) in the process of reducing sulphate (SO₄²⁻). The products of the reaction include hydrogen sulphide (H₂S) and bicarbonate alkalinity (HCO₃⁻). The bicarbonate produced as a by-product of this reaction acts to buffer the pH at about 6.5. In addition to bacterial alkalinity production, passive anaerobic treatment systems are often designed to incorporate limestone dissolution into the process.



Hydrogen sulphide generated by the SRB consortium reacts with divalent metal ions to form insoluble sulphide precipitates. As a simple example, Equation 2 represents the remineralization of dissolved zinc into sphalerite (ZnS) as a result of sulphide precipitation.



Due to the absence of dissolved oxygen, iron oxidation and precipitation reactions that would normally occur rapidly at neutral pH are prevented from occurring in passive anaerobic treatment systems. Hence, ferric hydroxide precipitation is not a significant threat to system performance under normal operating conditions.

Passive anaerobic treatment of AMD is typically conducted in a series of deep excavated ponds filled with organic matter. In the more successful systems, influent AMD flows vertically through the organic substrate that supports the SRB activity. System hydraulics are carefully designed and are not left to random chance, as is typical of natural wetlands. Successful upflow and downflow systems are documented.

Wildeman and Gusek (1997) have developed design guidelines for anaerobic treatment systems. At a pH of less than 3.0, SRB have been found to produce approximately 0.3 moles of bicarbonate alkalinity and 0.15 moles of sulphide per day from each cubic metre of organic matter (mole/m³/day). This functional relationship is dependent on environmental factors. At pH greater than 5.0, the criterion suggests designing for 0.3 mole/m³/day of sulphide production. During summer, rates as high as 2 moles/m³/day can be achieved. In warm climates, the higher rates may be appropriate for design; however, in cold climates, the lower rates should be used. Wildeman and Gusek (1997) design their systems to achieve an overflow rate of at least 20 square metres per litre per second (m²/L/sec) of flow. However, using the sulphide production rate for design typically provides ample hydraulic retention capacity.

Wildeman and Gusek (1997) recommend a staged approach to designing passive anaerobic treatment systems. The organic substrates of the most successful systems are carefully designed to address site-specific conditions through a sequence of laboratory-, pilot-, and field-scale tests prior to full-scale design. Experience has taught that the best organic substrates consist of mixtures of readily degradable and slowly degradable materials. Maintaining a high permeability in the organic substrate is critical to the long-term effectiveness of the anaerobic treatment systems.

5.3.1.4 Biosorption Treatment Methods

Certain types of microbial biomass can retain relatively high quantities of metal ions by passive sorption (adsorption and/or absorption) and/or complexation. This metal-sequestering process is commonly known as biosorption. Biosorption is caused by a number of different physicochemical mechanisms, depending on a number of external environmental factors, as well as on the type of metal, its ionic form, and on the type of a particular active binding site responsible for sequestering the metal. Microbial cells can continue to bind and accumulate metal ions even when the cells are not metabolically active or are dead. Biological metal-sorbing material or biosorbent is produced from the raw biomass which has a high metal-binding capacity.

The processes of sorption, ion exchange, and complexation with organic matter are important in metal removal. Sorption and complexation can remove 33 mg of iron per gram (dry weight) of *Sphagnum recurvum* moss (Wieder and Lang 1986). Plants can accumulate large quantities of metals. For example, *Sphagnum* can absorb so much iron that it petrifies. Most constructed wetlands are planted with *Typha latifolia* (cattails) which have appreciable cation exchange capacity to remove metal ions. Rushes and reeds in the natural environment and constructed wetlands have been reported to accumulate significant quantities of metals.

The separation of the growth of biomass from its function as a biosorbent is one of the major advantages of biosorption. It allows an independent propagation of microbial biomass in a separate process that can be operated specifically to produce a highly biosorbent biomass. Biosorbent, in some cases, can also be a by-product of well-established selected microbial processes operated by

pharmaceutical or chemical industries. Algae from marine or fresh water environments can also be used as biosorbents.

The biosorbent material should have characteristics that are suitable for selected process application. Some of these characteristics include hardness, porosity, particle size, density, and resistance to various solution parameters, such as temperature and pH. Examples of some highly biosorbent biomass which come from industrial fermentations are *Penicillium* and *Rhizopus*. Marine and fresh water algae, such as *Sargassum* and *Chlorella*, respectively, also have high biosorption capacities.

Several types of biosorbents are commercially available. There are a few enterprises in North America that are either developing or are selling developed biosorption processes for industrial applications. For example, Bio-Recovery Systems, Inc. in Las Cruces, New Mexico, developed a biosorbent from immobilized algae *Chlorella* in silica or polyacrylamate gels, and B.V. Sorbex, Inc., in Montreal, has also developed certain biosorbent processes. Many other commercially available biosorbents are discussed in MEND 3.14.1. Biosorbents have been used in constructed ponds to reduce the dissolved iron and manganese concentrations from AMD.

5.3.2. DISCUSSION OF MEND RESEARCH

The MEND program has advanced the state of knowledge and applicability of passive AMD treatment technologies through its sponsorship of key research projects at base metal mines under Canadian conditions. Relevant MEND research projects are summarized in the following paragraphs.

MEND 3.14.1 Review of Passive Systems for Treatment of Acid Mine Drainage: Phase I

MEND 3.14.1 summarized the state-of-the-art of passive treatment technologies, as of the mid-1990s. The project report presents a thorough and comprehensive summary of the design parameters, operating requirements, performance data, and cost information for four general technologies, including anoxic limestone drains, constructed wetlands, microbial bioreactor systems, and biosorption treatment systems. The term “bioreactor”, as used in MEND 3.14.1 includes both passive anaerobic treatment systems, as well as active batch or continuous tank systems.

Most of the operating passive treatment systems summarized in MEND 3.14.1 were designed to treat coal mine drainage in the eastern U.S. Laboratory-, pilot-, and full- scale systems are summarized. The report focuses on work performed by the U.S. Bureau of Mines (USBM) and documented by Hedin *et al.* (1994). Also, the work performed by Brodie and coworkers at the Tennessee Valley Authority (TVA) is frequently cited as the source of information on ALDs and

aerobic wetland treatment systems (Brodie *et al.* 1988; Brodie 1993a; Brodie 1993b). MEND 3.14.1 contains a wealth of information on passive AMD treatment, including the following:

- Detailed discussions of the theory and basis for design of the four technologies;
- Discussions of the applicability to Canadian metal mining sites;
- Discussions of the implications of long-term operation, including regeneration of spent treatment systems and future disposal of waste products;
- Well documented case studies of actual operating systems, including size data, flow and metals loading rates, influent and effluent chemistry, construction and operating costs, and treatment efficiencies; and
- An extensive bibliography containing references for dozens of operating systems.

MEND 3.14.1 presents a summary of the differences between AMD from coal mining or from Canadian metal and uranium mines. AMD from Canadian mines is characterized by low volume and high metals concentrations in the winter, and high volume and low concentrations in the spring due to dilution by the spring freshet. Low winter temperatures and short growing seasons are also cited as obstacles to the applicability of passive treatment systems in Canada. The report makes a number of conclusions. Little research and/or field applications of passive treatment systems is being done under Canadian climatic conditions or at Canadian mining sites. Biological based systems are expected to have only limited applicability in Canada due to their reduced effectiveness under extreme winter conditions and the high flow conditions associated with the spring freshet. However, the report suggests the potential obstacles to applying passive treatment systems in Canada could be solved if site-specific conditions are considered during design. The report concludes that “black-box” passive technologies are doomed to failure due to the vagaries of Canadian climate and mine drainage chemistry. Recommendations are made for additional investigations needed to address issues that prevent the use of passive treatment at Canadian metal mine sites, including:

- Adequately investigating issues related to disposal of spent substrates and treatment waste products, and developing clear regulatory guidelines for waste disposal;
- Investigating technology transfer from constructed wetlands for treating sewage in harsh winter climates to identify cold climate design parameters;
- Maximizing metals uptake through the use of wetland vegetation through improved understanding of plant physiology;
- Developing a mechanistic design approach based on a thorough understanding of the chemical, microbial, and plant components of the systems; and
- Incorporating cost-benefit analysis in the design of passive treatment systems to ensure their appropriateness for a particular AMD stream.

MEND 3.12.2 Panel Wetlands: A Case History of Partially Submerged Pyritic Uranium Tailings Under Water

MEND 3.12.2 investigated the mechanisms that mitigated the effects of AMD occurring in a natural wetland ecosystem that contained submerged uranium tailings. The report contains information and data relevant to understanding passive treatment processes occurring in wetland systems. The main goal of the study was to establish if a beaver-constructed natural wetland at Elliot Lake provided significant treatment and control over water quality parameters associated with the oxidation of pyritic tailings and control of contaminant migration. Another important project objective was to fully characterize the wetland hydrology, hydrogeochemistry, plant communities, and microbial populations. The final report provides detailed information on surface and groundwater hydrology, chemistry, water balance and its seasonal variations, solid phase characteristics of sediment/substrate, bacterial enumeration, and vegetation uptake of metals in the basin.

The Panel wetland study site is located in a small, 14.5 hectare (ha) basin located near the city of Elliot Lake, Ontario. The basin was inundated with approximately 236,000 tonnes of pyritic uranium tailings due to an accidental release in the late 1950s. A beaver dam constructed at the downstream, eastern end of the basin created a lake that submerged most (approximately 88%) of the tailings. Currently, an estimated 1.6 ha of tailings in the western end of the basin are not submerged and continue to generate AMD. The MEND project identified two zones within the natural wetland, the eastern, anaerobic, deep water zone and the central and western, aerobic, shallow water zone. The water in the eastern zone ranged from 0.4 to 1.4 m in depth, whereas the water in the central and western zones ranged from 0.1 to 0.5 m in depth. The west/central zone of the wetland was covered with dense vegetation, including cattails, grasses, sedges, sphagnum, and other mosses. Except for its eastern downstream end, the floor of the entire basin was covered by pyritic tailings. Tailings pore water exhibited low to neutral pH (2.1 to 7.5). The entire basin was originally covered with peat ranging from 0.4 m to 4 m deep prior to the tailings release.

The total volume of water in the wetland was estimated at 24,000 m³ and the average annual discharge through the basin was estimated at 4.4 L/s. Water in the western, vegetated end of the wetland was moderately acidic and contained low to medium concentrations of iron (1 to 80 mg/L) and sulphate (50 to 1000 mg/L). In the eastern and central parts of the basin, the tailings were permanently submerged. Water in the deeper area was moderately alkaline (pH 6.2 to 9.8) and contained low iron (0.002 to 0.4 mg/L) and sulphate (50 to 100 mg/L).

A groundwater flow component consisting of approximately 2 to 8% of the total volume of ponded water was identified at the study site. The groundwater was mostly tailings-derived and slightly acidic to neutral (pH 5.7 to 7.8). Shallow groundwater chemistry exhibited low acidity (10 to 200 mg/L as CaCO₃), variable alkalinity (0 to 1400 mg/L as CaCO₃), iron (0.5 to 70 mg/L), sulphate (800 to 1500 mg/L), and high radium-226 (280 to 10,900 mBq/L). Based on its chemistry, it

appears that at least some of the groundwater was net alkaline, which would partially explain the wetland's capacity to control the pH.

The study observed that the exposed unsaturated tailings were being oxidized at the surface and near the water table. The shallow submerged tailings were being oxidized in the root zone of the vegetation cover. Surface drainage and subsurface water from the oxidized areas were acidic (pH 3.4 to 5.5).

The microbial characterization of the wetland revealed that sulphate reducing bacteria (SRB) were present in all soil and sediments throughout the wetland. Strong sulphide odors in deep surface water and shallow groundwater provided evidence of bacterial sulphate reduction. Sulphur oxidizing bacteria, such as *Thiobacillus ferrooxidans*, were only found in significant numbers in the oxidized areas of the wetland. No clear trend in sulphur speciation was observed. Sulphide and sulphate concentrations were variable throughout all areas of the wetland. Wetland vegetation was found to be taking up metals in significant concentrations. This process occurred in all species, but was dominated by the cattails and grasses, which were the dominant species in the wetland ecosystem. No evidence of plant toxicity was noted.

Discharge water quality monitoring results confirmed that the wetland/water cover system in the Panel wetlands basin effectively controlled the acidic drainage from partially submerged pyritic uranium tailings. No improvement in surface water quality was observed in the shallow, vegetated and oxidized zones of the wetland where both the surface water and groundwater data indicated the vegetation was oxidizing the substrate rather than providing treatment. AMD from the exposed and shallow submerged areas appeared to be treated by dilution and mixing with clean water. It was estimated the AMD was diluted by a factor of 6 to 10 times. Further, the net alkaline groundwater entering the wetland appeared to neutralize the AMD and precipitate dissolved iron, aluminum, and manganese as hydroxides.

Up to 96% of the iron released due to oxidation and AMD generation processes is estimated to be retained in the wetland. Similar trends were observed for other metals, including calcium and radium-226. The investigators did not observe any significant seasonal variation in surface water quality, except for pH, which increased from 7.5 to 9.5 during the summer months. This phenomenon was attributed to bacterial nitrate reduction in the deep sediments and possible production of ammonia and hydroxyl radicals through aquatic plant photosynthesis. Additional investigation of this phenomenon was recommended.

MEND 3.12.2 concluded that the Panel wetland system would continue to control acidity and metals concentrations as long as the water cover is maintained. It was further concluded that the wetland's performance could be improved if all the tailings were completely submerged. This study confirmed that shallow water covers in combination with a natural wetland have the potential to

permit "walk-away" with minimal maintenance at some tailings sites. However, the residence time in the wetland was about 63 days, and such a long retention time would not be practical at most sites with large flow rates.

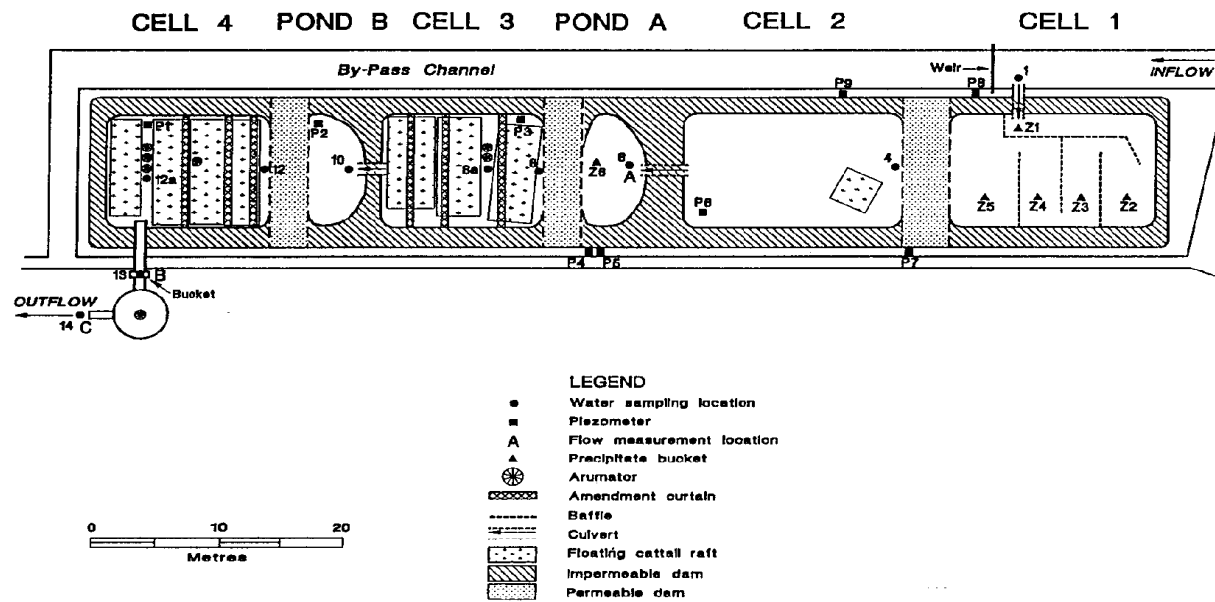
MEND 3.11.1 Treatment of Acidic Seepages Using Wetland Ecology and Microbiology

MEND 3.11.1 was a 4-year investigation into the potential of using wetland ecology and microbiology to reduce AMD from metal mines. A major objective was to develop design parameters for the Acid Reduction Using Microbiology (ARUM) process. The field tests were conducted at Inco's Copper Cliff tailings impoundment in Sudbury, Ontario, from 1989 through 1993. The ARUM system tested at Copper Cliff consisted of two aerobic cells for oxidizing and precipitating ferrous iron followed by two ARUM cells for removing non-ferrous metals, including copper, nickel, and zinc. The test cells received AMD at a flow rate of 1 L/min. Retention time in the ARUM cells was estimated to be approximately 131 days. The conceptual design of the test cells is depicted in Figure 5.3-2.

The oxidation ponds were designed to function similar to TVA's oxidation ponds. The ARUM ponds are described as anaerobic ponds covered by floating mats of living vegetation. The purpose of the vegetation mats is to provide reducing conditions throughout the water column by preventing oxygen diffusion and mixing. Additionally, the continuous cycling of organic carbon by the living vegetation is designed to replenish the organic substrate in the anaerobic ponds. The goal of the ARUM ponds was to create anaerobic sediment capable of generating excess alkalinity and removing metals through sulphide precipitation. The anaerobic cells were initially amended with organic substrates, including straw, alfalfa, and potato wastes. After two years, the ponds achieved 82 to 88% vegetative cover.

During the first year of the project (1989/1990), the test cells were constructed and flow control was established. However, the base of the tailings impoundment where the test cells were installed proved to be unstable, and flow control was problematic. The ARUM pond consisted of an 800 m³ fiberglass tank with an 800-L inner sleeve filled with organic matter. The first year's results were reported in June 1990 in MEND 3.11.1a. The results indicated the ARUM system raised the pH of the water from approximately 2.5 to 5.7 and reduced the influent nickel concentrations from 91 mg/L to 1.7 mg/L, albeit at a very low flow rate. The report concluded that the removal process occurred in the sediment and that a floating cattail mat was needed to enhance reducing conditions and provide a method of replenishing the organic matter in the sediment. The mechanism by which a reducing environment is created by the floating vegetation is not made clear in the report, i.e. cattail root systems are known to produce oxidizing conditions in shallow wetland sediments.

Figure 5.3-2 Makela Test Cells



Source: MEND 3.11.1a-d

The field tests were continued in the spring of the second year (1990/1991). The hydraulic regime was adjusted to maintain flows at approximately 3 to 5 L/min. Cells 1 and 2 were successful in oxidizing ferrous iron and precipitating the iron as ferric hydroxide so the influent to Cells 3 and 4 consisted of a clear, acidic solution containing low iron concentrations. Organic amendments were added to Cells 3 and 4, including hay and flax bales to act as the organic substrate for the sulphate reducing bacteria. Floating cattail mats were also established during the second year. The project conducted extensive laboratory studies to identify the environmental requirements of the microbial community. The results of the second year are documented in MEND 3.11.1b.

The third year (1991/1992) was the first opportunity to demonstrate the ARUM process after establishing the floating cattail mats in Cells 3 and 4. The flow rate was set at 1 L/min. By the end of the summer of 1991 approximately 50% of the nickel was removed from the low portions of the water column near the anaerobic sediment compared with the upper portions. Further, it was estimated that approximately 27 kg of alkalinity was generated in the system prior to discharge. However, the AMD appeared to be short-circuiting the treatment process, as the effluent pH and metals concentrations were only slightly changed from the influent concentrations. Also, the test cell's retention time was estimated to be about 4 months. Such a long retention time would be impractical for treating the AMD flows at most mine sites. The third year's results are documented in MEND 3.11.1c.

The test cells were monitored during the fourth year of the project (1992/1993). At a flow rate of 1 L/min, the system was capable of removing 80 to 87% of the nickel loading, 77 to 98% of the copper loading, and 47 to 73% of the acidity loading. The retention time was estimated at 131 days. The overall program assessment report, MEND 3.11.1a-d, was submitted in July of 1993. The final report entitled: *Treatment of Acidic Seepages Using Wetland Ecology and Microbiology: Overall Program Assessment*, summarized the field observations and measurements over 4 years, determined the operating parameters for the ARUM system, produced design criteria and conceptual designs, and estimated operating costs.

MEND 3.11.1 concluded that the ARUM process can create significant alkalinity (27 kg/tonne of water) and precipitate heavy metals as sulphides. However, the system was capable of handling only very low flows, less than 5 L/min. While the results showed that good water quality results had been achieved at a flow rate of 1 L/min, the ARUM process is not suitable for final treatment of large flows. Based on more current application of passive anaerobic treatment systems in the U.S., it seems likely the floating vegetation mats used in the ARUM system may be hindering treatment by creating an oxidizing environment in the cells. Also, the hydraulics of the test cells constructed during the MEND project appeared to be causing short-circuiting resulting in ineffective treatment.

Following completion of the MEND Project, the pilot system constructed in 1993 was left unattended for two years. The test cells were then extensively monitored during the summer of 1996. The 1996 monitoring program demonstrated that the ARUM cells effectively reduced the total acidity (91% removal) and metals concentrations (up to 99% removal) in the treated AMD (Kalin and Smith 1997). The principal investigators, Kalin and Smith, are currently scaling up the ARUM system for full-scale implementation at Mud Lake, in northwestern Ontario.

MEND 3.12.1a Assessment of Existing Natural Wetlands Affected by Low pH, Metal Contaminated Seepages

This study examined natural wetlands receiving AMD from six metal mines in eastern Canada. The purpose of the study was to identify natural wetlands that were mitigating the effects of AMD. A field program was conducted to describe and compare these sites in terms of water and sediment chemistry, hydrology, and vegetation. Two sampling periods, summer and late fall, were planned. However, only the early fall sampling event was conducted.

MEND 3.12.1a documented the random characteristics of natural wetlands. Large differences were observed among the sites, including metal loadings, retention times, influent metal concentrations, sediment chemistry, and vegetation. None of the wetlands included in this study significantly reduced the metal loadings they received. The researchers attributed this lack of treatment to three factors:

- Low water temperatures, i.e. circa 4°C;
- Short-circuiting caused by channeling of the flow patterns; and
- Inadequate contact between the AMD and the anaerobic sediments thought responsible for treatment.

Complex hydraulic regimes complicated the evaluation of the various wetlands studied. Most of the wetlands were receiving AMD from more than one source and also received significant groundwater contributions that further complicated the results. The project concluded that treatment processes occurring in natural wetlands were not effective, mainly due to the randomness of the flow through the wetland. Natural wetlands cannot be relied upon to treat AMD from Canadian metal mining sites. However, it was recognized that AMD treatment mechanisms occur in natural wetlands, but these processes need to be engineered to be effective. No further work was completed.

MEND 3.13.1a Passive Treatment Project at Heath Steele Mines, Phase I: Bench Evaluation of Four Prospective Processes

The objective of MEND 3.13.1a was to evaluate the applicability of four low-cost, passive AMD processes for treating small, acidic seepages. Bench-scale treatment tests were performed at the

Noranda Technology Centre in 1992. The bench-scale tests were operated continuously for more than 13 months.

The four technologies examined during the test were:

- Anoxic limestone (ALS) consisting of a 30-L column of 0.6 cm of limestone;
- A lime/organic mixture (LOM) consisting of a 30-L column filled with cow manure and 2.5 cm limestone;
- A biotrench (BT) consisting of an open trench filled with a mixture of straw and brewer's dried grain; and
- A biosorption (BIOS) system consisting of a 30-L column filled with a mixture of wood pulp, sawdust, and tree bark.

The columns were maintained in an anoxic state during the bench tests, whereas the biotrench was open to the atmosphere. Each column was fed a continuous flow of moderate strength AMD (pH, 2.5; iron, 160 mg/L; aluminum, 150 mg/L; zinc, 300 mg/L; copper, 60 mg/L; and sulphate, 4000 mg/L). The column flow rates were adjusted to achieve variable residence times, ranging from 1 to 14 days. Flow rates varied from 0.001 L/min to 0.02 L/min. The columns were operated in an upflow mode at an initial temperature of 20°C. Later, the temperature was lowered to 10°C. The AMD application rates were controlled by a peristaltic pump.

Operating at a residence time of 7 days and a temperature of 20°C, the LOM system raised the pH from 2.5 to 6.7, removed 100% of the metal contaminants, and removed 50% of the sulphate. The pH adjustment in the LOM column was attributed to alkalinity production resulting from bacterial sulphate reduction, as well as limestone dissolution. The high metal removal efficiencies were attributed to sulphide precipitation. When the operating temperatures were lowered to 10°C, the metals removal rates for all treatment processes were affected. The reduction in temperature resulted in a 40 to 50% reduction in the iron, aluminum, and sulphate removals in the LOM system.

The ALS column achieved 100% removal of all metals except zinc (72%) and only 30% of the sulphate, but achieved a pH of 6.6. The BIOS column demonstrated no appreciable increase in pH, very little metals removal except for zinc, and only 5% sulphate removal. The metals removal efficiency of the BIOS column improved when the residence time was extended to 14 days. However, the effects of low temperature were pronounced in the BIOS column, reducing the removal rates by up to 90%.

The BT system also removed 100% of the copper and 65% of the zinc, but failed to significantly raise the pH and removed only 18% of the sulphate. Because of its poor performance, operation of the BT system was discontinued early in the bench testing program.

MEND 3.13.1a concluded that the LOM system achieved nearly complete metals removal and significant pH adjustment at a residence time of 7 days. The researchers recognized that reductions in residence time and improvements in sulphate reduction could be achieved by combining the different systems in series. The researchers also recommended testing various combinations of systems, such as LOM-BIOS-ALS to address site-specific removal requirements. However, despite the positive bench-scale results, MEND 3.13.1a was discontinued after submission of the final bench testing report in 1994.

5.3.3 APPLICATIONS AND LIMITATIONS

In the past decade, passive AMD treatment systems have received widespread attention within the mining industry and regulatory communities. Treating AMD with only minimal labour, chemical, and energy inputs is an attractive concept that has sparked considerable investment and research. As documented in this Manual, MEND has been at the forefront of Canadian efforts investigating the applicability of passive treatment. Numerous pilot-scale and full-scale passive treatment systems have also been implemented in Australia, South Africa, the UK and the U.S. (SENES and Lakefield 1998).

Despite the widespread interest and extensive research, passive treatment systems have been deemed unreliable for treatment of AMD from metal mines in Canada. SENES and Lakefield (1998) stated that passive biological treatment systems have only limited applicability in Canada due to the cold climate and characteristically high metals loadings. The report notes that most passive treatment systems in Canada have been installed relatively recently, i.e. less than 5 years ago. The lack of data documenting long-term reliability is cited as an obstacle to the implementation of passive treatment at Canadian metal mining sites. Also, long-term storage and disposal of passive treatment residuals has not been addressed (MEND 3.14.1; SENES and Lakefield 1998).

In their report prepared for the British Columbia Ministry of Energy and Mines titled, *Guidelines for Metal Leaching and Acid Rock Drainage at Minesites in British Columbia*, Price and Errington (1998) state,

“Experience to date in British Columbia has shown that most forms of passive drainage treatment are incapable of handling high metal loads or high flow rates and reliably meeting low discharge concentrations. Passive treatment is best suited as a drainage polishing measure or for treating small seeps. Passive treatment is generally only recommended as the primary means of environmental protection where the use of other more reliable, but invasive mitigation measures, increases the net impact.”

The B.C. Ministry's report states that the term "passive" is misleading, citing systems that require regular monitoring, maintenance, and possibly complete replacement. The report states that some passive systems may actually require more monitoring than active AMD treatment systems due to the variability inherent in passive systems, although this statement is not supported by actual references and is debatable. Few, if any, of the potential benefits of passive AMD treatment are presented in the B.C. Ministry's report, whereas numerous potential disadvantages are cited (Price and Errington 1998). However, the report notes that most of the disadvantages and problems associated with passive AMD treatment in Canada, such as regulatory requirements, monitoring, low winter temperatures, and extreme fluctuations in metal loading, are also disadvantages and problems facing active treatment systems.

The perception that passive AMD treatment technologies are unreliable for treating large flows in cold climates is slowly changing. Better understanding of treatment mechanisms, design parameters, and operation and maintenance requirements is improving the feasibility of developing larger, more effective systems. It is generally accepted that the applicability of passive treatment is significantly improved when implemented in conjunction with hydraulic controls, such as run-on and run-off diversions, surge ponds, and infiltration barriers designed to reduce or equalise the seasonal variability typical of AMD flow volumes and metal loadings. Also, hybrid passive/active systems are being designed and tested to address some of the long-term reliability issues raised by SENES and Lakefield (1998) and Price and Errington (1998).

The subsections that follow provide specific information relating to the applicability and limitations of the specific types of passive AMD treatment systems described herein.

5.3.3.1 Anoxic Limestone Drains (ALDs)

MEND 3.14.1, *Review of Passive Systems for Treatment of Acid Mine Drainage*, states that the applicability of ALDs for treating AMD at Canadian base metal mines is limited because oxygen, ferric iron, and aluminum concentrations frequently exceed the generally accepted criteria. ALDs are generally considered feasible for treating AMD containing dissolved oxygen, ferric iron (Fe^{3+}), and aluminum in concentrations of less than 1 mg/L each. If these constituents are present in concentrations greater than 1 mg/L, the long-term effectiveness of ALDs is expected to be limited due to armouring and/or plugging of the limestone by ferric or aluminum hydroxide precipitates. Also, AMD containing sulphates greater than about 2000 mg/L are expected to limit the applicability of ALDs due to the potential for gypsum precipitation resulting in armouring of the limestone and plugging of the pore spaces.

Wildeman *et al.* (1997) conducted an investigation of AMD from over 50 metal mines in the Colorado Rocky Mountains to identify suitable candidates for ALD treatment. Their investigation included field and laboratory analyses of AMD samples collected at the mines. The investigation indicated that AMD emanating from the mines were closely correlated with modeling predictions of

metal solubilities in AMD. For example, ferric iron is generally absent from AMD at pH greater than about 3 and significant concentrations of dissolved Al persist up to about pH 4. Most AMD sources studied in Colorado contained dissolved oxygen concentrations exceeding the limits recommended by Hedin *et al.* (1994). The overall conclusion was that most AMD sources in Colorado are not suitable candidates for ALD treatment unless anoxic ponds are installed upstream of the ALD to reduce excessive dissolved oxygen concentrations. Research conducted in Colorado's Rocky Mountains is relevant to the Canadian experience because of the similarities in geologic and climatic conditions.

MEND 3.14.1 states ALDs have been designed to treat coal mine seeps flowing at rates from 0.5 L/min to 1855 L/min. Generally, larger ALDs are required to treat larger flows, although the size of an ALD is also related to the net acidity of the AMD being treated. Therefore, ALDs are only applicable to sites with sufficient space available to accommodate the site-specific size requirements.

ALDs are generally effective in neutralizing AMD with a net acidity of less than about 275 mg/L as calcium carbonate (CaCO₃). This limitation is due to the solubility limits of CaCO₃ in an anoxic, closed system of about 300 mg/L. In systems open to the atmosphere, the solubility of CaCO₃ would only be equivalent to 50 or 60 mg/L (MEND 3.14.1).

The conclusions of MEND-sponsored projects indicates that the applicability of ALDs at Canadian base metal mines is limited to a narrow group of sites with appropriate geochemistry, manageable AMD flow rates, and adequate space availability. Therefore, ALD's would fit a relatively small niche among Canadian AMD treatment options.

5.3.3.2 Aerobic Wetland Treatment Systems

Aerobic wetlands are only effective for treating net-alkaline waters. Wetlands should be designed solely for the oxidation of iron, aluminium, and manganese and subsequent precipitation and settling of these metal oxyhydroxides (Hedin *et al.* 1994; Watzlaf and Hyman 1995). Because of their effectiveness in removing these metals from net-alkaline drainage, dozens of aerobic wetlands have been successfully installed and operated in coal producing regions of the eastern U.S. However, aerobic wetlands frequently need to be installed in series with anaerobic systems to achieve complete treatment of net-acidic AMD from coal and metal mining sites.

The most efficient AMD treatment mechanisms occurring in wetlands are abiotic, chemical and physical processes. Biological AMD treatment methods include plant uptake of metals, plant-mediated oxidation, and biosorption. Constructed wetlands designed to treat AMD through plant-mediated metals uptake have limited applicability due to their long hydraulic retention and large surface area requirements. Numerous studies of naturally occurring wetlands and pilot-scale

constructed wetlands have demonstrated that plant uptake is a relatively ineffective AMD treatment mechanism (Hedin *et al.* 1994). At best, metal uptake by plants is considered a secondary polishing mechanism.

Plant-mediated oxidation is an important AMD treatment mechanism. Numerous studies have demonstrated the capability of the root zones of wetland plant communities to oxidize metals, such as ferrous iron. MEND 3.12.2 indicated the shallow submerged root zone of the Panel wetland played an important role in oxidizing ferrous iron. Also, MEND 3.11.1a-d demonstrated the ability of the floating vegetative mats used in the ARUM system to oxidize iron, thereby facilitating its removal as ferric hydroxide. The TVA and USBM wetlands used extensively in eastern U.S. coal regions usually contain vegetated shallow marshes to facilitate iron oxidation.

Vegetation-based wetland treatment systems have proven effective in treating small, low-strength, net-alkaline AMD flows from metal mining sites, but have proven somewhat unreliable in treating high-strength AMD. For example, Sobolewski *et al.* (1995) conducted an extensive wetland treatability study at the Bell Copper Mine located near Smithers, British Columbia. Wetlands were designed and built to alternately receive copper-containing AMD in low concentrations at 0.3 to 1.0 mg/L with a pH range of 7 to 8, and in high concentrations of 35 to 50 mg/L with a pH of 3.5. The Bell AMD also contained zinc, iron and sulphate concentrations exceeding 2000 mg/L. The objectives of the test were to determine the level of treatment achievable at a northern mine on a year-round basis, and to establish design parameters for construction of wetlands at Canadian mines. The biological, chemical and operational data from these tests were collected from 1991 through 1993.

The experimental wetlands at the Bell Copper Mine were constructed in 1990. The wetlands consisted of two membrane-lined ponds having nominal surface areas of 300 m² and 75 m². The ponds were fertilized and planted with floating peat mats approximately 45-cm thick. The peat mats supported the growth of sedges, such as *Carex aquatilis* and *C. laeviculmis*. Cattails (*Typha latifolia*) were also planted in the small wetland. Both wetlands were fully covered with vegetation by 1991. The large and small wetlands received AMD flow rates of 8 L/min and 2 L/min, respectively, during the pilot test. Retention times were 12 days for the large wetland and 22.5 days for the small wetland (Sobolewski *et al.* 1995).

During the period from April 1992 through June 1993, the wetlands received the low-strength mine drainage (0.3 to 1.0 mg/L copper and pH 7 to 8). The copper removal efficiency was greater than 98% for both wetlands throughout the trial. It should be noted that copper can precipitate chemically, without biological catalysis, at a pH of 7.5 to 8. By the end of June, 1993, copper concentrations of 35-50 mg/L were introduced to the wetlands. During the first six weeks, the copper was efficiently removed. However, the efficiency fell gradually to 40% in the large wetland and 80% in the small wetland by October 1993. The efficiency was tied directly to

the pH levels. The pH fell faster in the large wetland to a value of 4.7 by the end of August. The small wetland had a pH of 5.1. The conclusion was that the wetlands had three months of buffering capacity after the higher concentrations of copper were introduced. It was also noted that SRB were evident in the peat, and the peat in both wetlands remained anaerobic since 1991. However, SRB alkalinity generation was apparently not sufficient to prevent a sharp decrease in pH upon introduction of the high-strength AMD. The results of the tests confirm that vegetation-based wetlands can effectively treat some sources of low-strength, net-alkaline AMD in northern climates, but are not effective for treating net-acidic, high-strength AMD due to a lack of biogenic alkalinity production (Sobolewski *et al.* 1995).

Given sufficient land area and appropriate climatic and geochemical conditions, wetland treatment can be used to remove metals from net-alkaline metal mining effluent. Jones *et al.* (1995) describe a unique system based on algal oxidation and uptake at the Hilton Mine, located 20 km north of the city of Mt Isa, Australia. Flow rates of 2,000 to 6,000 m³/day are pumped from the Hilton Mine and discharged into primary settling ponds, where large quantities of flocculated iron hydroxide precipitate. The supernatant is pumped and flows freely down a hillside, approximately 50 m, to a 53,000 m³ evaporation pond. Then the water flows by gravity to Mt Isa down a channel approximately 1.4 km in length for use in ore processing. Jones *et al.* (1995) confirmed that the algal growth in the channel removed zinc and manganese from the water. Acid digests of algal samples showed large amounts of iron, zinc and manganese. However, the most significant reduction in metal is attributed to a rise in the pH following degassing of dissolved carbon dioxide. Analysis of this large-scale system documented hydraulic design problems and their solutions, diurnal pH shifts due to algal respiration, and other biological and physical mechanisms that resulted in AMD treatment.

Use of the bacterium *Leptothrix discophora* in oxidizing manganese has recently been incorporated into passive aerobic wetlands. The large, pilot-scale systems at the Wheal Jane Mine, for example, contained aerobic rock filters designed specifically to remove manganese. *Leptothrix discophora* is capable of oxidizing manganese at relatively low pH and precipitating the manganese as an oxide on the rock surfaces. These aerobic rock filters have proven highly successful in reducing the large size requirements for aerobic wetlands receiving manganese-laden AMD (Cambridge 1997; Gusek *et al.* 1998).

Researchers and mine operators alike have recognised that certain plant materials had the ability to adsorb heavy metals. *Sphagnum* moss, for example, is quite effective in removing metals from AMD in natural and constructed wetlands. The ability of plants to adsorb metals is discussed in its own section on biosorption.

Site-specific factors that may limit the applicability of constructed aerobic wetlands for treatment of AMD include the following:

- Lack of available land area;
- Lack of sufficient water needed to sustain wetland conditions year round;
- Inappropriate soils or construction materials;
- Climatic conditions, such as extremely cold or arid conditions; and
- Regulatory limitations, including wetland protection laws, mine operation and closure permits restrictions, threatened and endangered species laws, and archaeological survey requirements.

These limitations are discussed in depth in MEND 3.14.1.

5.3.3.3 Passive Anaerobic Treatment Systems

As a general rule, base metals such as cadmium, lead, nickel, and zinc are not effectively removed in aerobic wetland environments. Some minor removals of base metals may occur under aerobic conditions due to coprecipitation and adsorption reactions. However, if base metal contamination is a concern, passive anaerobic treatment systems should be provided. Frequently, the most effective passive method for treating AMD requires providing anaerobic systems in conjunction with aerobic wetlands to create a complete, integrated treatment system, including acid neutralization; base metal removal; and iron, aluminum, and manganese removal (Hedin *et al.* 1994). Wildeman *et al.* (1993) provide a detailed discussion of the differences in applicability of anaerobic and aerobic systems in their design manual entitled *Wetland Design for Mining Operations*. In contrast to aerobic wetlands, anaerobic systems perform at lower pH, can operate through the winter, and are capable of removing heavy metals that are not removed in constructed aerobic wetlands, such as cadmium, copper, lead, and zinc. Passive anaerobic treatment systems rely on subsurface flow to produce the reducing conditions, sulphide precipitation, and biogenic alkalinity production needed to treat net-acidic AMD, whereas aerobic wetlands emphasize surface flow and oxidizing conditions (Wildeman *et al.* 1993).

Examples of engineered pilot- and full-scale passive anaerobic treatment systems are documented in Canada, the UK, and the U.S. Some have been highly successful, whereas others have been only marginally successful at removing heavy metals and neutralizing acidity. As the knowledge and experience base evolves, more successful systems are being implemented.

Early in the development of passive anaerobic treatment systems, Béchard *et al.* (1995) constructed a pilot-scale system at the Halifax International Airport in 1989. Weathering of pyritic slate exposed during airport runway construction resulted in acidic metal-laden drainage. The pilot-scale treatment system consisted of open, clay-lined trenches filled with organic matter that were scaled up from laboratory reactors tested by CANMET. The trenches received a controlled flow of acidic drainage at a rate of 23 L/min and provided a residence time of 20 hours.

CANMET's system at Halifax International was operated and monitored for almost 900 days. During that period, discharge limits were met for a total of 13 consecutive weeks. The treatment process successfully treated the AMD at temperatures as low as 0°C, indicating the Canadian climate does not necessarily preclude the use of passive anaerobic systems for treating AMD. Béchard *et al.* (1995) noted that the hydraulic design of the system needed improvement to maintain anaerobic conditions. The final report is illustrative of the process by which passive AMD treatment systems have evolved. In particular, the CANMET system design recognized that it was not necessary for passive treatment systems to look like natural wetlands.

The Colorado School of Mines (CSM) was an early pioneer in the treatment of AMD from metal mines. CSM developed the *Handbook for Constructed Wetlands Receiving Acid Mine Drainage* (Wildeman 1991) under contract with the U.S. EPA's Superfund Innovative Technology Evaluation (SITE) program. The CSM handbook was based partly on laboratory and pilot-scale testing of passive anaerobic treatment systems conducted at the Big Five Tunnel in Idaho Springs, Colorado. The Big Five Tunnel drainage was highly acidic and contained heavy metals, including cadmium, lead, and zinc. While the CSM handbook describes the many and varied benefits of passive wetlands for treating AMD, it was one of the first reports to document the use of SRB and passive anaerobic treatment systems for generating alkalinity and removing metals from metal mine AMD in the U.S. CSM's work at the Big Five Tunnel documents the feasibility of using passive anaerobic treatment systems in cold climates, recognized the importance of hydraulic design for preventing short-circuiting, and was one of the first efforts to recognize that plant uptake is a relatively inefficient method of removing metals from AMD when compared to the high efficiencies associated with anaerobic treatment processes (Wildeman 1991).

The ARUM system described in MEND 3.11.1a-d recognized the importance of SRB and anaerobic treatment processes for treating AMD from metal mining processes. However, the extremely long hydraulic retention time required by the ARUM process severely limits its applicability for use in full-scale treatment. The ineffectiveness of the ARUM process demonstrated under MEND 3.11.1a-d is due to poor hydraulic design that causes the AMD to short-circuit the most effective treatment zone, the anaerobic sediments. Also, the concept of a self-regenerating system is appealing, but the floating vegetation mats that are characteristic of the ARUM system may actually be hindering treatment by oxygenating the ponds. Unfortunately, the perceptions of the Canadian mining and regulatory community toward passive anaerobic treatment methods may have been negatively influenced by the inefficiency of the ARUM test cells.

Sobolewski (1996) pilot tested a passive treatment system at a United Keno Hill silver mine in the Yukon Territory that was designed to mimic a natural wetland with a full complement of aquatic vegetation. The 180 m² system received AMD from an adit at a rate of 18 L/min. The adit drainage contained 20 to 30 mg/L zinc, as well as other heavy metals. After spending

considerable time establishing the wetland plant community, the pilot test was only run from August through September of 1995. The pilot-scale system removed 88% of the zinc. Other metals, including cobalt, iron, manganese, and nickel were also effectively removed. The treated effluent from the pilot-scale system was discharged to a natural wetland where most of the remaining zinc was removed. The hydraulic retention time in the pilot-scale treatment system was approximately 3.2 days. Initially, metals removal rates were poor due to channelization of the flow and short-circuiting. Baffles were later installed to correct the hydraulic problems which, in turn, resulted in improved metal removal efficiencies.

Although the Keno Hill treatment system was designed as a wetland, it was observed that microcosms within the system were obviously anaerobic, and almost complete metal removal was occurring. Plant up-take was determined to be ineffective in removing metals. Hence, most of the removal in the pilot treatment system was attributed to SRB activity in the anaerobic zones (Sobolewski 1996).

Kepler and McCleary (1994) made a significant breakthrough in passive AMD treatment by developing their successive alkalinity producing systems (SAPS). They recognized that the large surface areas and long retention times required to treat AMD in constructed wetlands represented a significant obstacle to applicability of passive treatment for net-acidic, metal-laden drainage. SAPS represent the second generation of passive anaerobic treatment systems designed specifically to overcome the problems associated with constructed wetlands receiving AMD. SAPS consist of deep anaerobic ponds designed to promote vertical flow through a mixture of organic substrate and limestone. SAPS contain no wetland vegetation, and are based on the recognition that treatment is more cost effectively managed in deep, open ponds than in shallow wetland marshes. Most importantly, SAPS represent one of the first mechanistic designs for passive treatment of net-acidic AMD. The mechanistic design approach allows for significantly more conservative sizing calculations based on an understanding of pH, alkalinity, and metal-loading rate functions.

Kepler and McCleary (1994) describe the operation of three full-scale SAPS receiving net-acidic coal mine AMD in Pennsylvania. The three systems were monitored over 2 full years. The systems demonstrated consistent acidity removals ranging from 200 to 350 mg/L as CaCO₃. The hydraulic residence times for the three systems ranged from 4 to 12 hours, representing a significant decrease compared with previous wetland designs. Because of the short residence times, the three full-scale SAPS were sized to be considerably smaller than comparable wetland designs. It should also be noted that winter conditions in Pennsylvania are comparable to eastern Canada. Kepler and McCleary (1994) recommended that SAPS be used in conjunction with aerobic wetlands to provide complete AMD treatment systems, including alkalinity production, metals removal, settling, and oxidation.

Knight Piesold conducted three separate passive treatment demonstrations at the Wheal Jane Mine in Cornwall, UK, during 1993 and 1994. The mine discharged AMD at flow rates ranging from 220 to 1,400 L/s. The pH of the AMD ranged between 2.8 and 3.0 and contained arsenic, cadmium, copper, iron, nickel, and zinc in concentrations exceeding environmental quality standards by several orders of magnitude. The Wheal Jane pilot tests documented the potential effectiveness of passive anaerobic treatment systems at metal mining sites (Cambridge 1997; Hamilton *et al.* 1997). The field-scale demonstrations successfully removed arsenic (94% to 100% removal), cadmium (100% removal), copper (100% removal), iron (66% to 93% removal), manganese (0% to 89% removal), and zinc (44% to 95% removal). AMD flow rates in the pilot treatment systems ranged from 6 to 30 L/min. The Wheal Jane project demonstrated that passive treatment technologies could be used to treat complex mine waters and achieve stringent water quality standards. However, at the Wheal Jane site, it is estimated that passive biological treatment could only achieve 50% compliance with environmental quality standards given the land area available for construction of aerobic and anaerobic treatment systems. Nevertheless, Knight Piesold's work at Wheal Jane provides important design and operating data for passive treatment of AMD from metal mining sites. Data presented by Hamilton *et al.* (1997) are an important resource providing information regarding system sizing, hydraulic residence times, metal loading rates at the Wheal Jane test site.

MEND 3.14.1 states that passive anaerobic treatment systems have to be supplemented with fresh organic substrate every six to twelve months and that the degraded substrate eventually gets saturated with sorbed metals and has to be removed periodically. However, with better understanding of system design parameters, successful full-scale systems have been installed that are projected to operate up to 30 years without significant maintenance requirements. For example, Knight Piesold's anaerobic treatment cell design at ASARCO's West Fork lead mine in Missouri is expected to operate up to 30 years without replacing the substrate (Gusek *et al.* 1998). These cells are successfully discharging 5,500 L/min of treated AMD that consistently meets drinking water standards. Figure 5.3-3 illustrates the configuration of the passive anaerobic treatment system constructed at the West Fork Mine.

The organic substrate used at the West Fork Mine consists of a mixture of sawdust, alfalfa mulch, manure, and limestone. Still, long-term operating requirements for passive anaerobic treatment systems remain uncertain because no full-scale systems have operated more than 10 years, and most have operated less than 5 years. The lack of long-term performance and operating and maintenance cost data is an obstacle to more widespread applications of passive anaerobic treatment systems. As stated in MEND 3.14.1, significant data gaps regarding the long-term costs and regulatory requirements for substrate management, future replacement, and system closure need to be filled.

5.3.3.4 Biosorption Treatment Methods

The quantity of metal removed using biosorption systems is a function of the influent water quality, residence time, influent temperature, and the capacity of the biosorbents to remove metals from solution. Depending on the quality of the influent, a biosorption system may or may not produce an effluent that meets the Canadian Metal Mining Liquid Effluent Regulations and Guidelines (MEND 3.14.1). For example, an efficient algal system accumulating up to 50,000 mg/kg Mn would only be capable of removing 4 mg/L of Mn from solution based on current wetland sizing criteria (Hedin 1989).

The biosorbent systems may become saturated with metals relatively quickly. Once saturated, biosorbents have to be replaced or regenerated. Data on the long-term use of biosorbents in AMD treatment are lacking. Hence, it is difficult to identify the performance, maintenance, and monitoring requirements for biosorption systems. Also, the short duration of the studies conducted to date provide little information on removal and disposal requirements of biosorbents.

Biosorbent systems can be used as secondary treatment units in conjunction with other types of systems such as chemical precipitation. According to the information available at this time, biosorbents do not seem to be an effective stand-alone system for treatment of AMD.

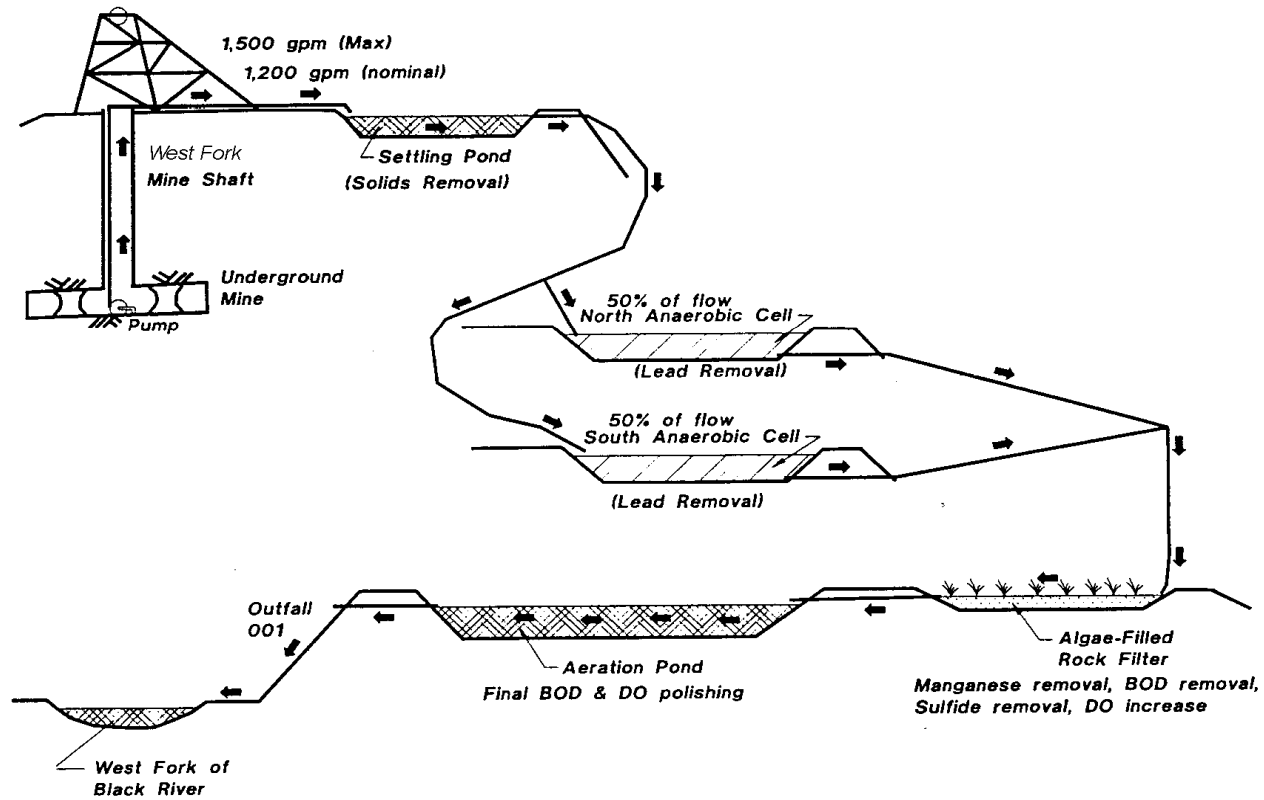
5.3.4 BASE METHOD

This section provides information on the base methods or typical successful operating systems utilizing passive methods for treating AMD. It is emphasized, however, that well defined “base methods” may not truly exist for passive treatment systems for two important reasons. Firstly, passive treatment designs must, by their natures, be site-specific and AMD-specific. It is unlikely a single black-box approach to passive AMD treatment will ever be developed. Secondly, passive treatment systems are innovative. Passive treatment technology is rapidly evolving and current base methods may soon be replaced by more highly evolved systems. Base methods representing the current state-of-the-art for passive treatment systems are presented in the following subsections.

5.3.4.1 Anoxic Limestone Drains (ALDs)

ALDs typically consist of subsurface limestone-filled trenches capped with a composite geotextile/soil cover designed to exclude air and prevent infiltration of oxygenated rain water. Figure 5.3 -4 illustrates a typical ALD design presented by Nairn *et al.* (1992). A key ALD design requirement is that the ALD remain saturated at all times. To prevent exposure to atmospheric

Figure 5.3-3 Design of the West Fork Passive Treatment System



Source: Gusek *et al.* (1998)

oxygen and maintain saturated conditions, ALDs are often excavated considerable distances into collapsed shafts or at toes of seepage areas. MEND 3.14.1 indicates the dimensions of ALDs are site-specific, depending on many factors, such as space limitations, flow rates, ground-water regimes, and surface topography. Most ALDs are narrow, about 0.6 to 1 m in width, and shallow, 1 to 2 m in depth. ALDs range in length from 50 to several hundred metres.

ALDs are sized to provide sufficient hydraulic residence time to achieve the greatest alkalinity possible for the maximum expected flow rates. MEND 3.14.1 reports the residence times achieved in more modern ALDs range from 14 hours to 23 hours, with 14 to 15 hours being the most commonly recommended residence times.

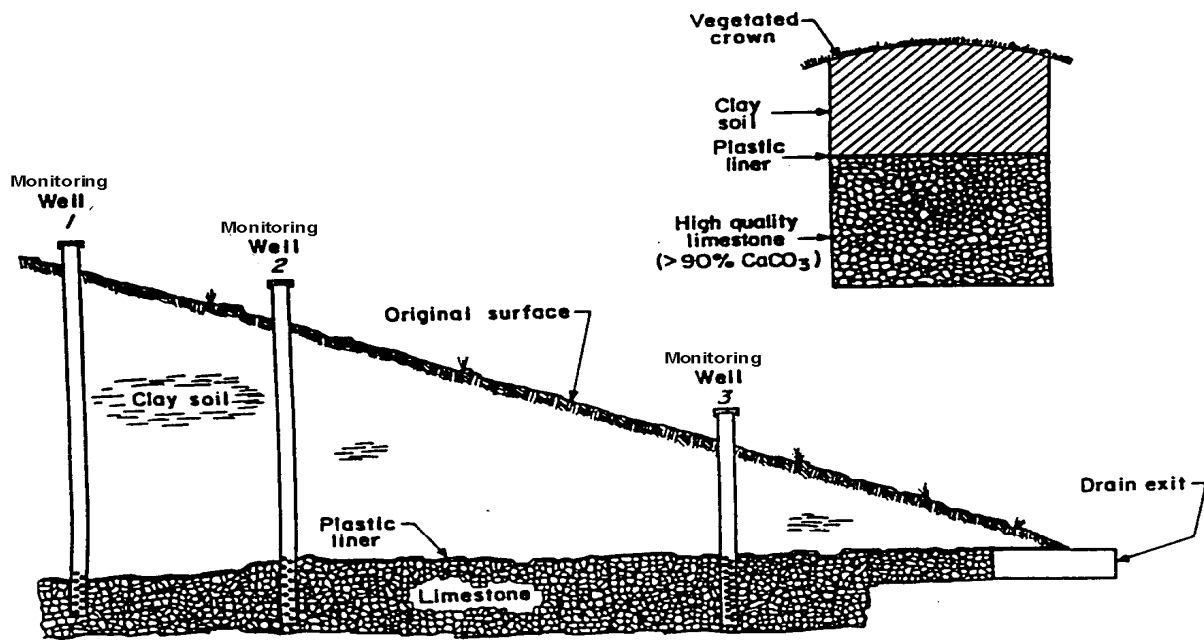
MEND 3.14.1 reports that the consensus among ALD practitioners is that high-calcium limestone is the most effective material of construction. The greatest alkalinity is achieved using limestone with about 90% CaCO₃ content (Hedin *et al.* 1994). Most successful ALDs are constructed of "baseball" sized particles to ensure adequate hydraulic conductivity. Those constructed of particles less than 2 cm have typically failed due to lack of sufficient hydraulic conductivity. Hedin and Watzlaf (1994) developed an empirical formula for estimating the mass of limestone needed to achieve the desired alkalinity over the design life of an ALD. This formula relates the required mass to process variables, including the desired alkalinity, design life, residence time, limestone quality, bulk density, and void volume of the limestone. Skousen (1996) also provides valuable empirical data for guidance in constructing ALDs, as well as cost data.

In summary, ALDs have proven applicable for treating AMD from coal mining sources with suitable chemistry, i.e. < 1.0 mg/L Fe³⁺, < 1.0 mg/L Al, and < 1.0 mg/L dissolved oxygen. As ALD technology improves and design guidelines are better understood and applied, ALDs are becoming effective, reliable, low cost, passive AMD treatment systems when applied under appropriate conditions. ALDs are currently applied exclusively in treating coal mine AMD. Studies showed that ALDs are generally not applicable for treating AMD from metal mining sites in Colorado, which are likely to be representative of metal mining sites in general.

5.3.4.2 Aerobic Wetland Treatment Systems

The decision flow chart presented in Figure 5.3-5 by Hedin and Nairn (1992) and Hedin *et al.* (1994) serves as the base method for selecting appropriate AMD treatment technologies. Using this decision chart, aerobic wetlands are recommended exclusively for removing dissolved iron, aluminum, and manganese from net-alkaline AMD at a pH greater than about 4.5. The U.S. Bureau of Mines (USBM) estimates over 400 wetlands have been constructed for the treatment of AMD (Kleinmann 1991) based on this approach.

Figure 5.3-4 Longitudinal-Section and Cross-Section of the Anoxic Limestone Drain



Source: Nairn *et al.* (1992)

The model developed by the Tennessee Valley Authority (TVA) known as the Staged Aerobic Wetlands for Acid Mine-Water Purification (SaWAMP) model is likely the best example of a base method for aerobic wetland treatment of AMD. The design, construction, and operation guidelines for the staged aerobic wetlands-based acid drainage treatment systems are provided in Brodie (1993a and 1993b). A typical staged aerobic constructed wetland is shown in Figure 5.3-6. Examples of several configurations of staged, aerobic wetlands for AMD treatment are shown in Figure 5.3-7. Depending on the site-specific treatment requirements, a SaWAMP wetland may consist of one or more of the following components:

- An ALD to provide sufficient alkalinity to buffer the pH at greater than 5.5;
- A deep pond for precipitation and sedimentation of ferric hydroxide and removal of suspended solids;
- A deep marsh for additional iron and manganese removal;
- A shallow marsh or rock filter to promote biological manganese removal;
- Limestone beds to add additional alkalinity after removal of the iron, manganese and aluminum; and
- A deep polishing pond.

Appropriate sizing is one of the most important factors for designing an aerobic wetland system. A key criterion for design of aerobic wetlands for iron removal is the surface loading rate expressed in terms of grams of iron loading per square metre per day ($\text{g}/\text{m}^2/\text{d}$). Design data collected by the USBM (Hedin *et al.* 1994) and TVA (Brodie 1993a, 1993b) are summarized in MEND 3.14.1. Table 5.3-1 summarizes the various sizing criteria used to design passive aerobic wetlands in the eastern U.S.

Figure 5.3-8 illustrates a simplified flowchart for designing staged aerobic wetlands (Brodie 1993a). The flowchart indicates that a surface loading rate of 2 to 11 $\text{g}/\text{m}^2/\text{d}$ is an appropriate wetland design criteria for achieving iron removal from coal mine drainage in the eastern and southeastern U.S. If manganese removal is an important treatment objective, surface loading rates of about 0.5 $\text{g}/\text{m}^2/\text{d}$ are appropriate. These design criteria are used to estimate the minimum required wetland surface area using the maximum iron or manganese concentration and maximum probable flow, as follows:

$$\text{Wetland Surface Area (A)} = \frac{[\text{Conc. (mg/L)} \times \text{Flow (L/min)} \times 1.44]}{\text{Recommended Chemical Loading Rate (g/m}^2/\text{d)}}$$

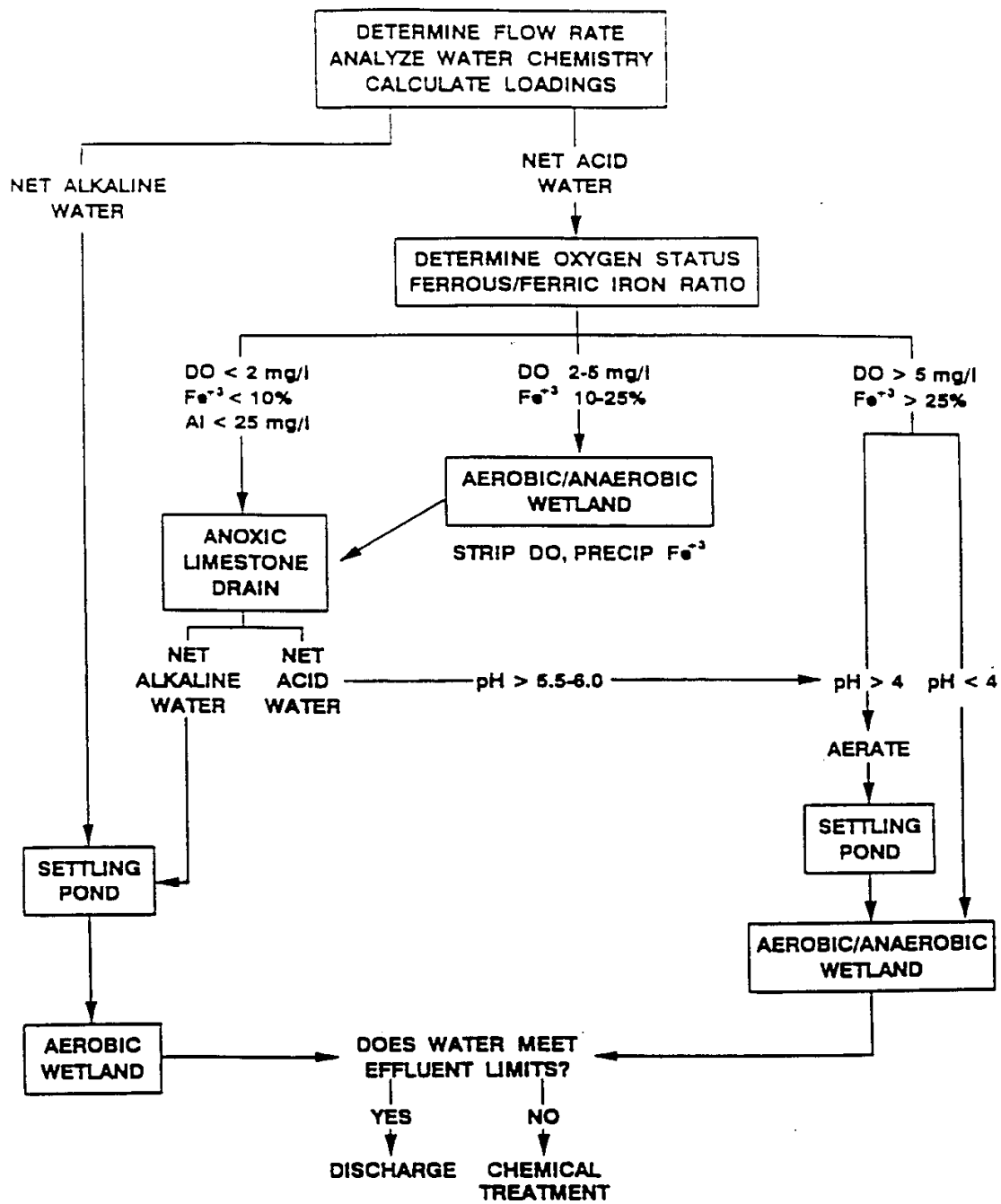
Using this method, an aerobic wetland receiving AMD containing 50 mg/L of iron and maximum flow rate of 150 L/min should be designed to provide at least 1,080 m^2 of surface area. It should be

**Table 5.3-1
Guidelines and Case Studies Data for Wetland Areas**

Case Study	Sizing Value	Applicability
Kleinmann <i>et al.</i> (1991)	2 m ² /mg Fe/min	Inflow pH <5.5 ; outflow Fe=3 mg/L
	0.75 m ² /mg Fe/min	Inflow pH > 5.5
	7 m ² /mg Mn/min	Infl. pH < 5.5; outflow Mn=2 mg/L
	2 m ² /mg Mn/min	If inflow pH > 5.5
Watson <i>et al.</i> (1989)	928 m ² /L/s	Range from 61.1 to 10,700 m ² /L/s
Kleinmann <i>et al.</i> (1991)	4.9 m ² /L/min (19-38 L/min)	pH > 4.0; Fe < 50 mg/L; Mn < 20 mg/L
Kleinmann <i>et al.</i> (1991)	0.15 m ² /mg Fe/min 0.75 m ² /mg Mn/min 200 to 500 m ² /kg acidity/d	Nd
Girts <i>et al.</i> (1987)	15 m ² /L/min	Nd
Brodie <i>et al.</i> (1989)	0.7 L/m ² /min 1.1 m ² /mg Fe/min 2.8 m ² /mg Mn/min	Nd
Hedin <i>et al.</i> (1994)	250 m ² for 5 kg Fe/d 1,300 m ² for 5 kg Fe/d	Alkaline waters Acidic waters

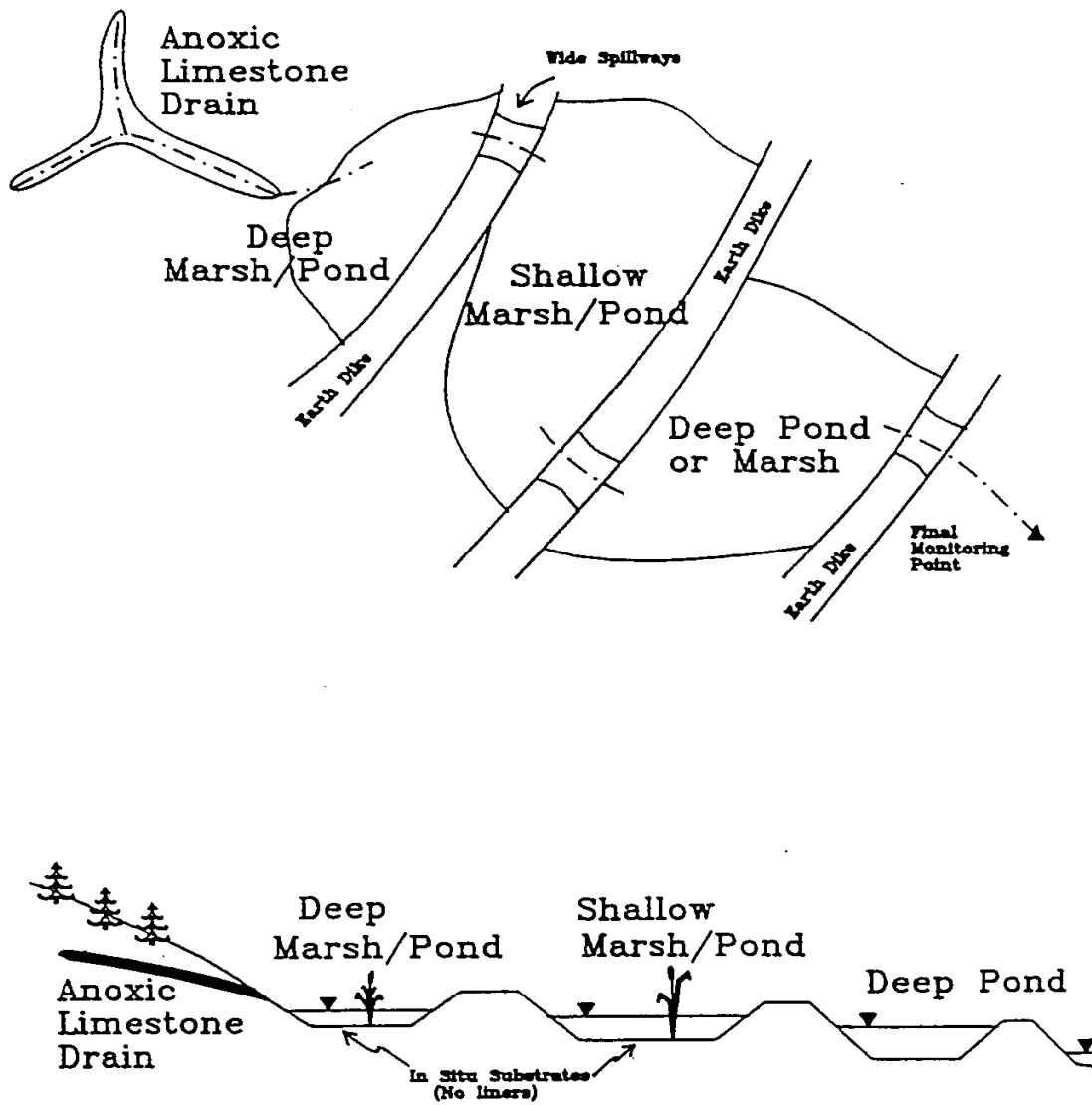
Source: MEND 3.14.1

Figure 5.3-5 Decision Flowchart for Designing and Sizing Passive Mine Drainage Treatment Systems



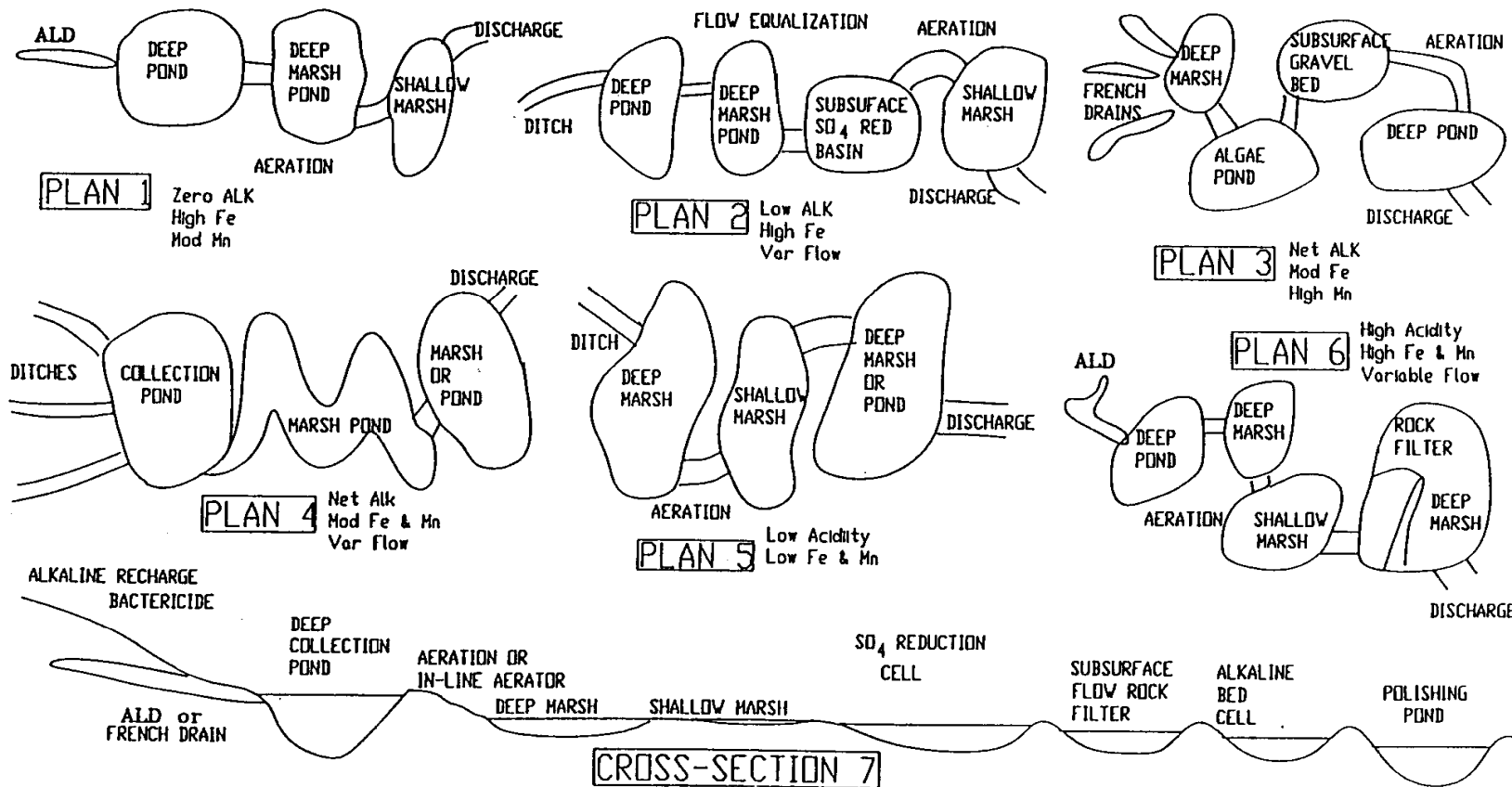
Source: Hedin and Nairn (1992)

Figure 5.3-6 Typical Stage, Aerobic Constructed Wetlands for Acid Minewater Purification



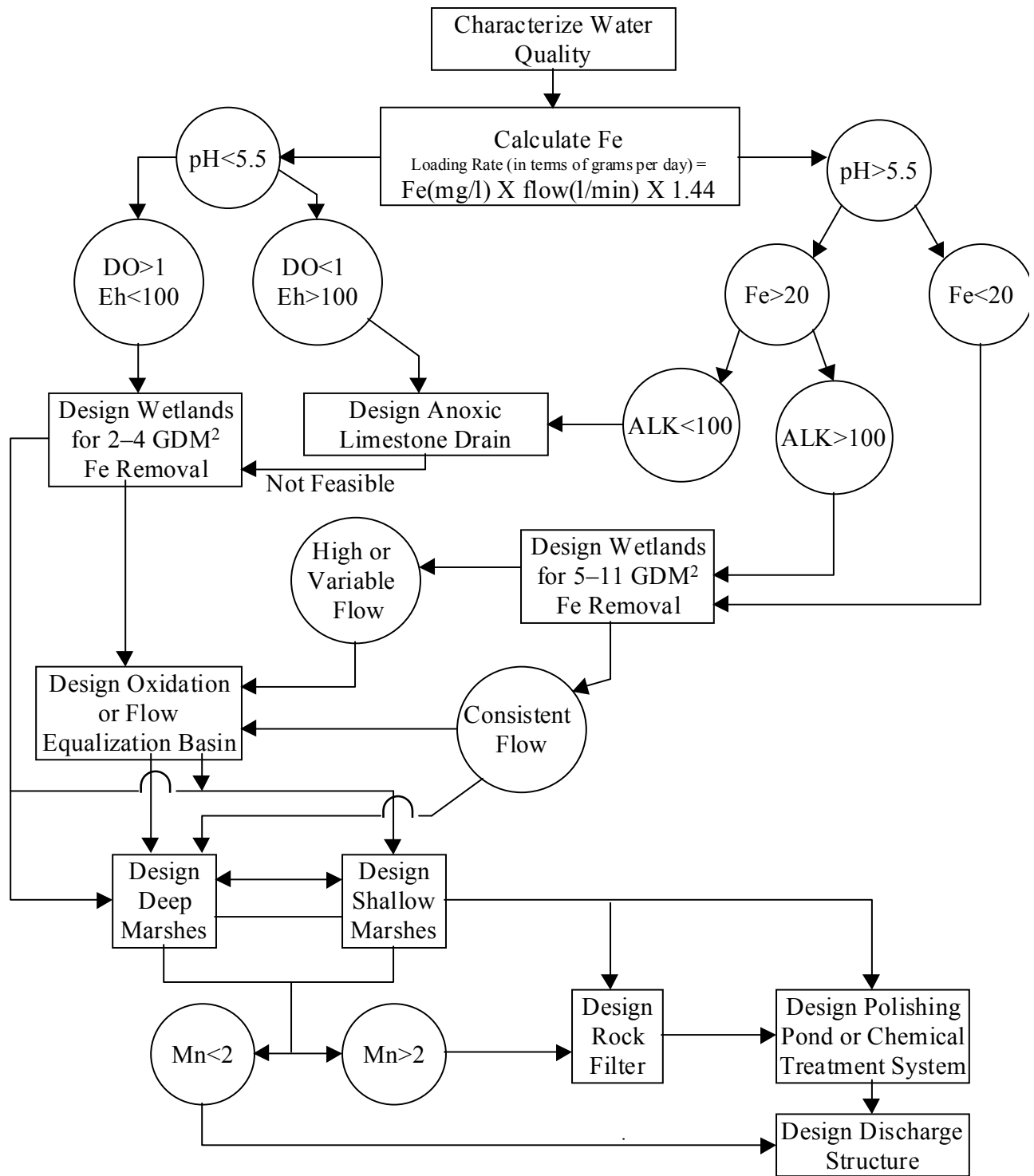
Source: Brodie (1993a)

Figure 5.3-7 Examples of Staged, Aerobic Wetlands for Acid Minewater Purification



Source: Brodie (1993a)

Figure 5.3-8 Simplified Flow Chart for Designing Staged, Aerobic Constructed Wetlands



Source: Brodie (1993a)

noted that these design criteria are only valid for net-alkaline AMD, i.e. AMD with sufficient alkalinity to buffer the pH above about 5.5.

Knight Piesold used pH-related surface loading criteria in designing the aerobic reed beds at the Wheal Jane Mine in Cornwall, UK. For AMD with a pH less than 5.5, Knight Piesold used design criteria ranging between 2 and 4 g Fe/m²/d. A design criteria of 5 to 11 g Fe/m²/d was used for AMD with a pH >5.5 (Hamilton *et al.* 1997).

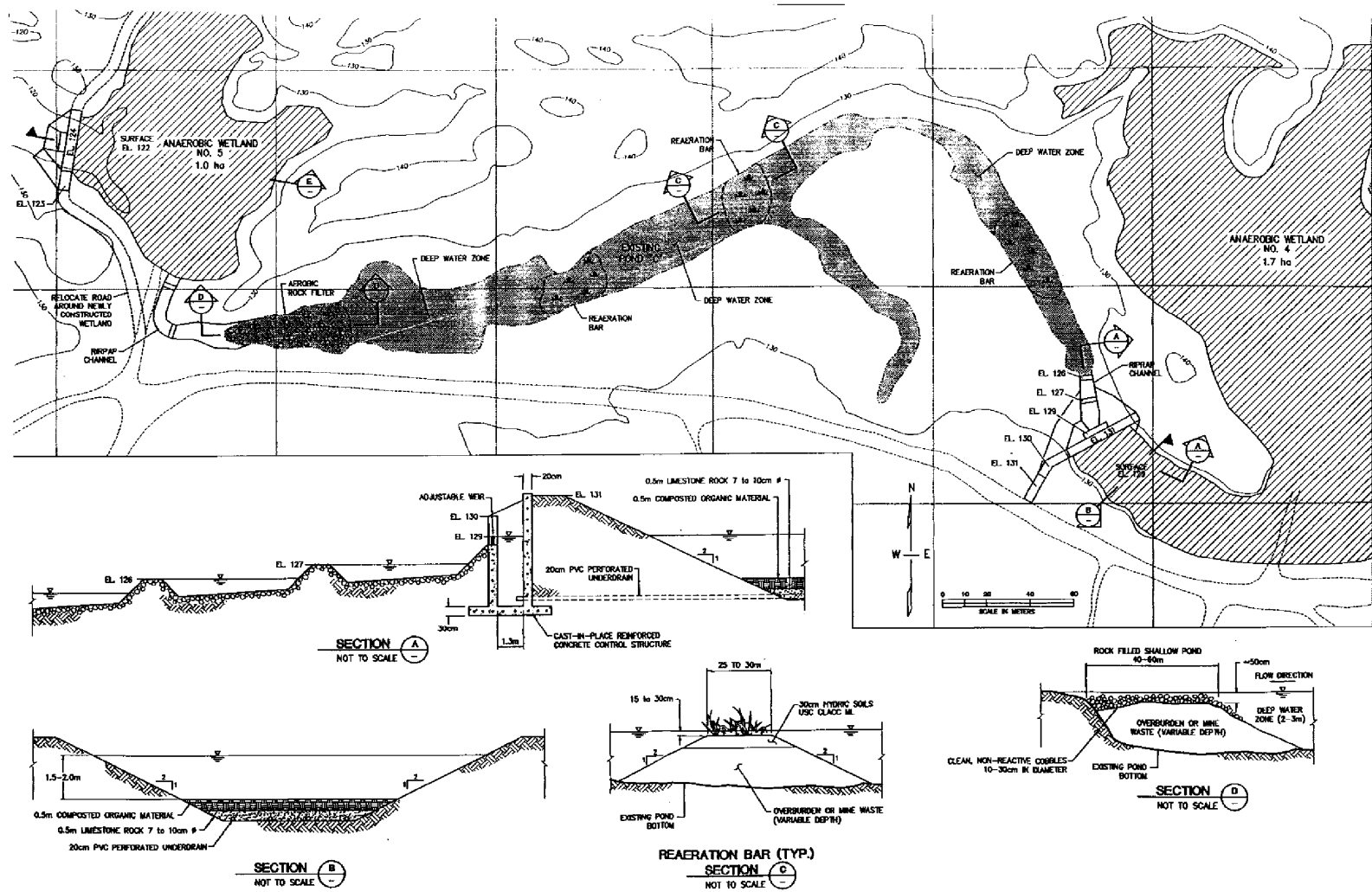
Aerobic wetlands are constructed by excavating a series of ponds which are typically planted with cattails (*Typha latifolia*), reeds (*Phragmites spp.*), or bullrush (*Scirpus spp.*). The hydraulics of the pond system are controlled by the strategic placement of earthen dams or dikes. For aerobic treatment, mechanical aeration systems consisting of rock-lined drop structures are usually provided between the ponds. Wetland plant communities are established to revegetate and stabilize disturbed areas, protect the wetlands from erosion and the effects of flooding, provide filtering mechanisms for removal of suspended solids, provide subsurface aeration, and improve the aesthetic qualities of the treatment system.

5.3.4.3 Passive Anaerobic Treatment Systems

In 1997, Dames & Moore designed a state-of-the-art passive anaerobic treatment system for treating net-acidic, metal laden AMD in southern Brazil. The Dames & Moore design is used as the base method because it incorporates the most current research available on passive AMD treatment. Figure 5.3-9 illustrates the design principals incorporated into Dames & Moore's system. The design consists of deep, open-water ponds overlying a layer of biodegradable organic matter, a layer of limestone, and underdrain system designed to provide hydraulic control. Hydraulic control structures promote regulated, downward, vertical flow through the ponds. The various components of the passive anaerobic treatment system are outlined below.

1. Deep Water Ponds. Water in the ponds is maintained at a minimum depth of 1 m to prevent the diffusion of atmospheric oxygen into the organic substrate layer at the bottom of the pond. The water depth is maintained by an earthen dike and hydraulic control structure at the outlet of the pond. The flow of water through the pond is downward. It is critical to the performance of the system that oxygen be prevented from diffusing into the organic substrate layer because the SRB are only active under highly reduced conditions. Also, the deeper the water, the higher the equilibrium partial pressure of CO₂ will be in the limestone layers. A high CO₂ partial pressure raises the CaCO₃ solubility, thereby increasing the alkalinity contributed by the limestone. Finally, the impounded water provides the hydraulic head needed to force the water downward through the underlying substrate and limestone layers.

Figure 5.3-9 Details and Sections of a Passive Acid Drainage Treatment System



Source: Dames & Moore (1997, 1999)

2. Organic Substrate Layer. The organic substrate layer consists of 1 m of composted animal and plant wastes. The thickness of the organic layer can be varied from 0.5 to 2 m. The key design requirement is to provide a volume of organic matter sufficient to neutralize the influent acidity and remove 99% of the heavy metals in the drainage. The purpose of the organic layer is to provide a food and energy source for SRB and to consume dissolved oxygen creating a reduced, anaerobic environment. Animal wastes also act as the source of SRB cultures within the system. A byproduct of the biological sulphate reduction reactions is the production of sulphide and bicarbonate ions.

3. Organic Materials Selection. A mixture of soluble and insoluble organic materials are needed to provide short-term and long-term organic carbon sources for the SRB. Typically, mixtures are developed in the field using locally available materials. Hence, there are no strict guidelines on the selection of organic materials. Typical mixtures contain approximately 1/3 soluble and 2/3 insoluble organic materials, such as the following:

- Animal wastes, such as sheep, cattle, or poultry manure to provide readily available organic carbon and to act as the source of SRB;
- Moderately soluble organic materials such as plant material, including grass hay, wheat straw, or rice straw; or food processing wastes, including spent mushroom compost, rice hulls; and
- Insoluble organic materials such as wood chips or sawdust.

4. Limestone Layer. A layer of high quality limestone cobbles is placed under the organic substrate layer. The limestone contributes to the total alkalinity produced by the system and functions as a hydraulic drainage layer. Given sufficient residence time, equilibrium conditions will be established between the bicarbonate produced through biological sulphate reduction and the solid CaCO_3 contained in the limestone. If the concentration of bicarbonate from sulphate reduction is less than the equilibrium concentration, some limestone will dissolve to make up the difference. Also, the decomposition of the organic substrate results in elevated partial pressures of CO_2 , which increases the equilibrium concentrations of dissolved carbonate and bicarbonate. The volume of limestone needed to neutralize half the acidity is estimated by an empirical formula developed by Hedin *et al.* (1994).

5. Underdrains and Hydraulic Controls. The underdrain and hydraulic control systems are designed to facilitate vertical downward flow through the organic substrate and limestone layer. The drains consist of large diameter, perforated PVC pipe. The drains penetrate the earthen dike and exit inside the concrete hydraulic control structure. Many different types of control structures are possible, such as low-cost concrete weirs that control the pond water level using simple stop-logs.

6. Liner System. An impermeable liner is placed on the bottoms and sides of the anaerobic pond to prevent leakage. Liners consist of 30 cm of compacted clay or flexible membranes with an in-place permeability of 10^{-7} cm/s or less. The liner is needed to ensure that the water level in the ponds remains at the desired static level during low flow periods. If excessive leakage occurs, the water level could drop, potentially exposing the organic layer to oxygen.

Because the presence of any dissolved oxygen would inhibit SRB activity, it is critical that the organic substrate layer exerts sufficient biochemical oxygen demand (BOD) to consume any dissolved oxygen in the water. Otherwise the biological treatment processes could be disrupted. Due to the production of excess bicarbonate, the pH of the water flowing through the organic layer is typically neutral, even though the influent pH may be as low as 2.5. Iron oxidation and precipitation reactions that would normally occur rapidly at neutral pH are prevented from occurring due to the absence of dissolved oxygen. Therefore, precipitation of ferric hydroxide is not a threat to system performance.

Empirical design criteria have been developed by Wildeman *et al.* (1993) and Wildeman and Gusek (1997). Their design criteria are the only ones currently available for estimating the volume of organic matter and hydraulic residence times needed to treat a given source of AMD using anaerobic treatment. At a pH of less than 3.0, SRB produce approximately 0.3 mole/m³ organic matter/day of bicarbonate alkalinity and 0.15 mole/m³ organic matter/day of sulphide. At pH greater than 5.0, the rule is to design for 0.3 mole/m³ organic matter/day of sulphide production. During summer, rates as high as 2 moles/m³/day can be achieved. In warm climates, the higher rates may be appropriate for design; however, in cold climates, the lower rates should be used. Wildeman and Gusek (1997) design their systems for an overflow rate of at least 20 m²/L/sec. However, using the sulphide production rate as the key design criterion usually provides ample hydraulic retention.

Effluent from the passive anaerobic treatment system described by Dames & Moore is discharged into an aerobic wetland and aerobic rock filter to oxidize and precipitate the iron and manganese, reduce residual sulphide concentrations, and remove BOD carried through the system (Figure 5.3-9). The aerobic wetland is also used to settle suspended solids.

5.3.4.4 Biosorption Treatment Methods

No true base method of implementing biosorption has been defined. Several companies in North America are either developing or selling biosorption processes for industrial applications. Examples include Bio-Recovery Systems, Inc. who developed a biosorbent from immobilized algae *Chlorella* in silica or polyacrylamate gels, and B.V. Sorbex, Inc., in Montreal, who has also developed a commercial biosorbent process. Other commercially available biosorbents are discussed in MEND 3.14.1.

Biosorption systems have many limitations as compared to other passive treatment methods. Biosorption as a method for AMD treatment is still in the developmental stage. Performance data for large-scale biosorption systems are still lacking.

5.3.5 VARIATIONS

Many variations in the design of ALDs, aerobic wetlands, and passive anaerobic treatment systems are reported in the published literature. The passive treatment design variations described in this section are representative of the continuing efforts being made to improve the effectiveness and applicability of passive treatment system and to adapt the base methods to specialized, site-specific conditions.

5.3.5.1 Anoxic Limestone Drains (ALDs)

Variations in ALD design and construction are usually attributable to site-specific constraints, such as topographic, hydraulic, or space limitations. Variations in ALD dimensions are most frequently cited. For example, MEND 3.14.1 indicates ALDs over 20 m in width have been constructed due to space or site constraints. These extra wide ALDs apparently produced alkalinity concentrations similar to conventionally shaped drains.

Site-specific hydraulic considerations are often responsible for variance in conventional ALD designs. Conventional ALDs are shallow to maintain saturated conditions over their entire depth. However, deeper drains have been constructed using creative hydraulic designs to maintain saturated conditions. Hydraulic variations include the use of outlet weirs or ponds to ensure saturation of the limestone.

A variation consisting of an anaerobic pond upstream of the ALD has been suggested when influent oxygen or ferric iron concentrations exceed acceptable levels of about 1 mg/L. The purpose of the anaerobic pond is to promote reducing conditions to consume dissolved oxygen and reduce iron from the ferric to ferrous state. Cambridge (1997) and Hamilton *et al.* (1997) describes the use of an anoxic pond upstream of an ALD used in a passive treatment system at the Wheal Jane Mine, a base metal mine in Cornwall, England.

The use of limestone beds downstream of aerobic wetland is a unique feature of the TVA wetland systems. An additional 50-60 mg/L of alkalinity can be added by providing an aerobic limestone drain after most of the iron, aluminum, and manganese have been removed. Armouring and plugging of the limestone is minimized in these downstream ALDs because a high percentage of the iron and manganese is removed upstream.

5.3.5.2 Open Limestone Channels

Ziemkiewicz *et al.* (1996) concluded that open limestone channels (OLCs) may be viable alternatives to ALDs under a limited set of site-specific conditions. OLCs appear to be mainly applicable for short term AMD treatment in one-time, watershed reclamation projects where strict water quality standards do not have to be met. However, OLCs may be applicable for treating AMD in situations where other treatment methods are infeasible or in combinations with other passive treatment technologies.

Armouring and plugging with iron and aluminum hydroxides is recognized as a serious obstacle to the applicability of ALDs. However, Ziemkiewicz *et al.* (1996) performed laboratory and field tests indicating that the problem of armouring, alone, may not preclude the use of limestone for passive AMD treatment. Laboratory tests indicate armoured limestone is only slightly less effective in neutralizing AMD than unarmoured limestone. Also, field studies of existing OLCs receiving AMD indicate that armoured limestone placed in open channels was neutralizing up to 62% of the acidity contained in the mine water. These field studies also showed the OLCs neutralized more acid than predicted by geochemical modeling. The plugging problem was shown to be preventable by designing open limestone channels to maintain flow velocities sufficient to flush the hydroxide precipitates out of the limestone's pore spaces.

Based on these studies, Ziemkiewicz *et al.* (1996) developed design guidelines for OLCs for treating AMD. The key design factor is to prevent iron and aluminum precipitates from settling in the limestone's void spaces. Field studies suggest that OLCs with slopes of 40% performed best due to their high flow velocities, and consequent flushing of the precipitate. Also, coarse limestone (15 to 30 cm sized) was found to perform best. OLCs must provide sufficient contact time to neutralize the AMD's acidity. However, the required contact time appears to be site-specific. Channel configuration (width, depth, length, slope, and water velocity) was found to play an important role in increasing acidity reductions.

5.3.5.3 Aerobic Wetland Treatment Systems

The algae-based system described by Jones *et al.* (1995) at the Hilton Mine in Australia represents a unique variation on aerobic wetland treatment technology. This passive aerobic system treats up to 5,000 m³/day of AMD supersaturated with carbon dioxide and containing both soluble and particulate forms of iron, zinc and manganese. The AMD is pumped from the large silver, lead, and zinc mine. Unit processes incorporated into the design include a deaeration zone, primary and secondary settling ponds, and a final polishing section utilizing a channel supporting algal growth. Jones *et al.* (1995) confirmed that the algal growth in the stream between the pond overflow and the Hilton Mine's pump weir are removing zinc and manganese from the water. However, even with the warm climate at the Hilton Mine, the residence time in the aerobic treatment system is about 11 days.

5.3.5.4 Passive Anaerobic Treatment Systems

Variations of the design approach and substrate selection used in the base method for passive anaerobic treatment systems are numerous and diverse. Initially, the common approach was to design vegetated wetlands that looked much like natural cattail or rock/reed marshes. Examples of this approach include the ARUM system (MEND 3.11.1a-d), and the wetland systems described by Sobolewski (1996) and Sobolewski *et al.* (1995). Plant-based systems are designed to provide a self-sustaining source of organic matter. However, none of these systems has performed consistently due to short-circuiting and oxygenation of the water by plant roots. Also, plant-based systems designed to remove heavy metals and add alkalinity generally require exceedingly long hydraulic residence times, which limit their applicability and cost-effectiveness. The ARUM system, for example, required retention times of about 130 days to achieve 80 to 90% removal of copper and nickel (MEND 3.11.1a-d). The wetlands at the Bell Copper Mine in British Columbia demonstrated that vegetation-based systems have little ability to generate alkalinity and are generally not applicable for treating net-acidic, high-strength AMD (Sobolewski *et al.* 1995).

In the early 1990s, it was widely recognized that plants were unnecessary and could actually hinder the performance of anaerobic systems designed to generate alkalinity and remove heavy metals. Béchard *et al.* (1995) designed their system at the Halifax International Airport without living plants. The Halifax International system consisted of long shallow trenches filled with decomposing hay and straw. This system performed well in winter and summer, but experienced problems related to maintaining anaerobic conditions due to the shallow depth of the trenches.

The SAPS design presented by Kepler and McCleary (1994) is the model for the base method. The key elements that make this design successful include, vertical subsurface flow, close attention to hydraulic design, relatively short residence times (6 to 12 hours), long-term substrate life, and sizing based on functional relationships between sulphide generating capacity and metal and acidity loading. SAPS consist of deep ponds with no emergent vegetation. These systems perform equally well in winter and summer in the eastern U.S.

5.3.5.5 Passive *In Situ* Treatment Methods

An *in situ* AMD treatment system was designed and tested by Waybrant *et al.* (1998). This *in situ* system consists of a permeable, subsurface, reactive barrier designed specifically to treat AMD. Previously, the University of Waterloo developed its reactive wall technology for treating groundwater contaminated with chlorinated organic compounds. A similar technique was used to intercept and treat acidic groundwater seeping from an inactive mine site in Sudbury, Ontario, before the groundwater could emerge at the surface as acidic drainage. Figure 5.3-10 illustrates the conceptual design schematic of the field-scale reactive wall described by Waybrandt *et al.* (1998).

The field-scale reactive wall was installed in the aquifer downgradient of the Nickel Rim tailings impoundment in 1995.

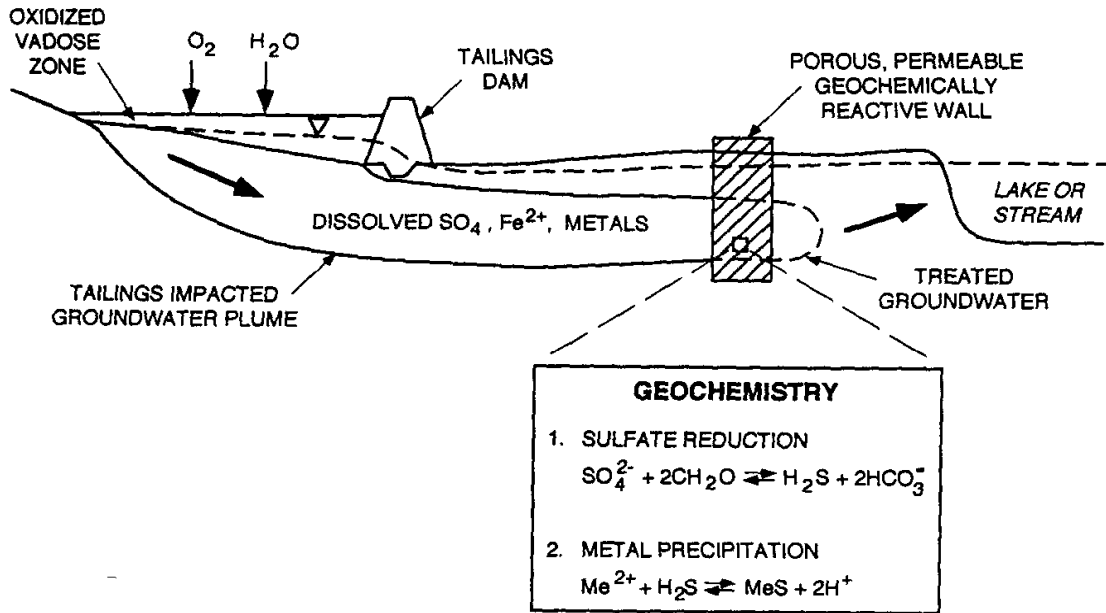
As illustrated in Figure 5.3-10, the wall consisted of a trench filled with organic substrate constructed perpendicular to the groundwater flow direction. The wall measured 15 m in length, 3.6 m deep, and 4 m wide. The reactive material placed in the trench consisted of composted leaf mulch, wood chips, sawdust, sewage sludge, creek sediments, agricultural limestone, and silica sand. Pea gravel was also added to this mixture to increase its permeability. Piezometers were installed in the aquifer and in the reactive wall parallel to the groundwater flow direction to facilitate monitoring of the *in situ* treatment processes.

The field-scale reactive wall was designed using data collected during a 14-month laboratory-scale pilot test conducted at Waterloo University (Waybrant *et al.* 1998; Waybrant *et al.* 1995; Blowes *et al.* 1995). The wall was designed to neutralize acidity and precipitate metals through bacterial sulphate reduction occurring in the organic substrate. After nine months of monitoring, Waybrant *et al.* (1997) observed that the field-scale reactive wall effectively transformed the groundwater flowing through the wall from a net-acid water to a net-alkaline water. Significant iron and sulphate removals were also observed. Alkalinity increases in the treated groundwater ranged from 600 mg/L to 2000 mg/L. The increase in alkalinity observed from the Sudbury reactive wall was two to 10 times greater than typically observed in anoxic limestone drains (ALDs).

After nine months of monitoring the Nickel Rim *in situ* system, the plume of treated groundwater extended more than 10 m downgradient from the reactive wall. Unfortunately, no data regarding the estimated AMD flow rate through the wall or other key design details are provided in the project's documentation. Also, no cost data for pilot testing or construction are provided in the paper. Such information would be of considerable value to the mining industry.

Other *in situ* biological treatment systems have been pilot-tested with only limited success. In 1994, CSM piloted an in-mine passive anaerobic treatment system inside the Eagle Mine in Colorado. This system was designed to demonstrate the new generation of passive AMD treatment systems that were not wetland-based systems. Although small-scale systems performed flawlessly inside the mine, a larger scaled-up version failed due to hydraulic problems related to the use of low permeability materials for the organic substrate (CSM, unpublished).

Figure 5.3-10 Schematic of a Permeable Reactive Wall at a Mine-Tailings Site



Source: Waybrandt *et al.* (1998)

5.3.5.6 Hybrid Active/Passive Treatment Systems

A wide array of active/passive hybrid systems have been developed, including active/passive chemical dosing systems and several variations on passive anaerobic treatment systems. Some of these hybrid active/passive systems are discussed in the following subsections.

1. Passive Chemical Dosing Systems

Chemical dosing systems are simple, low cost methods of neutralizing excess acidity in streams affected by AMD. Dosing tanks consist of drums or tanks of treatment chemicals such as sodium hydroxide (NaOH) equipped with passive metering systems. Metering systems consist of small tubes or control valves installed and operated to control the release of the chemical agents. Frequently, these systems are left unattended and are, therefore, considered partially passive. Operating principles are similar to active chemical treatment methods described in Section 5.2 of this Manual.

Other passive chemical delivery systems include solid dosing methods, such as the hydraulically driven screw conveyor found in the Aqua-Fix™ system. Aqua-Fix™ systems consist of large hoppers or silos for storing dry solid lime, soda ash, or sodium and magnesium hydroxide pellets or pebbles; a screw conveyor that controls the rate of chemical addition; and a water wheel that uses naturally occurring hydraulic gradients to power the screw conveyor. The system is simple and relatively low cost but is not entirely passive. The Aqua-Fix™ system requires periodic labour and chemical inputs, including refilling the chemical hopper and lubricating the machinery. However, the system requires significantly less active operation than conventional treatment systems.

Oxygen is a key chemical reagent in AMD treatment systems if significant quantities of iron and manganese are present. Iron is readily removed from AMD through simple aeration at pH greater than about 3.5. Passive mechanical aeration using jet pumps or venturi tubes, such as Hydro-Vac™ wastewater conditioners, have proven effective in removing iron by simply aerating the AMD.

To be effective, hybrid active/passive chemical treatment systems have to mimic the same unit processes as active treatment technologies. Therefore, passive chemical dosing or aeration systems should be viewed as one component of a complete passive treatment train. Complete passive treatment systems must include chemical mixing, sedimentation, and flow control systems in addition to simple chemical dosing methods. Passive chemical mixing can be achieved by utilizing natural turbulence or man-made cascades. Sedimentation can be achieved by settlings ponds designed to provide the residence time needed to promote clarification and long-term solids storage capacity. Flow control can be achieved with valves, weirs, dams, and flumes.

2. Active/Passive Anaerobic Treatment Systems

The pilot-scale anaerobic systems tested at the Wheal Jane Mine in 1994 included hybrid active/passive anaerobic and aerobic treatment systems. Three separate systems were tested, including lime-dosed and lime-free systems. Each of the three basic systems consisted of five aerobic reed beds, an anaerobic cell, and an aerobic rock filter. One of the treatment trains consisted of the basic lime-free system and one incorporated an anoxic limestone drain. The third system incorporated pretreatment in the form of active lime dosing and sludge collection channels. This system is considered an active/passive hybrid. Design and performance data presented by Hamilton *et al.* (1997) indicated the truly passive systems performed slightly better than the active/passive hybrid with respect to pH buffering, arsenic removal, iron removal, and zinc removal.

Rates of enzymatic microbial reactions are temperature sensitive and become significantly slower at low temperatures. Metal removal rates can decrease as much as 60% due to a 10°C decrease in temperature (MEND 3.14.1; MEND 3.13.1; Kuyucak *et al.* 1991). MEND 3.14.1 states that bioreactors can only be used if a constant temperature can be maintained and if the reactors are over sized to handle shock loading of AMD. However, Dames & Moore presented conceptual designs for a hybrid active/passive anaerobic treatment system in a cold northern climate that would use relatively cheap and abundant natural gas to heat the AMD stream several degrees to improve winter operating efficiencies. Economic analysis demonstrated that this system would be significantly more cost-effective than an active lime precipitation plant at the site. Also, the use of low-cost organic amendments, such as ethanol, proved remarkably cost-effective for supplementing the passive anaerobic treatment system during high loading periods (Dames & Moore 1999).

3. Bioreactor Treatment Systems.

Bioreactor treatment processes are examples of hybrid systems that incorporate passive, anaerobic, biological treatment mechanisms within the design frameworks of active treatment systems. For this reason, bioreactors are discussed in this section on passive treatment rather than in the active treatment section.

Treatment of AMD in anaerobic bioreactors is accomplished by the same microbial reactions that occur in passive anaerobic treatment systems. Bacterial consortia consisting of numerous genera and species catalyze these reactions. Cellulose from agricultural wastes or other sources is degraded by bacteria to generate free sugars and other metabolites. Facultative microorganisms degrade these products and provide substrate for the fermentative anaerobes. Anaerobic microorganisms utilize these free sugars to produce short chain organic acids which are utilized by SRB as their carbon substrate. The SRB reduce sulphate to H₂S which reacts with metal ions to precipitate metal sulphides. The SRB also consume hydrogen ions and produce CO₂ causing an increase in pH due to decreased concentration of free hydrogen ions and to the buffering effect of the CO₂/bicarbonate

buffer system (MEND 3.14.1). Methanogens, ammonia producers, and other microorganisms also contribute to the alkalinity production that is utilized in treatment of AMD.

Use of bioreactors for treating AMD is considered innovative. Numerous bench- and pilot-scale systems have been tested, but few full-scale bioreactors are currently in use for AMD treatment applications (MEND 3.14.1). Unfortunately, a clear definition of what constitutes a bioreactor has not been established. MEND 3.14.1 refers to any anaerobic AMD treatment system not associated with a wetland as a bioreactor, including open anaerobic pond systems. However, from a process engineering perspective, bioreactors are limited in definition to vessels or tanks designed to facilitate biologically-mediated chemical reactions under carefully controlled conditions. This process engineering definition is used throughout this section.

To date, bioreactors treating significant AMD flows consist of mainly active biological treatment systems. This reliance on active treatment technology limits the applicability of bioreactors as passive systems. However, as passive biological AMD treatment methods evolve, the technology appears to be trending toward active/passive hybrids. Many of the systems described in this Manual have incorporated elements of active and passive systems. Completely active systems are also described.

Despite the small number of operating systems, bioreactor technology for AMD applications has advanced rapidly over the past decade. Kuyucak *et al.* (1991) performed pioneering research in AMD treatment using bench-scale bioreactors at the Noranda Technology Centre in Pointe Claire. These tests were conducted to investigate the feasibility of using SRB to treat AMD in flooded open pit mines. A variety of treatment variables were tested, including pure versus mixed SRB cultures, variations in nutrient and organic substrate formulations, and continuous stirred tanks versus fixed media or sand bed reactor designs. Preliminary tests indicated heavy metals and sulphate can be effectively removed and the pH raised to near neutral using SRB reactors. The best results were obtained using an anaerobic upflow reactor in which the AMD was forced to flow through an anaerobic sand layer containing SRB. A cost comparison of various organic substrates versus lime neutralization costs indicated that the economics of SRB bioreactor technology compared favorably with lime neutralization (Kuyucak *et al.* 1991).

Given and Meyer (1998) describe aerobic and anaerobic bioreactor systems designed to treat tailings pond effluent at Homestake's Nickel Plate Mine, near Hedley in south central British Columbia. The active biotreatment system was designed to reduce cyanide, thiocyanide, metals, ammonia, total dissolved solids, sulphate and nitrate. Although this system was designed to treat mine process water, rather than AMD, it is cited as one of the few examples of a full-scale, active biological treatment system in use in the mining industry. The overall cost of operating and maintaining the plant is just over C\$ 0.03 per US gallon of treated water or less than C\$0.01 per litre (Given and Meyer 1998).

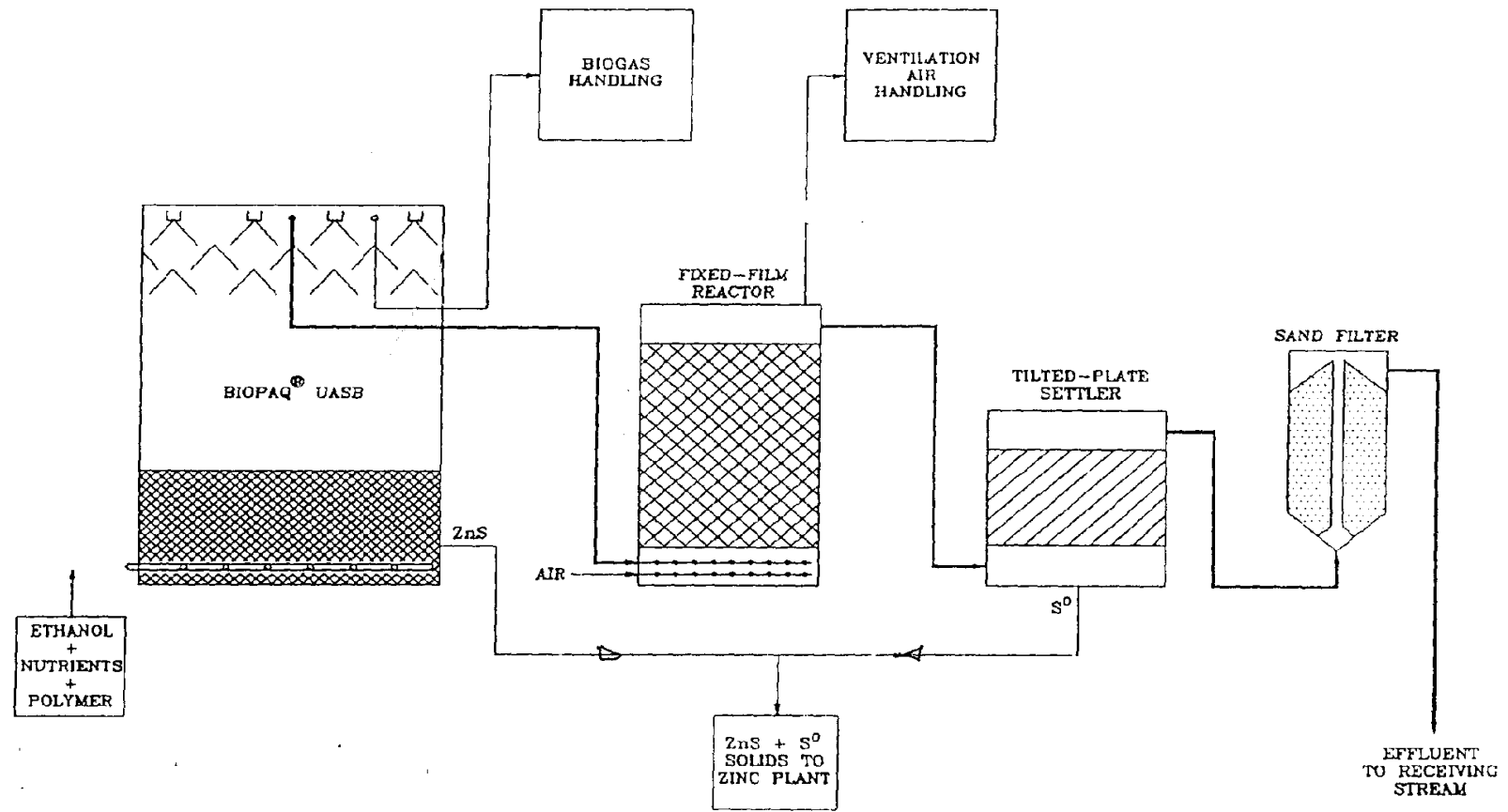
A large, full-scale bioreactor system based on anaerobic bacterial sulphate reduction followed by an aerobic sulphide-oxidizing bioreactor is operating successfully at the Budelco zinc refinery in the Netherlands. The Budelco refinery is owned by Billiton (The Netherlands) and Pasminco (Australia), which produces over 200,000 tonnes of zinc per year. Heavy metals and sulphate contaminate the groundwater below the plant to a depth of 30 m from over 100 years of industrial operations. Average groundwater contaminant concentrations include 50 mg/L zinc, 0.1 mg/L cadmium, and 500 mg/L sulphate. Groundwater data indicate the contaminant plume will eventually surpass the site perimeter. To avoid polluting nearby drinking water aquifers, a geohydrological control system was designed to pump and treat approximately 7,000 m³ of groundwater per day. The aboveground treatment system involves four main units, including an upflow anaerobic sludge blanket (UASB) bioreactor for metal and sulphate removal and an aerobic submerged fixed film (SFF) bioreactor for removal of residual sulphide. The bioreactors are followed by a tilted plate settler and a continuous sand filter for removal of suspended solids. Figure 5.3-11 illustrates the process flow diagram for the biological metal and sulfate treatment systems at Budelco.

The UASB bioreactor receives groundwater containing sulphate and heavy metals. This bioreactor is based on a unique and innovative design by Paques, B.V. called the Biopaq™ reactor. Figure 5.3-12 illustrates the design of the Biopaq™ UASB reactors at Budelco. These reactors use SRB and an organic carbon substrate consisting of ethanol to generate alkalinity, produce excess sulphide, and precipitate zinc and other metals. During the reaction process, methane, carbon dioxide and hydrogen sulphide gases are produced. It is necessary to scrub the hydrogen sulphide with caustic soda prior to burning to prevent sulphur dioxide emissions. Excess sulphide in the liquid effluent is converted to elemental sulphur in the aerated SFF reactor. The SFF reactors are also a unique design patented by Paques, B.V. called Thiopaq™ bioreactors. Thiopaq™ reactors consist of a water inlet system at the bottom, a ring-packed reaction chamber, and an air distribution system. The oxygen level must be closely monitored and controlled to prevent oxidation of sulphide back to sulphate. Solids removed from the system consist of elemental sulphur, metal sulphides, and biomass washed from the bioreactors.

Design of the full-scale Budelco bioreactor system was based on extensive pilot testing described by Scheeren *et al.* (1992). The treated effluent from the pilot plant contained less than 1 mg/L solids and 0.3 mg/L zinc. These values were obtained with a four-hour residence time in the UASB reactor, and less than one-half hour residence time in the SFF reactor. The pilot plant results show an overall treatment efficiency of greater than 99%.

Based on the successful pilot demonstration, the full-scale Budelco system was designed and installed by Paques, B.V. This plant has been operating successfully at 5,000 m³/day since May of 1992 (De Vegt and Buisman 1997).

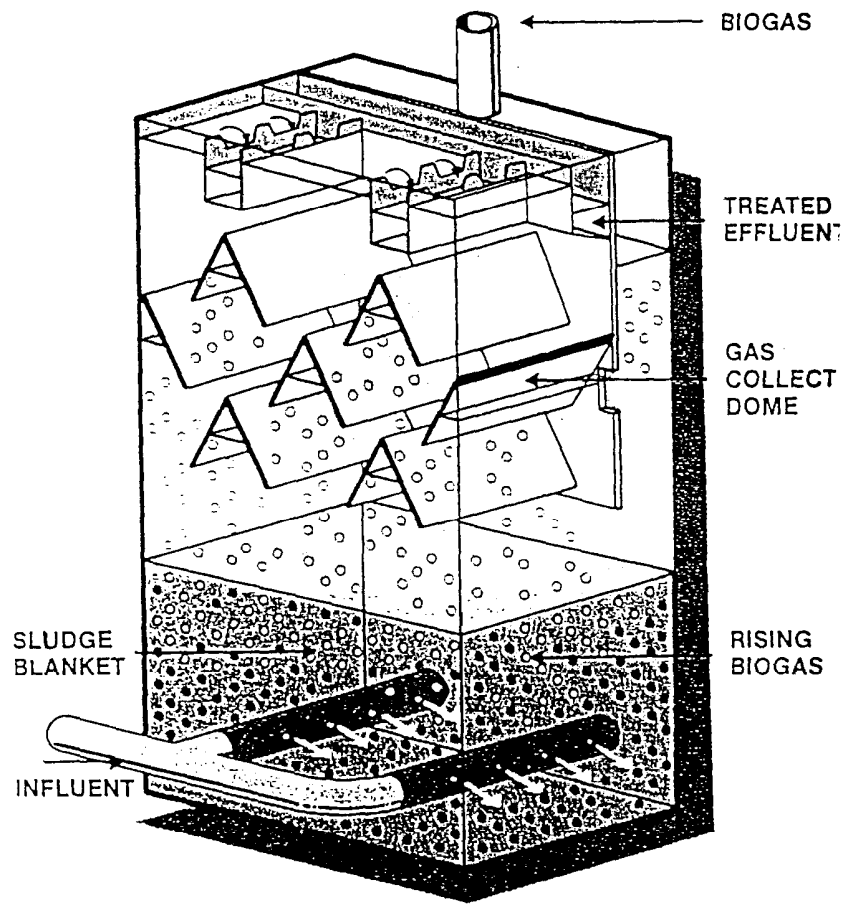
Figure 5.3-11 Simplified Process Diagram Biological Metal and Sulphate Reducing Plant at Budelco



Source: De Vegt and Buisman (1995)

Figure 5.3-12

Upflow Anaerobic Sludge Blanket Reactor Schematic



Source: De Vegt and Buisman (1995)

A new generation of bioreactors is being tested to selectively recover metals from AMD. Hammack *et al.* (1993) used biogenic H₂S to selectively recover copper and zinc from AMD at the Iron Mountain Mine near Redding, CA. Also, in 1995, Rowley *et al.* (1997) successfully demonstrated an active AMD treatment method utilizing biogenic sulphide precipitation at the former Britannia copper mine 50 km north of Vancouver, B.C. In contrast to the Budelco system, the Biosulphide™ process demonstrated at the Britannia copper mine consists of a unique design in which the sulphate reduction bioreactor is separated from the metals precipitation reactors. In this process, only a fraction of the AMD stream is treated in the sulphide generating bioreactors. Based on site-specific AMD characteristics and treatment objectives, metal-rich sulphide concentrates can be generated by the Biosulphide™ process.

High cost limits the use of bioreactor systems at many mine sites. Frequently, metal mines are located in remote mountainous areas where access to cheap supplies of agricultural wastes is extremely limited. However, cost effective bioreactor systems are possible. For example, the test results from the Britannia Mine demonstrate the feasibility of the Biosulphide™ process to operate at a net profit given a reasonable return for the metal sulphide precipitates that are generated (Rowley *et al.* 1997).

Initial attempts to utilize iron-oxidizing bacteria in AMD treatment were patterned after the conventional activated sludge sewage treatment process (Glover 1967). Glover reported limited success with biochemical oxidation in a continuous-flow reactor. Recycling the sludge solids increased the microbial activity. The activated sludge type reactors have met with limited success in treating AMD. Many types of fixed-film biological reactors, such as trickling filters, biological towers, and rotating biological contactors (RBCs), have been used in the treatment of wastewater. Olem and Unz (1977) conducted pilot studies with RBCs to provide optimized fixed-film biological Fe²⁺ oxidation in AMD treatment. Although the RBC efficiently transformed mine water Fe²⁺ to Fe³⁺ it was not a complete process for AMD treatment as the required chemical neutralization of mineral acidity and precipitation of Fe³⁺ hydrates did not accompany the Fe²⁺ oxidation process.

5.3.6 COSTS

Data relating to the capital and operating and maintenance (O&M) costs for passive AMD treatment systems is sorely lacking. Published papers rarely present cost information. Furthermore, design information, loading rates, hydraulic residence times, and other important data are rarely provided in sufficient detail to evaluate costs. Providing cost information in published papers would be a valuable contribution to the advancement of passive AMD treatment technology.

MEND 3.14.1 is relied upon heavily for the cost information on passive treatment systems presented in this section. This MEND report contains comprehensive cost summaries for the various types of treatment systems described in this Manual. Cost data from other sources is also provided, when available.

5.3.6.1 Anoxic Limestone Drains (ALDs)

ALDs are low-cost alternatives to conventional chemical treatment of AMD. The construction costs of ALDs reviewed during MEND 3.14.1 were less than US\$20,000. Costs ranged from Cdn\$4,000 to Cdn\$25,000 in 1995 Canadian dollars. Two case studies are cited as examples. The first example was for an ALD 50 m long, 0.6 m wide, and 2.5 m deep treating 7.5 L/min of AMD at a construction cost of Cdn\$4,000 in 1995 Canadian dollars. The second case was for an ALD 80 m long, 4.0 m wide, and 1.5 m deep treating 125 L/min at a constructed cost of Cdn\$22,500 in 1995 Canadian dollars (MEND 3.14.1). Skousen (1996) presents cost data for ALDs at three sites in the eastern U.S. Construction costs ranged from US\$1,660 for a 70 ton ALD to US\$18,150 for a 400 ton ALD.

A significant advantage of ALDs is that operation and maintenance (O&M) costs are negligible after construction and site restoration. If required, monitoring costs may be the only operating expenses associated with ALDs.

5.3.6.2 Aerobic Wetland Treatment Systems

Brodie (1993a; 1993b) presented cost information for constructed aerobic wetlands operating in the eastern U.S. Based on TVA experience, construction and operation costs for a typical wetland system for treating coal mine drainage are presented in Table 5.3-2. However, the actual costs are highly sensitive to site-specific factors. For example, wetland construction costs range from US\$10.80/m² to US\$140/m².

MEND 3.14.1 developed a detailed cost estimate for a generic constructed wetland for treatment of AMD at a Canadian mine. This hypothetical wetland was designed to treat 60 L/min of AMD with a surface area of 432 m². The total estimated capital cost for this wetland in 1995 was Cdn\$84,350. Annual O&M costs were estimated at Cdn\$10,000, mainly for inspection and monitoring.

5.3.6.3 Passive Anaerobic Treatment Systems

MEND 3.14.1 presents capital cost information for an idealized passive anaerobic treatment system; however, operation and maintenance costs are not presented. The anaerobic system considered for cost estimation was 20 m in length, 2 to 3 m wide, and 2 m deep, separated by porous dams or clay berms with transfer pipes. The organic substrate used was alfalfa and manure mixture, inoculated

with mud containing SRB. The flow rate for the reactor was assumed to be between 50 and 60 L/min and the retention time was 10 to 14 days. The capital cost was estimated to be Cdn\$33,500.

Table 5.3-2
Typical Cost Estimates for Constructed Wetlands

Cost Factor	Percent of Total Cost, %	Typical Total Cost, US\$
Design	12	6,000
Permitting	2	1,000
Land Acquisition	12	6,000
Construction:		
Equipment and Labour	24	12,000
Materials	12	6,000
Supervision	8	4,000
Operation and Maintenance	18	9,000
Miscellaneous	12	6,000
TOTAL	100	50,000

Source: Brodie (1993b)

Knight Piesold's passive anaerobic treatment system at ASARCO's West Fork Mine in Missouri cost approximately US\$500,000 to install, including installation of rock filters for reaerating the effluent from the anaerobic cells. The West Fork system treats approximately 5,500 L/min of effluent from the mine. This system was constructed in 1995 and has been operating successfully for three years. The O&M costs associated with the system were for monitoring effluent water quality. No specific O&M costs are provided, but these costs are expected to be minimal. The system was designed for up to 30 years of maintenance free operation without replacing the organic substrate (Gusek *et al.* 1998).

Capital construction costs for the passive anaerobic treatment systems, designed by Dames & Moore for use in southern Brazil, were estimated at approximately US\$1,850,000 (Dames & Moore 1997). This cost represents the total cost of constructing five separate systems designed to receive an estimated 26.5 m³/min of net-acidic, metal laden AMD.

5.3.6.4 Bioreactor Treatment Systems

MEND 3.14.1 presents a cost summary for a hypothetical closed bioreactor assumed to be a 38,000-L fibreglass tank. The metering pump and solution distribution system located on the top of the tank were included in the cost estimate. The tank could accommodate a flow rate of 75 to 100 L/min and a retention time of 7 to 14 days. The capital cost for the closed tank was estimated to be \$56,000 in 1995 Canadian dollars.

No capital or O&M cost data was available for the Paques system at the Budelco facility in the Netherlands, which was used as the base method for bioreactor technology. However, Given and Meyer (1998) provide good information regarding the O&M costs of Homestake's bioreactor systems at the Nickel Plate Mine in British Columbia. In summary, the combined O&M costs for the bioreactor and HDS systems are estimated at approximately Cdn\$7.9/m³ of treated effluent. These costs were reported in terms of 1997 Canadian dollars. These costs include the cost of operating the HDS process. The Homestake system was constructed by modifying the metallurgical circuit after closure of the concentrator, and these modifications were performed at low cost. No specific information on construction costs is provided (Given and Meyer 1998).

5.3.6.5 Biosorption Treatment Systems

The costs for biosorbent systems were obtained from Kuyucak (1990). The costs of biosorbents depends on the price of raw biomass. The price of raw biomass can range from no cost to US\$150/kg. A kilogram of dried marine algae costs US\$2 to US\$4. Specifically cultivated fresh water algae (e.g. *Chlorella vulgaris* supplied by Chlorella Corp., Taiwan) costs about US\$14/kg to US\$18/kg.

5.3.7 MEND AND RELEVANT PUBLICATIONS

- | | |
|--------------|--|
| MEND 3.11.1 | 1993. Treatment of Acidic Seepages Using Wetland Ecology and Microbiology: Overall Program Assessment. July. |
| MEND 3.12.1a | 1990. Assessment of Existing Natural Wetlands Affected by Low pH, Metal Contaminated Seepages (Acid Mine Drainage). May. |
| MEND 3.12.2 | 1993. Panel Wetlands - A Case History of Partially Submerged Pyritic Uranium Tailings Under Water. February. |
| MEND 3.13.1a | 1994. Passive Treatment Project at Heath Steele Mines, Phase I: Bench Evaluation of Four Prospective Processes. MEND Associate Report. Open file report available from the MEND Secretariat. |
| MEND 3.14.1 | 1996 (revised 1999). Review of Passive Systems for Treatment of Acid Mine Drainage. |

Ackman, T.E., Kleinmann, R.L.P. and Onysko, S.J. 1986. *In-Line Aeration and Treatment of Acid Mine Drainage*. In: Proceedings of the Reclamation, Treatment and Utilization of Coal Mining Wastes Symposium. Durham, England. 10 to 14 September. Paper 29, pp. 1-12.

Béchar, G., McCready, R.G.L., Koren, D.W. and Rajan, S. 1995. *Microbial Treatment of Acid Mine Drainage at Halifax International Airport*. In: Sudbury '95 – Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 2, pp. 545-554.

- Blowes, D.W., Ptacek, C.J., Bain, J.G., Waybrant, K.R. and Robertson, W.D. 1995. *Treatment of Mine Drainage Water Using In Situ Permeable Reactive Walls*. In: Sudbury '95 – Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 3, pp. 979-988.
- Brodie, G.A., Hammer, D.A. and Tomljanovich, D.A. 1988. *An Evaluation of Substrate Types in Constructed Wetlands Acid Mine Drainage Systems*. In: Proceedings of the Mine Drainage and Surface Mine Reclamation Conference. Pittsburgh, PA. 19 to 21 April. Vol 1, pp. 389-398.
- Brodie, G.A., 1993a. *Staged Aerobic Wetlands-Based Acid Drainage Treatment Systems; Design, Construction, and Operation*. In: Wetland Design for Mining Operations (Eds. T. Wildeman, G. Brodie, and J. Gusek) BiTech Publishers, pp. 1-35.
- Brodie, G.A., 1993b. *Staged Aerobic Constructed Wetlands to Treat Acid Drainage - Case History of Fabius Impoundment 1 and Overview of the Tennessee Valley Authority's Program*. In: Wetland Design for Mining Operations (Eds. T. Wildeman, G. Brodie, and J. Gusek) BiTech Publishers, pp. 1-14.
- Cambridge, M., 1997. *Wheal Jane: The Long-Term Treatment of Acid Mine Drainage*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia, 31 May to 6 June. Vol 3, pp. 1125 –1145.
- Dames & Moore, 1997. Unpublished design information, Randolph C. Fischer, P.E., Denver, CO.
- Dames & Moore, 1999. Unpublished design information, Randolph C. Fischer, P.E., Denver, CO.
- De Vegt, A.L. and Buisman, C.J.N. 1997. *Sulphur Compounds and Metal Removal Using Bioprocess Technology*. In: Proceedings of the 29th Annual Meeting of Canadian Mineral Processors. Ottawa, Ontario. 21 to 23 January. pp. 241-251.
- De Vegt, A.L. and Buisman, C.J.N. 1995. *Full-Scale Biological Treatment of Groundwater Contaminated with Heavy Metals and Sulfate*. In: Proceedings of the 11th Annual General Meeting of Biominet – Biotechnology and the Mining Environment. Ottawa, Ontario. 16 January. pp. 31-43.
- Dvorak, D.H., Hedin, R.S., Edenborn, H.M. and McIntire, P.E. 1991. *The Treatment of Metal-Contaminated Water Using Bacterial Sulphate Reduction: Results from Pilot-Scale Reactors*. In: Proceedings of the 2nd International Conference on the Abatement of Acidic Drainage. Montreal, Québec. 16 to 18 September. Tome 1, pp. 301-314.
- Given, B.S. and Meyer, S. 1998. *Biological Treatment of Tailings Solution at the Nickel Plate Mine*. In: Proceedings of the 22nd Annual British Columbia Mine Reclamation Symposium. Penticton, British Columbia. 14 to 17 September. pp. 157-171.

Glover, H. G., 1967. *The Control of Acid Mine Drainage Pollution by Biochemical Oxidation and Limestone Neutralization Treatment*. In: Proceedings of the 22nd Industrial Waste Conference. West Lafayette, IN. 2 to 4 May. Part 2, pp. 823-847.

Gusek, J.J., Wildeman, T.J., Miller, A. and Fricke, J.R. 1998. *The Challenges of Designing, Permitting, and Building a 1,200 GPM Passive Bioreactor for Metal Mine Drainage at the West Fork Mine, Missouri*. In: Proceedings of the 15th Annual National Meeting of the American Society for Surface Mining and Reclamation. St. Louis, MO. pp. 203-212.

Hamilton, Q.U.I., Lamb, H.M., Hallett, C. and Proctor, J.A. 1997. *Passive Treatment Systems for the Remediation of Acid Mine Drainage, Wheal Jane, Cornwall, UK*. In: Treatment of Mine Water Using Wetlands, Proceedings of the CIWEM National Meeting. University of New Castle, UK. Vol 1, pp. 33-53.

Hammack, R.W., Dvorak, D.H. and Edenborn, H.M. 1993. *The Use of Biogenic Hydrogen Sulphide to Selectively Recover Copper and Zinc from Severely Contaminated Mine Drainage*. Biohydrometallurgical Technologies (Eds. A.E. Torma, M.L. Apel and C.L. Brierly). The Minerals, Metals & Materials Society. pp. 631-639.

Hedin, R.S., 1989. *Treatment of Acid Coal Mine Drainage with Constructed Wetlands*. In: *Wetlands Ecology, Productivity, and Values: Emphasis on Pennsylvania* (Eds. S. K. Majumdar, R. P. Brooks, F. J. Brenner and R.W. Tiner, Jr.) Pennsylvania Academy of Science, Easton, PA. pp. 349-362.

Hedin, R.S. and Nairn, R.W. 1992. *Designing and Sizing Passive Mine Drainage Systems*. In: Proceedings from the 13th West Virginia Surface Mine Drainage Task Force Symposium, Morgantown, WV. 8 to 9 April.

Hedin, R.S., Nairn, R.W. and Kleinmann, R.L.P. 1994. *Passive Treatment of Coal Mine Drainage*. U.S. Bureau of Mines Information Circular 9389.

Hedin, R.S. and Watzlaf, W.C. 1994. *The Effects of Anoxic Limestone Drains on Mine Water Chemistry*. In: Proceedings of the International Land Reclamation and Mine Drainage Conference and the 3rd International Conference on the Abatement of Acidic Drainage. Pittsburgh, PA. 24 to 29 April. Vol 1, pp.185-194.

Jablonowski, E. 1995. *Using Wetlands to Treat AMD*. Coal, Vol 32, pp. 36-.

Jones, D.R., Chapman, B.M. and Jung, R.F. 1995. *Passive Treatment of Mine Water In: Sudbury '95 – Mining and the Environment Conference Proceedings*. Sudbury, Ontario. 28 May to 1 June. Vol 2, pp. 755-763.

Kalin, M. and Smith, M.P. 1997. *Microbial Acid Reduction in Sediments – Concepts and Application*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia, 31 May to 6 June. Vol 3, pp. 1321 –1334.

- Kepler, D.A. and McCleary, E.C. 1994. *Successive Alkalinity-Producing Systems (SAPS) for the Treatment of Acidic Mine Drainage*. . In: Proceedings of the International Land Reclamation and Mine Drainage Conference and the 3rd International Conference on the Abatement of Acidic Drainage. Pittsburgh, PA. 24 to 29 April. Vol 1, pp.195-204.
- Kleinmann, R.L.P. 1991. *Biological Treatment of Mine Water – An Overview*. In: Proceedings of the 2nd International Conference on the Abatement of Acidic Drainage. Montreal, Québec. 16 to 18 September. Tome 4, pp. 27-42.
- Kuyucak, N., Lyew, D., St-Germain, P. and Wheeland, K.G. 1991. *In Situ Bacterial Treatment of AMD in Open Pits*. In: Proceedings of the 2nd International Conference on the Abatement of Acidic Drainage. Montreal, Québec. 16 to 18 September. Tome 2, pp. 337-353.
- Kuyucak, N. 1990. *Feasibility of Biosorbents Application*. In: Biosorption of Heavy Metals (Ed. B. Volesky) pp. 371-378.
- Nairn, R.W., Hedin, R.S. and Watzlaf, G.R. 1992. *Generation of Alkalinity in an Anoxic Limestone Drain*. In: Proceeding from the 9th Annual Meeting of the American Society for Surface Mining and Reclamation. Duluth, MN. 14 to 18 June. pp. 206-219.
- Olem, H. and Unz, R.F. 1977. *Acid Mine Drainage Treatment with Rotating Biological Contactors*. Biotechnology and Bioengineering, Vol 19, pp. 1475-1491.
- Price, W.A. and Errington, J.C. 1998. Guidelines for Metal Leaching and Acid Rock Drainage at Mine Sites in British Columbia. Prepared for the British Columbia Ministry of Energy and Mines, pp. 63-64.
- Rowley, M.V., Warkentin, D.D. and Sicotte, V. 1997. *Site Demonstration of the Biosulfide Process at the Former Britannia Mine*. . In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia, 31 May to 6 June. Vol 4, pp. 1549 –1564.
- Scheeren, P.J.H., Koch, R.O., Buisman, C.J.N., Barnes, L.J. and Versteegh, J.H. 1992. *New Biological Treatment Plant for Heavy Metal Contaminated Groundwater*. Trans IMM, The Institute of Mining and Metallurgy, London, Vol 101, Section C, pp. 190-200.
- Sencindiver, J.C. and Bhumbla, D.K. 1988. *Effects of Cattails (Typha) on Metal Removal from Mine Drainage*. In: Proceedings of the Mine Drainage and Surface Mine Reclamation Conference. Pittsburgh, PA. 19 to 21 April. Vol 1, pp. 359-366.
- SENES Consultants Limited and Lakefield Research Limited. 1998. Report on Technologies Applicable to the Management of Canadian Mining Effluent. Report prepared for Environment Canada, Environmental Protections Services, Minerals and Metal Division. December.

Skousen, J.G. 1996. *Anoxic Limestone Drains for Acid Mine Drainage Treatment*. In: Acid Mine Drainage Control and Treatment, 2nd Edition. (Eds. J.G. Skousen, and P.F. Ziemkiewicz). West Virginia University and the National Mine Land Reclamation Center, Morgantown, WV. pp. 261-266.

Skousen, J., Sexstone, A., Garbutt, K. and Sencindiver, J. 1996. *Wetlands for Treating Acid Mine Drainage*. In: Acid Mine Drainage Control and Treatment, 2nd Edition. (Eds. J.G. Skousen, and P.F. Ziemkiewicz). West Virginia University and the National Mine Land Reclamation Center, Morgantown, WV. pp. 249-260.

Sobolewski, A. 1996. *Development of a Wetland Treatment System at United Keno Hill Mines, Elsa, Yukon Territory*. In: Proceedings of the 20th Annual British Columbia Mine Reclamation Symposium, Kamloops, British Columbia. 17 to 20 June. pp. 64-73.

Sobolewski, A. 1997. *The Capacity of Natural Wetlands to Ameliorate Water Quality: A Review of Case Studies*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia, 31 May to 6 June. Vol 4, pp. 1659 –1672.

Sobolewski, A., Gormely, L. and Kistritz, R.U. 1995. *Copper Removal from Mine Drainage by an Experimental Wetland at Bell Copper Mine, Smithers, B.C.* In: Sudbury '95 – Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 2, pp. 683-692.

Stark, L.R., Kolbash, R.L., Webster, H.J., Stevens, S.E. Jr., Dionis, K.A. and Murphy, E.R. 1988. *The Simco #4 Wetland: Biological Patterns and Performance of a Wetland Receiving Mine Drainage*. In: Proceedings of the Mine Drainage and Surface Mine Reclamation Conference. Pittsburgh, PA. 19 to 21 April. Vol 1, pp. 332-344.

Stillings, L.L., Gryta, J.J. and Ronning, T.A. 1988. *Iron and Manganese Removed in a Typha-Dominated Wetland During Ten Months Following Its Construction*. In: Proceedings of the Mine Drainage and Surface Mine Reclamation Conference. Pittsburgh, PA. 19 to 21 April. Vol 1, pp. 317-324.

Watzlaf, G. R. and Hyman, D.M. 1995. *Limitations of Passive Systems for the Treatment of Mine Drainage*. In: Proceedings from the 17th Annual Conference of the National Abandoned Mine Land Program. French Lick, IN. 15 to 19 October. pp. 186-199.

Waybrant, K.R., Blowes, D.W. and Ptacek, C.J. 1998. *Selection of Reactive Mixtures for Use in Permeable Reactive Walls for Treatment of Mine Drainage*. Environmental Science & Technology, Vol 32, pp. 1972-1979.

Waybrant, K.R., Blowes, D.W., Ptacek, C.J. and Benner, S.G. 1997. *A Geochemical and Mineralogical Investigation of Porous Reactive Walls for the Prevention of Acid Mine Drainage*. In: Proceedings of the 4th International Conference on Acid Rock Drainage, Vancouver, British Columbia, 31 May to 6 June. Vol 4, pp. 1643-1658.

Waybrant, K.R., Blowes, D.W. and Ptacek, C.J. 1995. *Selection of Reactive Mixtures for the Prevention of Acid Mine Drainage Using Porous Reactive Walls*. In: Sudbury '95 – Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 3, pp. 945-954.

Weider, R. K. and Lang, G.E. 1986. *Fe, Al, Mn, and S Chemistry of Sphagnum Peat in Four Peatlands with Different Metal and Sulphur Input*. Water, Air, and Soil Pollution, Vol 29, pp. 309-320.

Wildeman, T. R. 1991. Handbook for Constructed Wetlands Receiving Acid Mine Drainage. U.S. Environmental Protection Agency, Superfund Innovative Technology Evaluation Program, SITE Emerging Technology Project. Contract No. CR 815325

Wildeman, T.R. and Gusek, J.J. 1997. AMD Treatment Short-Course Notes. Presented at the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June.

Wildeman, T. R., Gusek, J.J. and Brodie, G. 1993. Wetland Design for Mining Operations, BiTech Publishers Ltd., Richmond, B.C.

Wildeman, T.R., Dinkel, J.W., Smith, R.M. and McCallister, M.L. 1997. *Field Assessment of Fe(III), Al, and Dissolved O₂ for Passive Treatment Options*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 4, pp. 1659 –1672.

Ziemkiewicz, P.F., Skousen, J.G., Brant, D.L., Sterner, P.L. and Lovett, R.J. 1996. *Acid Mine Drainage Treatment with Armoured Limestone in Open Limestone Channels*. In: Acid Mine Drainage Control and Treatment, 2nd Edition. (Eds. J.G. Skousen, and P.F. Ziemkiewicz). West Virginia University and the National Mine Land Reclamation Center, Morgantown, WV. pp. 281-297.

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

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*

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

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

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

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

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

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

TREATMENT/TRAIITEMENT

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

MONITORING/SURVEILLANCE

- 4.1.1 Field Sampling Manual for Reactive Sulphide Tailings, November 1989.
Contractor: Canect Environmental Control Technologies Limited, Vancouver BC
- 4.2.1 Review of Canadian and United States Legislation Relevant to Decommissioning Acid Mine Drainage Sites, September 1993.
Contractor: Jacques Whitford Environmental Limited, Ottawa ON
- 4.3.1 RTS-1, RTS-2, RTS-3 and RTS-4: Sulphide Ore Mill Tailings Reference Materials, April 1990
Contractor: Natural Resources Canada, Ottawa ON
- 4.5.1-1 Review of Waste Rock Sampling Techniques, June 1994.
*Contractors: SENES Consultants Limited, Richmond Hill ON
Golder Associ e Lt ee, Pointe-Claire QC
Laval University, Sainte-Foy QC*
- 4.5.1-2 Handbook for Waste Rock Sampling Techniques, June 1994.
Contractor: SENES Consultants Limited, Richmond Hill ON
- 4.5.4 Guideline Document for Monitoring Acid Mine Drainage, and Appendix A - Technical Summary Note: Guideline Document for Monitoring Acid Mine Drainage, October 1997
*Contractors: Terrestrial & Aquatic Environmental Managers (TAEM) Ltd., Saskatoon SK
SENES Consultants Limited, Richmond Hill ON*
- 4.6.1 Applications of Geophysical Methods for Monitoring Acid Mine Drainage, December 1994.
Contractor: INCO Exploration and Technical Services Inc., Copper Cliff ON
- 4.6.3 Application of Remote Sensing and Geophysics to the Detection and Monitoring of Acid Mine Drainage, September 1994.
*Contractors: Paterson, Grant & Watson Limited, Toronto ON
Geomatics International Inc., Burlington ON*
- 4.6.5ac A Survey of *In Situ* Oxygen Consumption Rates on Sulphide Tailings: Investigations on Exposed and Covered Tailings, November 1997.
*Contractors: University of Waterloo, Waterloo ON
Beak International Incorporated, Brampton ON*
- 4.6.5b A Rapid Kinetic Technique for Measuring Reactivity of Sulphide Waste Rock: The Oxygen Consumption Method, December 1997.
Contractor: University of Waterloo, Waterloo ON
- 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.
Contractor: AECL Research, Chalk River ON

TECHNOLOGY TRANSFER/TRANSFERT DE LA TECHNOLOGIE

- 5.7.1 1992 Revised Research Plan/Plan de recherche révisé 1992, August 1992.
Contractor: Natural Resources Canada, Ottawa ON
- 5.8 E Report of Results of a Workshop on Mine Reclamation. Toronto, Ontario, March 10-11, 1994.
- 5.8 F Résultats de l'atelier sur la réhabilitation des sites miniers. Toronto, Ontario, les 10 et 11 mars, 1994.
Contractor: Natural Resources Canada, Ottawa ON
- 5.8.1 Economic Evaluation of Acid Mine Drainage Technologies, January 1995.
Contractor: Geocon (SNC-Lavalin), Willowdale ON
- 5.9 Evaluation Study of the Mine Environmental Neutral Drainage Program (MEND), October 1996.
Contractor: Young & Wiltshire Management Consultants, Ottawa ON

NEW IDEAS/NOUVELLES IDÉES

- 6.1 Preventing AMD by Disposing of Reactive Tailings in Permafrost, December 1993.
Contractor: Geocon (SNC-Lavalin), Willowdale ON
- 6.2 Polymer-Modified Clay as Impermeable Barriers for Acid Mining Tailings, April 1994.
Contractor: Alberta Research Council, Edmonton AB
- 6.3 A Critique of Japanese Acid Mine Drainage Technology. April 1994.
Contractor: Laurentian University, Sudbury ON

ASSOCIATE PROJECTS/PROJETS ASSOCIÉS

- PA-1 Hydrogeology of Waste Rock Dumps, July 1995.
*Contractors: University of British Columbia, Vancouver BC
AGRA Earth & Environmental Limited, Calgary AB
Morwijk Enterprises Ltd., Vancouver BC*
- PA-2 Metal Transport and Immobilization at Mine Tailings Impoundments, March 1997.
Contractor: University of Waterloo, Waterloo ON
- APC -1 Subaqueous Deposition of Tailings in the Strathcona Tailings Treatment System, September 1996.
Contractor: Lakefield Research Limited, Lakefield ON
- 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
Contractor: Cogema Resources Inc., Saskatoon SK

BC AMD TASK FORCE REPORTS

- 1.15.1a Acid Drainage from Mine Walls: The Main Zone Pit at Equity Silver Mines. September 1990.
Contractor: Morwijk Enterprises Limited, Vancouver BC
- 2.23.1 Draft Acid Rock Drainage Technical Guide. Volume I. August 1989.
Draft Acid Rock Drainage Technical Guide. Volume II. May 1990.
*Contractors: Steffen Robertson and Kirsten Inc., Vancouver BC
Norecol Environmental Consultants, Vancouver BC
Gormely Process Engineering, Vancouver BC*
- 2.32.1 Kutcho Creek Project: Blending and Segregation - Acid Generation Testwork - Final Report. March 1992.
Contractor: Rescan Environmental Services Ltd.
- 2.33.1 Acid Rock Drainage Remediation Measures at Four Norwegian Mines. November 1991.
Contractor: Steffen Robertson and Kirsten Inc., Vancouver BC
- 4.5.2 Field QA/QC Protocols for Monitoring and Predicting Impacts of Acid Rock Drainage. March 1992.
Contractor: Norecol Environmental Consultants Ltd., Vancouver, BC
- 4.7.1 Monitoring Acid Mine Drainage. August 1990.
*Contractors: Emily Robertson, Biometrician,, Langley, BC
Steffen Robertson and Kirsten (BC) Inc., Vancouver BC*
- 4.7.2 Literature Review for Biological Monitoring of Heavy Metals in Aquatic Environments. September 1990.
Contractor: EVS Environment Consultants, North Vancouver BC
- 4.7.4 Review of Sediment Monitoring Techniques. November 1990.
Contractor: EVS Environment Consultants, North Vancouver BC
- 4.7.5 British Columbia Mine: Ion Speciation Model. August 1992.
Contractor: C.B. Research International Corporation, Sidney BC
- 4.7.6 Use of Paleolimnological Techniques to Assess the Effects of Acid Rock Drainage. March 1992.
Contractor: Norecol Environmental Consultants Ltd., Vancouver BC

OPEN FILE REPORTS/DOSSIERS PUBLICS

- 1.16.2a Interlaboratory Measurement Program for the Standard ARD Material NBM-1, July 1994
Contractor: Natural Resources Canada, Ottawa ON
- 2.13.3a Preliminary Hydrogeochemical Investigation of the Falconbridge New Tailings Impoundment - Fall 1990 - Final Report.
Contractor: University of Waterloo, Waterloo ON

-
- 2.13.3b WATAIL 1.0 User's Manual - A Tailings Basin Model to Evaluate Transient Water Quality of Acid Mine Drainage.
Contractor: University of Waterloo, Waterloo ON
- 2.14.1 Field Evaluation of Wet Cover Alternatives of High Sulphide Tailings. August 1991.
*Contractors: Falconbridge Limited, Falconbridge ON
Natural Resources Canada, Elliot Lake ON*
- 2.32.2a Bassin de co-déposition de stériles et de résidus - Les Mines Selbaie, Joutel, Québec. Mars 1992.
*Contractors: Golder Associés Ltée, Pointe-Claire PQ
Natural Resources Canada, Ottawa ON*
- 2.41.1a Electrochemical Methods for the Prevention of the Oxidation of Sulphide Tailings and the Resultant Acid Generation. September 1991.
Addendum to the Final Report on Electrochemical Methods for the Prevention of the Oxidation of Sulphide Tailings and the Resultant Acid Generation. April 1992.
Contractor: Natural Resources Canada, Ottawa ON
- 4.5.3 ARD Technical Monitoring Manual. February 1994.
*Contractors: EVS Consultants, North Vancouver BC
Steffen, Robertson and Kirsten (Canada) Inc., Vancouver BC*
- 4.6.4 Piezocone Technology – Demonstration Project. 1994.
Contractor: University of British Columbia, Vancouver BC
- 4.8.1 Auscultation de la fosse Solbec - Rapport final, première année d'observation. Mars 1993.
Auscultation de la fosse Solbec - Rapport final, deuxième année d'observation. Mars 1994.
Contractor: Serrener Consultation inc., Rock Forest PQ

APPENDIX B – BIBLIOGRAPHY

BIBLIOGRAPHY

	MEND PROJECT
Aachib, M., Aubertin, M. and Chapuis, R.P. 1994. <i>Column Tests Investigation of Milling Wastes Properties Used to Build Cover Systems</i> . In: Proceedings of the International Land Reclamation and Mine Drainage Conference and 3 rd International Conference on the Abatement of Acidic Drainage. Pittsburgh, PA. 24 to 29 April. Vol 2, pp. 128-137.	2.22.2
Aachib, M., Aubertin, M. and Chapuis, R.P. 1998. <i>Essais en colonne sur des couvertures avec effets de barrière capillaire</i> . In: Proceedings of the 51 st Canadian Geotechnical Conference. Edmonton, Alberta. 4 to 7 October. Vol 2, pp. 837-844.	2.22.2
Ahmed, S.M. 1991. <i>Electrochemical and Surface Chemical Methods for the Prevention of the Atmospheric Oxidation of Sulphide Tailings and Acid Generation</i> . In: Proceedings of the 2 nd International Conference on the Abatement of Acidic Drainage. Montréal, Québec. 16 to 18 September. Tome 2, pp. 305-320.	2.41.1a
Ahmed, S.M. 1994. <i>Surface Chemical Methods of Forming Hardpan in Pyrrhotite Tailings and Prevention of the Acid Mine Drainage</i> . In: Proceedings of the International Land Reclamation and Mine Drainage Conference and 3 rd International Conference on the Abatement of Acidic Drainage. Pittsburgh, PA. 24 to 29 April. Vol 2, pp. 57-66.	2.41.1a
Ahmed, S.M. 1995. <i>Chemistry of Pyrrhotite Hardpan Formation</i> . In: Sudbury '95 – Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 1, pp. 171-180.	2.41.1a
Aiken, S.R., Pettit, C.M., Halbert, B.E. and Knapp, R.A. 1999. <i>Whistle Mine Closure – Modelling Studies and Water Treatment Considerations</i> . In: Sudbury' 99 – Mining and the Environment II Conference Proceedings. Sudbury, Ontario. 13 to 17 September. Vol 2, pp. 771-780.	1.41.4
Al, T.A. and Blowes, D.W. 1995. <i>Storm-Water Hydrograph Separation of Run off from the Kidd Creek Mine-Tailings Impoundment, Timmins Ontario</i> . In: Sudbury '95 – Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 2, pp. 693-702.	2.23.2d
Al, T.A., Blowes, D.W. and Jambor, J.L. 1994. <i>The Pore-Water Geochemistry of the Cu-Zn Mine Tailings at Kidd Creek, Near Timmins, Ontario, Canada</i> . In: Proceedings of the International Land Reclamation and Mine Drainage Conference and 3 rd International Conference on the Abatement of Acidic Drainage. Pittsburgh, PA. 24 to 29 April. Vol 2, pp. 208-217.	2.23.2d

- Al, T.A., Blowes, D.W., Jambor, J.L. and Scott, J.D. 1994. *The Geochemistry of Mine-Waste Pore Water Affected by the Combined Disposal of Natrojarosite and Base-Metal Sulphide Tailings at Kidd Creek, Timmins, Ontario*. Canadian Geotechnical Journal, Vol 31, No. 4, pp. 502-512. 2.23.2d
- Amyot, G. and Vézina, S. 1996. *L'inondation : solution efficace au drainage minier acide du parc Solbec*. Colloque sur le programme de Neutralisation des eaux de drainage dans l'environnement minier. Rouyn-Noranda, Québec. 29 et 30 octobre. Vol 2, pp. 65-88 2.13.2
- Amyot, G. and Vézina, S. 1997. *Flooding as a Reclamation Solution to an Acidic Tailing Pond: The Solbec Case*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 2, pp. 681-696. 2.13.2
- Anderson, M.E., Scharer, J.M. and Nicholson, R.V. 1999. *The Oxygen Consumption Method (OCM): A New Technique for Quantifying Sulphide Oxidation Rates in Waste Rock*. In: Sudbury '99 – Mining and the Environment II Conference Proceedings. Sudbury, Ontario. 13 to 17 September. Vol 3, pp. 1133-1142. 4.6.5b
- Atkins, R.J., Hay, D. and Robertson, J. 1997. *Shallow Water Cover Design Methodology and Field Verification*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 1, pp. 211-228. 2.11.5ab
- Aubé, B.C. and Zinck, J.M. 1999. *Comparison of AMD Treatment Processes and their Impact on Sludge Characteristics*. In: Sudbury '99 – Mining and the Environment II Conference Proceedings. Sudbury, Ontario. 13 to 17 September. Vol 1, pp. 261-270. 3.42.2b
- Aubé, B.C., St-Arnaud, L.C., Payant, S.C. and Yanful, E.K. 1995. *Laboratory Evaluation of the Effectiveness of Water Covers for Preventing Acid Generation from Pyritic Rock*. In: Sudbury '95 – Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 2, pp. 495-504. 2.36.2
- Aubertin, M., Aachib, M., Bussière, B., Chapuis, R.P. 1996. *Recouvrements multicouches avec effets de barrière capillaire pour contrôler le drainage minier acide : Étude en laboratoire et in situ*. Présentation invitée. Symposium international - Exemples majeurs et récents en géotechnique de l'environnement. École centrale de ponts et chaussées, Paris, pp. 181-199. 2.22.2
- Aubertin, M., Aachib, M., Chapuis, R.P. and Bussière, B. 1996. *Recouvrements multicouches avec effets de barrière capillaire pour contrôler le drainage minier acide : études en laboratoire et in situ*. Colloque sur le programme de Neutralisation des eaux de drainage dans l'environnement minier. Rouyn-Noranda, Québec. 29 et 30 octobre. Vol 1, pp. 1-20. 2.22.2

- Aubertin, M., Aachib, M., Crespo, J.R., Chapuis, R.P. and Bussière, B. 1996. *Une modélisation numérique des écoulements non saturés dans des couvertures multicouches en sols*. Colloque sur le programme de Neutralisation des eaux de drainage dans l'environnement minier. Rouyn-Noranda, Québec. 29 et 30 octobre. Vol 1, pp. 21-33. 2.22.2
- Aubertin, M., Aachib, M., Joanes, A.-M., Monzon, M. and Authier, K. 1999. *Évaluation du flux d'oxygène à travers les matériaux de recouvrement*. In: Congrès APGGQ – Les sciences de la terre : une vision planétaire. Rouyn-Noranda, Québec. 15 to 16 April. pp. 19-30. 2.22.2
- Aubertin, M., Aachib, M., Monzon, M., Chapuis, R.P. and Bussière, B. 1996. *Le contrôle du drainage minier acide à l'aide de barrières de recouvrement*. Colloque sur le programme de Neutralisation des eaux de drainage dans l'environnement minier. Rouyn-Noranda, Québec. 29 et 30 octobre. Vol 2, pp. 131-156. 2.22.2
- Aubertin, M., Bussière, B., Aachib, M and Chapuis, R.P. 1996. *Une modélisation numérique des écoulements non saturés dans des couvertures multicouches en sols* Hydrogéologie, Vol 1, pp. 3-13. 2.22.2
- Aubertin, M., Bussière, B., Barbera, J.-M., Chapuis, R.P., Monzon, M. and Aachib, M. 1997. *Construction and Instrumentation of In situ Test Plots to Evaluate Covers Built with Clean Tailings*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 2, pp. 715-730. 2.22.2
- Aubertin, M., Bussière, B. and Chapuis, R.P. 1996. *Hydraulic Conductivity of Homogenized Tailings from Hard Rock Mines*. Canadian Geotechnical Journal, Vol 33, pp. 470-482. 2.22.2
- Aubertin, M., Bussière, B. and Chapuis, R.P. 1994. *Hydrogeological Properties of Homogenized Tailings Used in Covers Over Reactive Wastes*. In: Proceedings of the 47th Canadian Geotechnical Conference. Halifax, Nova Scotia. 21 to 23 September. pp. 483-493. 2.22.2
- Aubertin, M., Chapuis, R.P., Aachib, M., Ricard, J.F., Tremblay, L. and Bussière, B. 1994. *Cover Technology for Acidic Tailings: Hydrogeological Properties of Milling Wastes Used as Capillary Barrier*. In: Proceedings of the 1st International Congress on Environmental Geotechnics. Edmonton, Alberta. 10 to 15 July. pp. 427-432. 2.22.2
- Aubertin, M., Chapuis, R.P., Bouchentouf, A. and Bussière, B. 1997. *Unsaturated Flow Modelling of Inclined Layers for the Analysis of Covers*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 2, pp. 731-746. 2.22.2

- Aubertin, M., Chapuis, R.P., Bussière, B. and Aachib, M. 1993. *Propriétés des résidus miniers utilisés comme matériau de recouvrement pour limiter le drainage minier acide (DMA)*. In: Géoconfine 93. Rotterdam, Netherlands Vol 1, pp. 299-308. 2.22.2a
- Aubertin, M., Chapuis, R.P., Bussière, B. and Aachib, M. 1993. *On the Use of Tailings as Cover to Prevent AMD*. In: Compte rendu de la Conférence nationale conjointe de la SCGC-ASCE sur le génie environnemental. Vol 1, pp. 195-202. 2.22.2
- Aubertin, M., Chapuis, R.P., Bussière, B., Aachib, M., Ricard, J.F. and Tremblay, L. 1993. *Propriétés des rejets de concentrateur utilisés par la construction de barrières de recouvrement multicouches*. Colloque sur le programme de Neutralisation des eaux de drainage dans l'environnement minier. Val d'Or, Québec. 3 et 4 novembre. Vol 1, pp. 155-175. 2.22.2
- Aziz, M.L. and Ferguson, K.D. 1997. *Equity Silver Mine – Integrated Case Study*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 1, pp. 181-196. MEND Associate
- Balins, J.K., Welch, D.E., Knapp, R.A. and Maltby, J.W. 1991. *Decommissioning of the Quirke Uranium Tailings Basin to Eliminate Acid Production*. In: Proceedings of the 2nd International Conference on the Abatement of Acidic Drainage. Montréal, Québec. 16 to 18 September. Tome 1, pp. 379-398. 2.13.1
- Barbour, S.L., Wilson, G.W. and St-Arnaud, L.C. 1993. *Evaluation of the Saturated-Unsaturated Groundwater Conditions of a Thickened Tailings Deposit*. Canadian Geotechnical Journal, Vol 30, pp. 935-946 2.23.2ab
- Beaudoin, P. and McMullen, J. 1990. *L'approche environnementale pour le contrôle des effluents miniers acides à la mine Doyon*. Colloque sur la réduction et le drainage des effluents acides générés par les activités minières. Val d'Or, Québec. 28 novembre. pp. 85-95. 1.14.2
- Béchar, G. 1990. *Développement d'un procédé microbiologique pour traiter le drainage minier acide*. Colloque sur la réduction et le drainage des effluents acides générés par les activités minières. Val d'Or, Québec. 28 novembre. pp. 227-246. MEND Associate
- Béchar, G., McCready, R.G.L. and Goudey, P. 1991. *Microbiological Process for the Treatment of Acidic Drainage at the Halifax International Airport*. In: Proceedings of the 2nd International Conference on the Abatement of Acidic Drainage. Montréal, Québec. 16 to 18 September. Tome 3, pp. 171-184. MEND Associate

- Béchar, G., McCready, R.G.L., Koren, D.W. and Rajan, S. 1995. *Microbial Treatment of Acid Mine Drainage at Halifax International Airport*. In: Sudbury '95 – Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 2, pp. 545-554. MEND Associate
- Bell, A.V., Riley, M.D. and Yanful, E.K. 1994. *Evaluation of a Composite Soil Cover to Control Acid Waste Rock Pile Drainage*. In: Proceedings of the International Land Reclamation and Mine Drainage Conference and 3rd International Conference on the Abatement of Acidic Drainage. Pittsburgh, PA. 24 to 29 April. Vol 2, pp. 113-121. 2.31.1a
- Bell, A.V., Surges, L. and Yanful, E.K. 1991. *An Update on the Acid Waste Rock Fields Trials at Heath Steele Mines New Brunswick*. In: Proceedings of the 2nd International Conference on the Abatement of Acidic Drainage. Montréal, Québec. 16 to 18 September. Tome 3, pp. 319-340. 2.31.1ab
- Bennett, J.W., Garvie, A.M., Pantelis, G., Ritchie, A.I.M., Bell, A.V. and Noël, M. 1995. *Comparison of Measured and Predicted Transport Processes Controlling Oxidation in the Waste Rock Piles at the Heath Steele Mine Site*. In: Sudbury '95 – Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 3, pp. 1017-1026. 1.22.1
- Benzaazoua, M. and Bussière, B. 1999 *Désulfuration de résidus miniers dans un but environnemental: faisabilité, optimisation et modélisation*. In: Séminaire Mines écologiques présentés dans le cadre du Congrès APGGQ – Les sciences de la terre : une vision planétaire. Rouyn-Noranda, Québec. 14 April. 29p. 2.22.3
- Benzaazoua, M. and Bussière, B. 1999. *Desulphurization of Tailings with Low Neutralizing Potential: Kinetic Study and Flotation Modeling*. In: Sudbury '99 – Mining and the Environment II Conference Proceedings. Sudbury, Ontario. 13 to 17 September. Vol 1, pp. 29-38. 2.22.3
- Benzaazoua, M., Bussière, B., Kongolo, M., McLaughlin, J. and Marion, P. 2000. *Environmental Desulphurization of Four Canadian Mine Tailings Using Froth Flotation*. International Journal of Mineral Processing. Vol 60, pp. 57-74. 2.22.3
- Benzaazoua, M., Bussière, B. and Lelièvre, J. 1998. *Flottation non-sélective des minéraux sulfurés appliquée dans la gestion environnementale des rejets miniers*. In: Proceedings of the 30th Annual Meeting of the Canadian Mineral Processors Conference. Ottawa, Ontario. 20 to 22 January. pp. 682-695. 2.22.3
- Benzaazoua, M., Bussière, B. and Lelièvre, J. 1998. *Non-Selective Froth Flotation of Sulphide Minerals for Environmental Tailings Management*. In: Proceedings of the 30th Annual Meeting of the Canadian Mineral Processors Conference. Ottawa, Ontario. 20 to 22 January. pp. 696a-696m. 2.22.3

- Benzaazoua, M., Bussière, B., Nicholson, R.V. and Bernier, L. 1998. *Geochemical Behaviour of a Multi-Layered Cover Composed of Desulfurized Mine Tailings*. In: Proceedings of the 5th International Conference on Tailings and Mine Waste '98. Fort Collins, CO. 26 to 28 January. pp. 389-398. 2.22.3
- Benzaazoua, M., Kongolo, M. and Bussière, B. 2000. *Effect of the Granulometry on the Desulphurization Feasibility of Mine Tailings*. In: Proceedings of the 5th International Conference on Acid Rock Drainage. Denver, CO. 21 to 24 May. Vol 2, pp. 853-861. 2.22.3
- Bienvenu, L. 1993. *Études et expérimentation de l'ennoiement des résidus miniers du parc Solbec Cupra*. Colloque sur le programme de Neutralisation des eaux de drainage dans l'environnement minier. Val d'Or, Québec. 3 et 4 novembre. Vol 2, pp. 81-95. 2.13.2
- Blanchette, M. 1993. *Monitoring Committee – Status Report*. Colloque sur le programme de Neutralisation des eaux de drainage dans l'environnement minier. Val d'Or, Québec. 3 et 4 novembre. Vol 1, pp. 105-121. General MEND Monitoring
- Blanchette, M. 1993. *Prediction Committee – Status Report*. Colloque sur le programme de Neutralisation des eaux de drainage dans l'environnement minier. Val d'Or, Québec. 3 et 4 novembre. Vol 1, pp. 17-34. General MEND Prediction
- Blowes, D.W., Ptacek, C.J., Bain, J.G., Waybrant, K.R. and Robertson, W.D. 1995. *Treatment of Mine Drainage Water Using In Situ Permeable Reactive Walls*. In: Sudbury '95 – Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 3, pp. 979-988. MEND Associate
- Brooks, B.W. 1990. *Overview of the Manual of Methods Used in the Revegetation of Reactive Sulphide Tailings Basins*. Colloque sur la réduction et le drainage des effluents acides générés par les activités minières. Val d'Or, Québec. 28 novembre. pp. 247-268. 2.24.1
- Broughton, L.M. and Healey, P.M. 1992. *Mine Site Decommissioning: Technology for Assessment and Control of Acid Rock Drainage*. In: Proceedings of the 2nd International Conference on Environmental Issues and Management of Waste in Energy and Mineral Production. Calgary, Alberta. 1 to 4 September. Vol 2, pp. 789 - 797. 2.23.1
- Bussière, B. and Aubertin, M. 1999. *Clean Tailings as Cover Material for Preventing Acid Mine Drainage – An In situ Experiment*. In: Sudbury '99 – Mining and the Environment II Conference Proceedings. Sudbury, Ontario. 13 to 17 September. Vol 1, pp. 19-28. 2.22.2
- Bussière, B., Aubertin, M., Aachib, M. and Chapuis, R.P. 2000. *The Use of Low Sulphide Tailings as the Moisture Retaining Layer in Engineered Cover Systems to Prevent AMD*. In: Proceedings CSCE Annual Conference. London. 2.22.2

- Bussi re, B., Aubertin, M. and Chapuis, R.P. 2000. *An Investigation of Slope Effects on the Efficiency of Capillary Barriers to Control AMD*. In: Proceedings of the 5th International Conference on Acid Rock Drainage. Denver, CO. 21 to 24 May. Vol 2, pp. 969-977. 2.22.4b
- Bussi re, B., Aubertin, M. and Chapuis, R.P. 1999. * tude num rique du comportement hydrique de syst mes de recouvrements inclin s visant   limiter le flux d'oxyg ne*. In: Proceedings of the 52nd Canadian Geotechnical Conference. Regina, Saskatchewan. pp. 373-380. 2.22.2
- Bussi re, B., Aubertin, M., Aachib, M., Chapuis, R.P. and Crespo, R.J. 1995. *Unsaturated Flow Modeling of Covers for Reactive Tailings*. In: CAMI '95 – Proceedings of the 3rd Canadian Conference on Computer Applications in the Mineral Industry. Montr al, Qu bec. 22 to 25 October. pp. 853-862. 2.22.2
- Bussi re, B., Aubertin, M., Benzaazoua, M. and Gagnon, D. 1999. * valuation de l'efficacit  de r siduals miniers d sulfur s comme couche de r tention d'eau dans une CEBC*. In: S minaire Mines  cologiques, Congr s APGGQ – Les sciences de la terre : une vision plan taire. Rouyn-Noranda, Qu bec. 14 April. 25p. 2.22.3
- Bussi re, B., Aubertin, M., Benzaazoua, M. and Gagnon, D. 1999. *Mod le d'estimation des co ts de restauration de sites miniers g n rateurs de DMA*. In: S minaire Mines  cologiques, Congr s APGGQ – Les sciences de la terre : une vision plan taire. Rouyn-Noranda, Qu bec. 14 April. 27p. 2.22.2
2.22.3
- Bussi re, B., Aubertin, M., Morel-Seytoux, H.J. and Chapuis, R.P. 1998. *A Laboratory Investigation of Slope Influence on the Behavior of Capillary Barriers*. In: Proceedings of the 51st Canadian Geotechnical Conference. Edmonton, Alberta. Vol 2, pp. 831-836. 2.22.2
2.22.4b
- Bussi re, B., Bois, D. and Benzaazoua, M. 1997. *Valorisation des r siduals miniers g n rateurs de drainage minier acide par la d sulfuration*. In: Proceedings of the 20th Symposium on Wastewater, 9th Workshop on Drinking Water. pp. 275-289. 2.22.3
- Bussi re, B., Leli vre, J., Ouellet, J. and Bois, D. 1995. *Utilisation de r siduals miniers d sulfur s comme recouvrement pour pr venir le DMA : analyse technico- conomique sur deux cas r els*. In: Sudbury '95 – Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 1, pp. 59-68. 2.22.3
- Bussi re, B., Nicholson, R.V., Aubertin, M. and Benzaazoua, M. 1997. *Evaluation of the Effectiveness of Covers Built With Desulfurized Tailings for Preventing Acid Mine Drainage*. In: Proceedings of the 50th Canadian Geotechnical Conference. Ottawa, Ontario. 20 to 22 October. Vol 1, pp. 17-25. 2.22.3

- Bussière, B., Nicholson, R.V., Aubertin, M. and Servant, S. 1997. *Effectiveness of Covers Built with Desulphurized Tailings: Column Tests Investigation*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 2, pp. 763-778. 2.22.3
- Bussière, B., Servant, S., Ouellet, J., Lelièvre, J. and Aubertin, M. 1996. *Utilisation des résidus désulfurés pour la construction de recouvrements multicouches*. Colloque sur le programme de Neutralisation des eaux de drainage dans l'environnement minier. Rouyn-Noranda, Québec. 29 et 30 octobre. Vol 1, pp. 85-103. 2.22.3
- Coleman, M.M.D., Whalen, T.J. and Landva, A. 1997. *Investigation on the Placement of Lime Neutralization Sludge on Acid Generating Waste Rock*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 3, pp. 1163-1178. MEND Associate
- Davé, N. and Blanchette, M. 1999. *Role of Cold Climatic Conditions in Management of Reactive Mining Waste in Northern Canada*. In: Proceedings of the 5th International Symposium on Mining in the Arctic. Yellowknife, Northwest Territories. 14 to 17 June, 1998. pp.115-124. 1.61.2
- Davé, N. and Michelutti, R.E. 1991. *Field Evaluation of Wet Cover Alternatives for High Sulphide Tailings*. In: Proceedings of the 2nd International Conference on the Abatement of Acidic Drainage. Montréal, Québec. 16 to 18 September. Tome 3, pp. 61-82. 2.14.1
- Davé, N.K. and Vivyurka, A.J. 1993. *Shallow Water Cover on Acid Generating Uranium Tailings*. In: Proceedings of the International Symposium on Drying, Roasting, Calcining and Acid Plant Design and Operation. Québec City, Québec. 29 August to 2 September. pp. 287-305. 2.13.1
- Davé, N.K. and Vivyurka, A.J. 1994. *Water Cover on Acid Generating Uranium Tailings – Laboratory and Field Studies*. In: Proceedings of the International Land Reclamation and Mine Drainage Conference and 3rd International Conference on the Abatement of Acidic Drainage. Pittsburgh, PA. 24 to 29 April. Vol 1, pp. 297-306. 2.13.1
- Davé, N.K., Lim, T.P., Horne, D., Boucher, Y. and Stuparyk, R. 1997. *Water Cover on Reactive Tailings and Wasterock: Laboratory Studies of Oxidation and Metal Release Characteristics*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 2, pp. 779-794. 2.15.1
- Davé, N.K., Lim, T.P., Vivyurka, A.J., Bihari, B. and Kay, D.A. 1990. *Development of Wet Barriers on Pyritic Uranium Tailings, Elliot Lake, Ontario*. Colloque sur la réduction et le drainage des effluents acides générés par les activités minières. Val d'Or, Québec. 28 novembre. pp. 209-225. 2.13.1

- David, D.J. and Nicholson, R.V. 1995. *Field Measurements for Determining Rates of Sulphide Oxidation*. In: Sudbury '95 – Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 1, pp. 201-210. 2.13.3
- Day, S.J. 1994. *Evaluation of Acid Generating Rock and Acid Consuming Rock Mixing to Prevent Acid Rock Drainage*. In: Proceedings of the International Land Reclamation and Mine Drainage Conference and 3rd International Conference on the Abatement of Acidic Drainage. Pittsburgh, PA. 24 to 29 April. Vol 2, pp. 77-86. 1.19.1
- Delaney, T., Hockley, D. and Sollner, D. 1997. *Applications of Method for Delaying the Onset of Acidic Drainage*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 2, pp. 795-810. 2.37.2
- Denholm, E. 1991. *A Review of Acid Generation Research at the Samatosum Mine*. In: Proceedings of the 2nd International Conference on the Abatement of Acidic Drainage. Montréal, Québec. 16 to 18 September. Tome 2, pp. 561-578. MEND Associate
- Desrochers, C. 1990. *Restauration du site de la mine Solbec-Cupra*. Colloque sur la réduction et le drainage des effluents acides générés par les activités minières. Val d'Or, Québec. 28 novembre. pp. 115-177. 2.13.2
- Elliot, L.C.M. and Liu, L. 1997. *Subaqueous Deposition of Acid Generating Tailings into an Acidic Lake Environment: Pilot Column Test Results*. In: Proceedings of the 29th Annual Meeting of the Canadian Mineral Processors Conference. Ottawa, Ontario. 21 to 23 January. pp. 255-271. APC-1
- Elliot, L.C.M., Liu, L. and Stogran, S.W. 1997. *Organic Cover Material for Organic Tailings: Do They Meet the Requirements of an Effective Long Term Cover?* In: Proceedings of the 13th Annual General Meeting of BIOMINET – Biotechnology and the Mining Environment. Ottawa, Ontario. 20 January. pp. 1-14. 2.25.3
- Elliott, L.C.M., Davison, J.G., Liu, L. and Stogran, S.W. 1997. *Evaporative Losses, Salt Migration and Mineralogical Changes in Dry Covers over Oxidized Tailings*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 3, pp. 1211-1230. 2.25.3
- Elliott, L.C.M., Liu, L. and Stogran, S.W. 1997. *Organic Cover Materials for Tailings: Do They Meet the Requirements of an Effective Long Term Cover?* In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 2, pp. 811-824. 2.25.3
- Feasby, D.G. and Tremblay, G.A. 1995. *Role of Mineral Processing in Reducing Environmental Liability of Mine Wastes*. In: Proceedings of the 27th Annual Meeting of the Canadian Mineral Processors. Ottawa, Ontario. 17 to 19 January. pp. 217-234. General MEND

- Feasby, D.G. and Tremblay, G.A. 1995. *New Technologies to Reduce Environmental Liability from Acid Generating Mine Wastes*. In: Sudbury '95 – Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 2, pp. 643-648. General MEND
- Feasby, D.G., Tremblay, G.A. and Weatherell, C.J. 1997. *A Decade of Technology Improvement to the Challenge of Acidic Drainage – A Canadian Perspective*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 1, pp. i-ix. General MEND
- Feasby, D.G., Tremblay, G.A. and Blanchette, M. 1991. *The Mine Environment Neutral Drainage (MEND) Program*. In: Proceedings of the 2nd International Conference on the Abatement of Acidic Drainage. Montréal, Québec. 16 to 18 September. Tome 1, pp. 1-26. General MEND
- Filion, M.P., Ferguson, K.D. and Sirois, L.L. 1990. *Acid Mine Drainage Research in Canada*. Colloque sur la réduction et le drainage des effluents acides générés par les activités minières. Val d'Or, Québec. 28 novembre. pp. 7-34. General MEND
- Filion, M.P. and Ferguson, K.D. 1989. *Acid Mine Drainage Research in Canada*. In: Proceedings of the 1989 Annual General Meeting of BIOMINET. Laval, Québec. 5 October. pp. 27-44. General MEND
- Filion, M.P. and Ferguson, K.D. 1990. *Acid Mine Drainage Research in Canada*. In: Proceedings of the 22nd Annual Meeting of the Canadian Mineral Processors Conference. Ottawa, Ontario. 16 to 18 January. pp. 276-291. General MEND
- Filion, M.P., Firlotte, F.W., Julien, M.R. and Lacombe, P.F. 1994. *Regulatory Controlled Design – Louvicourt Project – A Case Study*. In: Proceedings of the International Land Reclamation and Mine Drainage Conference and 3rd International Conference on the Abatement of Acidic Drainage. Pittsburgh, PA. 24 to 29 April. Vol 2, pp. 22-31. 2.12.1
- Filion, M.P., Sirois L.L. and Ferguson, K.D. 1990. *Acid Mine Drainage in Canada*. CIM Bulletin. Vol 83, No. 944. December. pp. 33-40. General MEND
- Filion, M.P., Sirois, L.L. and Ferguson, K.D. 1991. *Acid Drainage Research in Canada*. In: Proceedings of the 23rd Annual Meeting of the Canadian Mineral Processors Conference. Ottawa, Ontario. 22 to 24 January. Paper 10, 21 p. General MEND
- Firlotte, F.W., Knapp, R.A., McMullen, J. and Gélinas, P. 1991. *Acid Drainage Treatment at La Mine Doyon: Evolution and Future Direction*. In: Proceedings of the 2nd International Conference on the Abatement of Acidic Drainage. Montréal, Québec. 16 to 18 September. Tome 4, pp. 119-140. 1.14.2

- Fraser, W.W. 1997. *MEND at Work – Designing Mines for Closure*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 2, pp. 825-834. General MEND
- Fraser, W.W. and Robertson, J.D. 1994. *Subaqueous Disposal of Reactive Mine Waste: An Overview and Update of Case Studies – MEND/Canada*. In: Proceedings of the International Land Reclamation and Mine Drainage Conference and 3rd International Conference on the Abatement of Acidic Drainage. Pittsburgh, PA. 24 to 29 April. Vol 1, pp. 250-259. 2.11.1
- Fyson, A., Kalin, M. and Smith, M.P. 1995. *Microbially-Mediated Metal Removal from Acid Mine Drainage*. In: Sudbury '95 – Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 2, pp. 459-466. 3.11.1
- Fytas, K., Bordeleau, D., Soto, H. and Evangelou, B. 1996. *Enrobage de la pyrite par des phosphates ferriques*. Colloque sur le programme de Neutralisation des eaux de drainage dans l'environnement minier. Rouyn-Noranda, Québec. 29 et 30 octobre. Vol 2, pp. 189-213. New Ideas
- Fytas, K., Hadjigeorgiou, J., Cecile, J.L. and Dauphin, P. 1992. *Continuous Monitoring of Acid Rock Drainage*. International Journal of Environmental Issues in Minerals and Energy Industry, Vol 1, No 1, pp. 11-16. 4.6.2
- Fytas, K. and Hadjigeorgiou, J. 1993. *Surveillance en continu du drainage rocheux acide : méthodologie et équipement*. Colloque sur le programme de Neutralisation des eaux de drainage dans l'environnement minier. Val d'Or, Québec. 3 et 4 novembre. Vol 2, pp. 33-53. 4.6.2
- Gélinas, P.J., Isabel, D., Choquette, M. and Lefebvre, R. 1993. *Le génération de drainage minier acide à la mine Doyon : études des bilans énergétiques, hydrologiques et de masse*. Colloque sur le programme de Neutralisation des eaux de drainage dans l'environnement minier. Val d'Or, Québec. 3 et 4 novembre. Vol 2, pp. 55-79. 1.14.2
- Gélinas, P.J., Lefebvre, R. and Choquette, M. 1992. *Monitoring of Acid Mine Drainage in a Waste Rock Dump*. In: Proceedings of the 2nd International Conference on Environmental Issues and Management of Waste in Energy and Mineral Production. Calgary, Alberta. 1 to 4 September. Vol. 2, pp. 747-756. 1.14.2
- Gerencher, E.H., Konasewich, D.E., Wong, J.Y. and van Dyk, R. 1991. *The Use of Mine Tailings in Concrete Surface Covers to Control Acid Mine Drainage in Waste Rock Dumps*. In: Proceedings of the 2nd International Conference on the Abatement of Acidic Drainage. Montréal, Québec. 16 to 18 September. Tome 4, pp. 69-84. 2.34.1

- Ghomshei, M., Holmes, A., Denholm, E., Lawrence, R. and Carriou, T. 1997. *Acid Rock Drainage from the Samatsum Waste Dump, British Columbia, Canada*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 1, pp. 351-366. MEND Associate
- Hanton-Fong, C.J., Blowes, D.W. and Stuparyk, R.A. 1997. *Evaluation of Low Sulphur Tailings in the Prevention of Acid Mine Drainage*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 2, pp. 835-852. 2.45.2
- Hope, G. 1992. *AMD Prevention and Control Methods Used in Canada*. In: Proceedings of the 13th Annual West Virginia Surface Mine Drainage Task Force Symposium. Morgantown, WV. April. General MEND P & C
- Humber, A.J. 1995. *Separation of Sulphide Minerals from Mill Tailings*. In: Sudbury '95 - Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 1, pp. 149-158. 2.45.1a
- Itzkovitch, I.J. and Feasby, D.G. 1993. *Le programme de neutralisation des eaux de drainage dans l'environnement minier (NEDEM)*. Colloque sur le programme de Neutralisation des eaux de drainage dans l'environnement minier. Val d'Or, Québec. 3 et 4 novembre. Vol 1, pp. 1-16. General MEND
- 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. 399-416. 1.21.2
- Jones, C.E. and Wong, J.Y. 1994. *Shotcrete as a Cementitious Cover for Acid Generating Waste Rock Piles*. In: Proceedings of the International Land Reclamation and Mine Drainage Conference and 3rd International Conference on the Abatement of Acidic Drainage. Pittsburgh, PA. 24 to 29 April. Vol 2, pp. 104-112. 2.34.1
- Kalin, M. 2001. *Biogeochemical and Ecological Considerations in Designing Wetland Treatment Systems in Post-Mining Landscapes*. Waste Management. Vol 21, pp. 191-196. 3.11.1
- Kalin, M. and Smith, M.P. 1997. *Microbial Acid Reduction in Sediments - Concepts and Application*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 3, pp. 1321-1334. 3.11.1
- Kalin, M., Fyson, A. and Smith, M.P. 1995. *Microbially-Mediated Metal Removal from Acid Mine Drainage*. In: Sudbury '95 - Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 2, pp. 459-466. 3.11.1

- Kalin, M., Fyson, A. and Smith, M.P. 1993. *ARUM - Acid Reduction Using Microbiology*. In: Proceedings of the International Biohydrometallurgy Symposium, Biohydrometallurgical Technologies, Fossil Energy Materials, Bioremediation, Microbial Physiology. Jackson Hole, WY. 22 to 25 August. Vol 2, pp. 319-328. 3.11.1
- Kalin, M., van Everdingen, R.O. and McCready, R.G.L. 1992. *Ecological Engineering - Interpretation of Hydrogeochemical Observations in a Sulphide Tailings Deposit*. CIM Bulletin. Vol 85, No. 965. pp. 64-67. 3.11.1
- Kalin, M. and Smith, M.P. 1991. *Biological Amelioration of Acidic Seepage Streams*. In: Proceedings of the 2nd International Conference on the Abatement of Acidic Drainage. Montréal, Québec. 16 to 18 September. Tome 1, pp. 355-368. 3.11.1
- Kalin, M. and Smith, M.P. 1991. *Biological Amelioration of Acidic Seepage Streams*. In: Proceedings of the 15th Annual British Columbia Mine Reclamation Symposium and 16th Annual Canadian Land Reclamation Meeting: Reclamation and Sustainable Development. Kamloops, British Columbia. 24 to 28 June. pp. 351-362. 3.11.1
- Kalin, M. 1991. *Biological Alkalinity Generation in Acid Mine Drainage*. In: Proceedings of the 23rd Annual Meeting of the Canadian Mineral Processors Conference. Ottawa, Ontario. 22 to 24 January. Paper 9, 10p. 3.11.1
- 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 3, pp. 853-870. 2.13.1
- Kelly, G.J. and Slater, R.J. 1994. *The Mining Environment Database on Abandoned Mines, Acid Mine Drainage and Land Reclamation*. In: Proceedings of the International Land Reclamation and Mine Drainage Conference and 3rd International Conference on the Abatement of Acidic Drainage. Pittsburgh, PA. 24 to 29 April. Vol 4, pp. 352-357. 5.3.1
- King, A.R. and Hynes, T. P. 1994. *Applications of Geophysical Methods for Monitoring Acid Mine Drainage*. In: Proceedings of the International Land Reclamation and Mine Drainage Conference and 3rd International Conference on the Abatement of Acidic Drainage. Pittsburgh, PA. 24 to 29 April. Vol 1, pp. 317-326. 4.6.1
- Knapp, R.A., Pettit, C.M. and Martin, J.C. 1995. *Waste Rock Sampling Techniques for Acid Rock Drainage (ARD) Assessment*. In: Sudbury '95 - Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 2, pp. 587-596. 4.5.1

- Kondos, P., MacDonald, R.J.C. and Zinck, J.M. 1991. *Studies on the Removal of Heavy Metals from Acidic Mineral Effluents*. In: Proceedings of the 2nd International Conference on the Abatement of Acidic Drainage. Montréal, Québec. 16 to 18 September. Tome 2, pp. 47-70. 3.21.1a
- Kwong, Y.T.J. 1991. *Acid Generation in Waste Rock as Exemplified by the Mount Washington Minesite, British Columbia, Canada*. In: Proceedings of the 2nd International Conference on the Abatement of Acidic Drainage. Montréal, Québec. 16 to 18 September. Tome 1, pp. 175-190. MEND Associate
- Kwong, Y.T.J. 1992. *Generation, Attenuation and Abatement of Acidic Drainage in an Abandoned Minesite on Vancouver Island, Canada*. In: Proceedings of the 2nd International Conference on Environmental Issues and Management of Waste in Energy and Mineral Production. Calgary, Alberta. 1 to 4 September. pp. 757-762. MEND Associate
- Kwong, Y.T.J. 1993. *Minesite Acid Rock Drainage Assessment and Prevention - A New Challenge for a Mining Geologist*. In: Proceedings of the International Mining Geology Conference. Kalgoorlie-Boulder, Western Australia. 5 to 8 July. pp. 213-217. 1.32.1
- Kwong, Y.T.J. 1995. *Influence of Galvanic Sulfide Oxidation on Mine Water Chemistry*. In: Sudbury '95 – Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 2, pp. 477-483. 1.32.1
- Kwong, Y.T.J. and Ferguson, K.D. 1990. *Water Chemistry and Oxidation Mineralogy at Mount Washington – Implications to Acid Generation and Metal Leaching*. In: Acid Mine Drainage: Designing for Closure, GAC/MAC Joint Annual Meeting. Vancouver, British Columbia. 16 to 18 May. pp. 217-230. MEND Associate
- Kwong, Y.T.J. and Van Stempvoort, D.R. 1994. *Attenuation of Acid Rock Drainage in a Natural Wetland System*. In: Environmental Geochemistry of Sulfide Oxidation, ACS Symposium Series. C.N. Alpers and D.W. Blowes, editors. Vol 550, pp. 382-392. MEND Associate
- Lawrence, R.W. and Sherlock, E.J. 1995. *Databases for Acid Rock Drainage Prediction and Monitoring*. In: CAMI '95 – Proceedings of the 3rd Canadian Conference on Computer Applications in the Mineral Industry. Montréal, Québec. 22 to 25 October. pp. 825-833. 1.12.1
- Lawrence, R.W. and Wang, Y. 1997. *Determination of Neutralization Potential in the Prediction of Acid Rock Drainage*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 1, pp. 449-464. 1.16.3

- Lee, D. R. and Dal Bianco, R. 1994. *Methodology for Locating and Quantifying Acid Mine Drainage in Ground Waters Entering Surface Waters*. In: Proceedings of the International Land Reclamation and Mine Drainage Conference and 3rd International Conference on the Abatement of Acidic Drainage. Pittsburgh, PA. 24 to 29 April. Vol 1, pp. 327-335. 4.8.2
- Lefebvre, R. and Gélinas, P.J. 1995. *Numerical Modelling of AMD Production in Waste Rock Dumps*. In: Sudbury '95 – Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 3, pp. 869-878. 1.14.2
- 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. 2.12.1
- Li, M.G. 2000. *Unsaturated Flow and Solute Transport Observations in Large Waste Rock Columns*. In: Proceedings of the 5th International Conference on Acid Rock Drainage. Denver, CO. 21 to 24 May. Vol 1, pp. 247-257. 2.36.2
- Li, M.G. and Bernier, L. 1999. *Contributions of Carbonates and Silicates to Neutralisation Observed in Laboratory Tests and their Field Implications*. In: Sudbury '99 – Mining and the Environment II Conference Proceedings. Sudbury, Ontario. 13 to 17 September. Vol 1, pp. 69-78. 2.12.1
- Li, M.G. and St-Arnaud, L. 1997. *Hydrogeochemistry of Secondary Mineral Dissolution: Column Leaching Experiment Using Oxidized Waste Rock*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 1, pp. 465-478. 2.36.2
- 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. 2.12.1
- Li, M.G., Catalan, L.L. and St-Germain, P. 2000. *Rates of Oxygen Consumption by Sulphidic Tailings Under Shallow Water Covers – Field Measurements and Modelling*. In: Proceedings of the 5th International Conference on Acid Rock Drainage. Denver, CO. 21 to 24 May. Vol 2, pp. 913-920. 2.12.1
- Liseth, P. and Miljøplan, V. 1991. *Abatement Measures for the Acid Mine Drainage at Skorovos Mine, Norway*. In: Proceedings of the 2nd International Conference on the Abatement of Acidic Drainage. Montréal, Québec. 16 to 18 September. Tome 4, pp. 43-68. 2.33.1

- Mailhiot, K. and Feasby, D.G. 1993. *Comité traitement – Résumé des travaux*. Colloque sur le programme de Neutralisation des eaux de drainage dans l'environnement minier. Val d'Or, Québec. 3 et 4 novembre. Vol 1, pp. 87-103. General MEND Treatment
- Marcoux, L. and Grenier, R.A. 1990. *Simulation de l'inondation du parc à résidus de la Solbec-Cupra*. Colloque sur la réduction et le drainage des effluents acides générés par les activités minières. Val d'Or, Québec. 28 novembre. pp. 97-114. 2.13.2
- Maynard, A.W. and Thomas, K.B. 1994. *The Laboratory Quality Assurance Component of Environmental Monitoring: A Case Study Involving Subaqueous Tailings Research*. In: Proceedings of the International Land Reclamation and Mine Drainage Conference and 3rd International Conference on the Abatement of Acidic Drainage. Pittsburgh, PA. 24 to 29 April. Vol 1, pp. 260-269. 2.11.1
- McLaughlin, J. and Robertson, G. 1994. *Test Production of Low Sulphur Rock Tailings at Inco's Clarabelle Mill*. In: Proceedings of the 26th Annual Meeting of the Canadian Mineral Processors. Ottawa, Ontario. 18 to 20 January. Paper 21, 15 p. 2.45.2
- McMullen, J., Firlotte, R., Knapp, R. and Aubertin, M. 1997. *Les Terrains Aurifères Site – Site Closure and Rehabilitation, Conceptual to Construction*. In: Proceedings of the 29th Annual Meeting of the Canadian Mineral Processors Conference. Ottawa, Ontario. 21 to 23 January. pp. 273-292. 2.22.4a
- Mehling, P.E., Day, S.J. and Sexsmith, K.S. 1997. *Blending and Layering Waste Rock to Delay, Mitigate or Prevent Acid Generation: A Case Study Review*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 2, pp. 951-970. 2.37.1
- Mohamed, A.M.O., Yong, R.N., Caporuscio, F., Yanful, E.K. and Bienvenu, L. 1993. *Chemical Interaction of Cyclic Freeze-Thaw Effects on the Integrity of the Soil Cover for the Waite Amulet Tailings*. International Journal of Environmental Issues in Minerals and Energy Industry. pp. 121-128. 2.21.2
- Mohamed, A.M.O., Yong, R.N., Caporuscio, F., Yanful, E.K. and Bienvenu, L. 1993. *Chemical Interaction of Cyclic Freeze-Thaw Effects on the Integrity of the Soil Cover for the Waite Amulet Tailings*. In: Proceedings of the Joint CSCE-ASCE National Conference on Environmental Engineering. Montréal, Québec. 12 to 14 July. Pp. 259-272. 2.21.2
- Morin, K.A. and Hutt, N.M.. 1994. *An Empirical Technique for Predicting the Chemistry of Water Seeping from Mine-Rock Piles*. In: Proceedings of the International Land Reclamation and Mine Drainage Conference and 3rd International Conference on the Abatement of Acidic Drainage. Pittsburgh, PA. 24 to 29 April. Vol 1, pp. 12-19. 1.11.1

- Morin, K.A. and Hutt, N.M. 1995. *MINEWALL 2.0: A Technique for Predicting Water Chemistry in Open-Pit and Underground Mines*. In: Sudbury '95 – Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 3, pp. 1007-1016. 1.15.2
- Morin, K.A. and Hutt, N.M. 1998. *Kinetic Tests and Risk Assessment for ARD*. In: 5th Annual BC MEM – MEND 2000 Metal Leaching and ARD Workshop. Vancouver, British Columbia. 9 to 10 December. 10 p. 2.37.3
- Morin, K.A. and Hutt, N.M. 1999. *Prediction of Drainage Chemistry in Post-Mining Landscapes Using Operational Monitoring Data*. Ecology of Post-Mining Landscapes. Cottbus, Germany. 15 to 19 March. 1.27.1
- Morin, K.A. and Hutt, N.M. 1999. *Prediction of Water Chemistry in Acid Mine Lakes: The Minewall Approach*. Ecology of Post-Mining Landscapes. Cottbus, Germany. 15 to 19 March. 1.15.2
- Morin, K.A. and Hutt, N.M. 1999. *Relocation of Net-Acid-Generating Waste Rock to Improve Post-Mining Water Chemistry*. Ecology of Post-Mining Landscapes. Cottbus, Germany. 15 to 19 March. 1.44.1
- Morin, K.A. and Hutt, N.M. 2000. *Discrete-Zone Mixing of Net-Acid-Neutralizing and Net-Acid-Generating Rock: Avoiding the Argument Over Appropriate Ratios*. In: Proceedings from the 5th International Conference on Acid Rock Drainage. Denver, CO. 20 to 26 May. Vol 2, pp. 797-803. 2.37.1
2.37.3
- Morin, K.A. and Hutt, N.M. 2000. *Relocation and Submergence of Net-Acid-Generating Waste Rock for Control of Acidic Drainage: A Case Study*. In: Proceedings from the 5th International Conference on Acid Rock Drainage. Denver, CO. 20 to 26 May. Vol 2, pp. 819-825. 1.44.1
- Morin, K.A., Horne, I.A. and Riehm, D. 1994. *High-Frequency Geochemical Monitoring of Toe Seepage from Mine-Rock Dumps, BHP Minerals' Island Copper Mine, British Columbia*. In: Proceedings of the International Land Reclamation and Mine Drainage Conference and 3rd International Conference on the Abatement of Acidic Drainage. Pittsburgh, PA. 24 to 29 April. Vol 1, pp. 346-354. 1.11.1
- Morin, K.A., Hutt, N.M. and Ferguson, K.D. 1995. *Measured Rates of Copper and Zinc Leaching in the International Kinetic Database*. In: Proceedings of the 19th Annual British Columbia Mine Reclamation Symposium. Dawson Creek, British Columbia. 19 to 23 June. pp. 255-263. 1.11.1

- Morin, K.A., Jones, C.E. and van Dyk, R.P. 1994. *Internal Hydrogeologic Monitoring of an Acidic Waste-Rock Dump at Westmin Resources' Myra Falls Operations, British Columbia*. In: Proceedings of the International Land Reclamation and Mine Drainage Conference and 3rd International Conference on the Abatement of Acidic Drainage. Pittsburgh, PA. 24 to 29 April. Vol 1, pp. 355-364. 1.11.1
- Nicholson, R.V., Akindunni, F.F., Sydor, R.C. and Gillham, R.W. 1991. *Saturated Tailings Covers Above the Water Table: The Physics and Criteria for Design*. In: Proceedings of the 2nd International Conference on the Abatement of Acidic Drainage. Montréal, Québec. 16 to 18 September. Tome 1, pp. 443-460. 2.21.1
- Nicholson, R.V., Elberling, B. and Williams, G. 1995. *A New Oxygen Consumption Technique to Provide Rapid Assessment of Tailings Reactivity in the Field and the Laboratory*. In: Sudbury '95 – Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 3, pp. 999-1006. 4.6.5ac
- Nicholson, R.V., Scharer, J.M., Elberling, B. and Kwong, E.C.M. *Selected Modelling Approaches to Assess Sulphide Mineral Oxidation in Mine Wastes*. In: CAMI '95 – Proceedings of the 3rd Canadian Conference on Computer Applications in the Mineral Industry. Montréal, Québec. 22 to 25 October. pp. 834-843. 2.13.3
- Nicholson, R.V., Scharer, J.M., Kwong, E., Annable, W. and Williams, G. 1995. *An Application of the WATAIL Model to Develop a Management Strategy for a Pyrrhotite Tailings Impoundment*. In: Sudbury '95 – Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 3, pp. 1043-1052. 2.13.3
- Orava, D.A., Hallam, C.E. and Swider, R. 1995. *Evaluating Alternative Long-Term Strategies for Treatment of Acid Mine Drainage (AMD)*. In: Sudbury '95 – Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 2, pp. 505-514. 3.32.1
- Orava, D.A., Tremblay, G.A., Tibble, P.A. and Nicholson, R.V. 1997. *Prevention of Acid Rock Drainage through the Application of In-Pit Disposal and Elevated Water Table Concepts*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 3, pp. 971- 988. 2.36.1
2.17.1
- Otwinowski, M. 1997. *Meso-Scale Characterization of the Geochemical and Physical Processes Responsible 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. 567-586. 1.19.2

- Paktunc, A.D. and Davé, N.K. 1999. *Acidic Drainage Characteristics and Residual Sample Mineralogy of Unsaturated and Saturated Coarse Pyritic Uranium Tailings*. In: Sudbury '99 – Mining and the Environment II Conference Proceedings. Sudbury, Ontario. 13 to 17 September. Vol 1, pp. 221-230. 2.13.1
- Paktunc, A.D. and Davé, N.K. 2000. *Prediction of Acidic Drainage and Accompanying Metal Releases from Unsegregated Pyritic Uranium Mill Tailings Based on Effluent Chemistry and Post Leaching Sample Mineralogy*. In: Proceedings of the 5th International Conference on Acid Rock Drainage. Denver, CO. 21 to 24 May. Vol 2, pp. 891-900. 2.13.1
- Paterson, N. and Stanton-Gray, R. 1995. *Application of Remote Sensing and Geophysics to the Detection and Monitoring of Acid Mine Drainage*. In: Sudbury '95 – Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 3, pp. 955-968. 4.6.3
- Payant, S., St-Arnaud, L.C. and Yanful, E.K. 1995. *Evaluation of Techniques for Preventing Acidic Rock Drainage*. In: Sudbury '95 – Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 2, pp. 485-494. 2.35.2
- Pedersen, T.F., Martin, A.J. and McNee, J.J. 1999. *Contrasting Trace Metal Dynamics in Contaminated Lago Junin, Peru and Submerged Tailings Deposits in Canadian Lakes: The Importance of Permanent Submergence*. In: Sudbury '99 – Mining and the Environment II Conference Proceedings. Sudbury, Ontario. 13 to 17 September. Vol 1, pp. 165-176. 2.11.1
- Pedersen, T.F., McNee, J.J., Flather, D., Mueller, B., Sahami, A. and Pelletier, C.A. 1997. *Geochemistry of Submerged Tailings in Buttle Lake and the Equity Silver Tailings Pond, British Columbia and Anderson Lake, Manitoba: What Have We Learned?* In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 3, pp. 989- 1006. 2.11.3
2.11.4
2.11.5
- Pedersen, T.F., McNee, J.J., Mueller, B., Flather, D.H. and Pelletier, C.A. 1994. *Geochemistry of Submerged Tailings in Anderson Lake, Manitoba: Recent Results*. In: Proceedings of the International Land Reclamation and Mine Drainage Conference and 3rd International Conference on the Abatement of Acidic Drainage. Pittsburgh, PA. 24 to 29 April. Vol 1, pp. 288-296. 2.11.3
- Pedersen, T.F., Mueller, B., McNee, J.J. and Pelletier, C.A. 1991. *Diagenetic Reactivity of Mine Tailings in Mesotrophic and Oligotrophic Lakes in Manitoba and British Columbia*. In: Proceedings of the 2nd International Conference on the Abatement of Acidic Drainage. Montréal, Québec. 16 to 18 September. Tome 4, pp. 199-226. 2.11.1

- Pedersen, T.F., Mueller, B., McNee, J.J. and Pelletier, C.A. 1993. *The Early Diagenesis of Submerged Sulphide-Rich Mine Tailings in Andersen Lake, Manitoba*. Canadian Journal of Earth Sciences. Vol 30, pp. 1099-1109. 2.11.1
- Pelletier, C.A. 1991. *Subaqueous Disposal of Reactive Mine Wastes: An Overview of the Practice with Case Studies*. In: Proceedings of the 2nd International Conference on the Abatement of Acidic Drainage. Montréal, Québec. 16 to 18 September. Tome 3, pp. 185-200. 2.11.1
- Perkins, E.H., Gunter, W.D, Nesbitt, H.W. and St-Arnaud, L.C. 1997. *Critical Review of Classes of Geochemical Computer Models Adaptable for Prediction of Acidic Drainage from Mine Waste Rock*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 2, pp. 587-602. 1.42.1
- Pierce, W.G., Belzile, N., Wiseman, M. E. and Winterhalder, K. 1994. *Composted Organic Wastes as Anaerobic Reducing Covers for Long Term Abandonment of Acid-Generating Tailing*. In: Proceedings of the International Land Reclamation and Mine Drainage Conference and 3rd International Conference on the Abatement of Acidic Drainage. Pittsburgh, PA. 24 to 29 April. Vol 2, pp. 148-157. 2.25.1
- Poirier, P.J. and Roy, M. 1997. *Acid Mine Drainage Characterization and Treatment at La Mine Doyon*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 4, pp. 1485-1498. 1.14.2
- Ricard, J.F., Aubertin, M., McMullen, J., Pelletier, P. and Poirier, P. 1999. *Performance of a Dry Cover Made of Tailings for the Closure of Les Terrains Aurifères Site, Malartic, Québec, Canada*. In: Sudbury '99 – Mining and the Environment II Conference Proceedings. Sudbury, Ontario. 13 to 17 September. Vol 1, pp. 155-164. 2.22.4b
- Ricard, J.F., Aubertin, M., Firlotte, F.W., Knapp, R., McMullen, J. and Julien, M. 1997. *Design and Construction of a Dry Cover Made of Tailings for the Closure of Les Terrains Aurifères Site, Malartic, Québec, Canada*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 4, pp. 1515-1530. 2.22.4a
- Ricard, J.F., Aubertin, M., Garand, P. and McMullen, J. 1997. *Field Performance of a Dry Cover Made of Tailings for the Closure of Barrick-Bousquet “Les Terrains Aurifères Site” Malartic, Québec, Canada*. In: Proceedings of the 50th Canadian Geotechnical Conference. Ottawa, Ontario. Vol 1, pp. 185-192. 2.22.4a

- Ritcey, G.M., Lawrence, R.W., Marchant, P.B. and Poling, G.W. 1990. *Assessment of Predictive Methods for the Determination of AMD Potential in Mine Tailings and Waste Rock*. Colloque sur la réduction et le drainage des effluents acides générés par les activités minières. Val d'Or, Québec. 28 novembre. pp. 181-197. 1.16.1a
- Riveros, P.A. 1995. *Application of Ion Exchangers to the Treatment of Acid Mine Drainage*. In: Sudbury '95 – Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 2, pp. 441-450. 3.21.1b
- Robertson, J.D. 1992. *Subaqueous Tailings Disposal: A Promising Method for the Effective Control of Reactive Waste Materials*. In: Proceedings of the 24th Annual Meeting of the Canadian Mineral Processors Conference. Ottawa, Ontario. 21 to 23 January. Paper 33, 10 p. 2.11.1
- Robertson, J.D., Kuit, W.J., Campanella, R.G., Frew, D., McLeod, H.N. and Davies, M.P. 1997. *The Use of In Situ Testing for the Characterization of Sulphide Mine Tailings*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 4, pp. 1761-1777. 4.6.4
- Robertson, J.D., Tremblay, G.A. and Fraser, W.W. 1997. *Subaqueous Tailing Disposal: A Sound Solution for Reactive Tailing*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 3, pp. 1027-1044. 2.11.1
- Robinsky, E.I., Barbour, S.L., Wilson, G.W., Bordin, D. and Fredlund, D.G. 1991. *Thickened Sloped Tailings Disposal – An Evaluation of Seepage and Abatement of Acid Drainage*. In: Proceedings of the 2nd International Conference on the Abatement of Acidic Drainage. Montréal, Québec. 16 to 18 September. Tome 1, pp. 529-550. 2.23.2
- Ross, A., Matte, S. and Belle-Isle, F. 1993. *Auscultation de la fosse Solbec, première année d'observation*. Colloque sur le programme de Neutralisation des eaux de drainage dans l'environnement minier. Val d'Or, Québec. 3 et 4 novembre. Vol 2, pp. 1-32. 4.8.1
- Sheremata, T.W., Yanful, E.K., St-Arnaud, L.C. and Payant, S.C. 1991. *Flooding and Lime Addition for the Control of Acidic Drainage from Mine Waste Rock: A Comparative Laboratory Study*. In: Proceedings of the 1st Canadian Conference on Environmental Geotechnics. Montréal, Québec. 14 to 16 May. pp. 417-423. 2.36.2
- Smith, F.E. 1995. *The Treatment of Metalliferous Industrial Effluents in Japan*. In: Sudbury '95 – Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 3, pp. 915-924. 6.3

- St-Arnaud, L.C. 1994. *Water Covers for the Decommissioning of Sulfidic Mine Tailings Impoundments*. In: Proceedings of the International Land Reclamation and Mine Drainage Conference and 3rd International Conference on the Abatement of Acidic Drainage. Pittsburgh, PA. 24 to 29 April. Vol 1, pp. 279-287. 2.15.1a
- St-Arnaud, L.C. 1990. *Hydrogéochimie des résidus miniers de Waite-Amulet*. Colloque sur la réduction et le drainage des effluents acides générés par les activités minières. Val d'Or, Québec. 28 novembre. pp. 35-63. 1.17.1d
- St-Arnaud, L.C. and Yanful, E.K. 1993 *Recouvrements d'eau pour la fermeture des parcs à résidus miniers sulfureux – Études de cas de Mattabi Mines*. Colloque sur le programme de Neutralisation des eaux de drainage dans l'environnement minier. Val d'Or, Québec. 3 et 4 novembre. Vol 1, pp. 67-86. 2.15.1a
- St-Arnaud, L.C. and Yanful, E.K. 1993. *Water Covers for the Decommissioning of Sulphidic Mine Tailings Impoundments: Mattabi Mines Case Study*. In: Proceedings of the CIM Conference of Metallurgist, Part II: Advances in Environmental Protection for the Metallurgical Industries. Québec City, Québec. 29 August to 2 September. pp. 275-286. 2.15.1a
- St-Arnaud, L.C., Aubé, B.C., Wiseman, M.E. and Aiken, S.R. 1994. *Mitigation of Acid Mine Drainage by the Porous Envelope Effect*. In: Proceedings of the International Land Reclamation and Mine Drainage Conference and 3rd International Conference on the Abatement of Acidic Drainage. Pittsburgh, PA. 24 to 29 April. Vol 2, pp. 87-95. 2.23.3
- St-Arnaud, L.C., Yanful, E.K., Prairie, R. and Davé, N.K. 1989. *Evolution of Acidic Pore Water at the Waite Amult Tailings Site, Noranda, Québec*. In: Proceedings of the International Symposium on Tailings and Effluent Management. Halifax, Nova Scotia. 20 to 24 August. pp. 93-102. 2.21.2
- Steger, H.F., Halbert, B.E., Scharer, J.M., Snodgrass, W.J., Nicholson, R.V. and Southwood, J. 1990. *RATAP.BMT – A Predictive Model for Reactive Tailings*. Colloque sur la réduction et le drainage des effluents acides générés par les activités minières. Val d'Or, Québec. 28 novembre. pp. 199-208. 1.21.1
- Stogran, S.W. and Wiseman, M.E. 1995. *A Comparison of Organic and Inorganic Covers for Long Term Prevention or Amelioration of Acid Mine Drainage*. In: Sudbury '95 – Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 2, pp. 555-564. 2.25.3
- Stogran, S.W. and Wiseman, M.E. 1995. *Technical Evaluation of Subaqueous Disposal of Alkaline, Unoxidized, Sulphide Containing Tailings in Acidic Water*. In: Sudbury '95 – Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 2, pp. 829-836. MEND Associate

- Stogran, S.W., Elliott, L.C.M. and Liu, L. 1997. *Subaqueous Deposition of Acid Generating Tailings into an Acidic Environment: Pilot Column Test Results*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 3, pp. 1059-1074. MEND Associate
- Stuparyk, R.A., Kipkie, W.B., Kerr, A.N. and Blowes, D.W. 1995. *Production and Evaluation of Low Sulphur Tailings at INCO's Clarabelle Mill*. In: Sudbury '95 – Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 1, pp. 159-170. 2.45.2
- Swanson, D.A., Barbour, S.L., Wilson, G.W. and O'Kane, M. 1995. *Components in the Design of Engineered Soil Cover Systems for Acid Generating Mine Wastes*. In: CAMI '95 – Proceedings of the 3rd Canadian Conference on Computer Applications in the Mineral Industry. Montréal, Québec. 22 to 25 October. pp. 844-852. 1.25.1
- Swanson, D.A., Barbour, S.L., Wilson, G.W. and O'Kane, M. 1995. *Modelling the Performance of Engineered Soil Covers for Acid Generating Mine Waste*. In: Sudbury '95 – Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 3, pp. 861-868. 1.25.1
- Tassé, N. 1999. *Long Term Efficiency of Wood Waste Covers: Indications from Pore Gases Compositions*. In: Sudbury '99 – Mining and the Environment II Conference Proceedings. Sudbury, Ontario. 13 to 17 September. Vol 2, pp. 655-660. 2.25.5
- Tassé, N. 2000. *Efficient Prevention of Sulphide Oxidation by an Organic Cover: For How Long can a Reactive Barrier be Reactive?* In: Proceedings of the 5th International Conference on Acid Rock Drainage. Denver, CO. 21 to 24 May. Vol 2, pp. 979- 986. 2.22.5
- Tassé, N., Germain, D., Dufour, C. and Tremblay, R. 1996. *Le recouvrement de résidus organiques au parc East Sullivan : au-delà de la barrière d'oxygène*. Colloque sur le programme de Neutralisation des eaux de drainage dans l'environnement minier. Rouyn-Noranda, Québec. 29 et 30 octobre. Vol 1, pp. 105-128. 2.25.5
- Tassé, N., Germain, D., Dufour, C. and Tremblay, R. 1997. *Organic-Waste Cover Over the East Sullivan Mine Tailings: Beyond the Oxygen Barrier*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 4, pp. 1627-1642. 2.25.5
- 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. 647-662. 4.6.5ac

- Tremblay, G.A. 1993. *Comité prévention et contrôle – Synthèse des résultats*. Colloque sur le programme de Neutralisation des eaux de drainage dans l'environnement minier. Val d'Or, Québec. 3 et 4 novembre. Vol 1, pp. 35-66. General MEND P & C
- Tremblay, G.A. 1996. *Dry Covers Technologies to Reduce Environmental Liability from Acid Generating Mine Wastes*. Colloque sur le programme de Neutralisation des eaux de drainage dans l'environnement minier. Rouyn-Noranda, Québec. 29 et 30 octobre. Vol 1, pp. 197-207. General MEND Dry Covers
- Tremblay, G.A. 1997. *Programme canadien de neutralisation des eaux de drainage dans l'environnement minier (NEDEM)*. Colloque sur la recherche et l'innovation dans l'exploitation des mines. Rouyn-Noranda, Québec. 29 et 30 octobre. Vol 2, pp. 1-18. General MEND
- Tremblay, G.A. 1999. *Using Tailings in Dry Covers*. R-NET (Recycling Technology Newsletter). Vol 4, Issue 1. June. pp. 2-4. 2.22.2
2.22.4
- Tremblay, G.A. 1999. *Utilisation des résidus miniers dans les couvertures sèches*. R-NET (Bulletin d'information sur la technologie du recyclage). Vol 4, Numéro 1. Juin. pp. 2-4. 2.22.2
2.22.4
- Tremblay, R.L. 1993. *Étude sur l'efficacité d'une barrière humide construite à partir de résidus forestiers – Le projet East Sullivan*. Colloque sur le programme de Neutralisation des eaux de drainage dans l'environnement minier. Val d'Or, Québec. 3 et 4 novembre. Vol 1, pp. 123-142. 2.25.2
- Tremblay, R.L. 1994. *Controlling Acid Mine Drainage Using an Organic Cover: The Case of the East Sullivan Mine, Abitibi, Québec*. In: Proceedings of the International Land Reclamation and Mine Drainage Conference and 3rd International Conference on the Abatement of Acidic Drainage. Pittsburgh, PA. 24 to 29 April. Vol 2, pp. 122-127. 2.25.2
- Veillette, G. and Desrochers, C.J. 1991. *Reclamation of the Solbec Mine Site by Flooding Waste Rock in Open Pit*. In: Proceedings of the 2nd International Conference on the Abatement of Acidic Drainage. Montréal, Québec. 16 to 18 September. Tome 3, pp. 219-238. 2.13.2
- Waybrant, K.R., Blowes, D.W. and Ptacek, C.J. 1995. *Selection of Reactive Mixtures for the Prevention of Acid Mine Drainage Using Porous Reactive Walls*. In: Sudbury '95 – Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 3, pp. 945-954. MEND Associate

- Woyshner, M. R. and St-Arnaud, L.C. 1994. *Hydrogeologic Evaluation and Water Balance of a Thickened Tailings Deposit Near Timmins, ON, Canada*. In: Proceedings of the International Land Reclamation and Mine Drainage Conference and 3rd International Conference on the Abatement of Acidic Drainage. Pittsburgh, PA. 24 to 29 April. Vol 2, pp. 198-207. 2.23.2
- Woyshner, M.R. and Yanful, E.K. 1995. *Modelling and Field Measurements of Water Percolation through an Experimental Soil Cover on Mine Tailings*. Canadian Geotechnical Journal. Vol 32, No. 4. pp. 601-609. 2.21.2
- Woyshner, M.R., St-Arnaud, L.C. and Wiseman, M.E. 1995. *Neutralization Potential and the Porous Envelope Effect: Two Favourable Conditions for Decommissioning of the Fault Lake Tailings near Falconbridge, Ontario*. In: Sudbury '95 – Mining and the Environment Conference Proceedings. Sudbury, Ontario. 28 May to 1 June. Vol 2, pp. 785-794. 2.23.3
- Yanful, E.K. 1990. *Recouvrements géologiques pour contrôler le drainage minier acide*. Colloque sur la réduction et le drainage des effluents acides générés par les activités minières. Val d'Or, Québec. 28 novembre. pp. 65-83. 2.21.2
- Yanful, E.K. 1991. *The Waite Amulet Hydrogeochemical Evaluation*. In: Proceedings of the 2nd International Conference on the Abatement of Acidic Drainage. Montréal, Québec. 16 to 18 September. Tome 1, pp. 91-114. 1.17.1
- Yanful, E.K. 1993. *Oxygen Diffusion through Soil Covers on Sulphidic Mill Tailings*. ASCE Journal of Geotechnical Engineering, American Society of Civil Engineers. Vol 119, No. 8. pp. 121-128. 2.21.2
2.31.1
- Yanful, E.K. and Aubé, B. 1993. *Efficacité des recouvrements géologiques à contrôler le drainage minier acide – Le projet Waite-Amulet*. Colloque sur le programme de Neutralisation des eaux de drainage dans l'environnement minier. Val d'Or, Québec. 3 et 4 novembre. Vol 1, pp. 143-154. 2.21.2
- Yanful, E.K., Aubé, B.C., Woyshner, M. and St-Arnaud, L.C. 1994. *Field and Laboratory Performance of Engineered Covers on the Waite Amulet Tailings*. In: Proceedings of the International Land Reclamation and Mine Drainage Conference and 3rd International Conference on the Abatement of Acidic Drainage. Pittsburgh, PA. 24 to 29 April. Vol 2, pp. 138-147. 2.21.2
- Yanful, E.K. and Nicholson, R.V. 1991. *Engineered Soil Covers for Reactive Tailings Management: Theoretical Concepts and Laboratory Development*. In: Proceedings of the 2nd International Conference on the Abatement of Acidic Drainage. Montréal, Québec. 16 to 18 September. Tome 1, pp. 461-486. 2.21.1

- Yanful, E.K. and St-Arnaud, L.C. 1991. *Design, Instrumentation, and Construction of Engineered Soil Covers for Reactive Tailings Management*. In: Proceedings of the 2nd International Conference on the Abatement of Acidic Drainage. Montréal, Québec. 16 to 18 September. Tome 1, pp. 487-504. 2.21.2
- Yanful, E.K. and St-Arnaud, L.C. 1991. *The Hydrogeochemistry and Geotechnique of the Waite Amulet Tailings Site near Rouyn-Noranda, Québec, Canada*. In: Proceedings of the 1st Canadian Conference on Environmental Geotechnics. Montréal, Québec. 14 to 16 May. pp. 263-270. 2.21.2
- Yanful, E.K. and St-Arnaud, L.C. 1992. *Migration of Acidic Pore Waters at the Waite Amulet Tailings Site near Rouyn-Noranda, Québec, Canada*. Canadian Geotechnical Journal. Vol 29, No. 3. pp. 466-476. 2.21.2
- Yanful, E.K. and Varma, A. 1998. *Predicting Resuspension in Flooded Mine Tailings*. In: Proceedings of the 51st Canadian Geotechnical Conference. Edmonton, Alberta. 4 to 7 October. Vol 1, pp. 113-121. 2.15.3
- Yanful, E.K., Bell, A.V. and Woysner, M.R. 1993. *Design of a Composite Soil Cover for an Experimental Waste Rock Pile near Newcastle, New Brunswick, Canada*. Canadian Geotechnical Journal. Vol 30, No. 4. pp. 578-587. 2.31.1
- Yanful, E.K., Mycroft, J., Pratt, A.R. and St-Arnaud, L.C. 1997. *Factors Controlling Metal Leaching from Mine Rock: The Case of Stratmat and Selbaie Waste Rocks*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 2, pp. 663-680. 2.35.2
- Yanful, E.K., Riley, M.D., Woysner, M.R. and Duncan, J. 1993. *Construction and Monitoring of a Composite Soil Cover on an Experimental Waste Rock Pile near Newcastle, New Brunswick, Canada*. Canadian Geotechnical Journal. Vol 30, No. 4. pp. 588-599. 2.31.1
- Yanful, E.K., Shikatani, K.S. and Quirt, D.H. 1995. *Hydraulic Conductivity of Natural Soils Permeated with Acid Mine Drainage*. Canadian Geotechnical Journal. Vol 32, No. 4. pp. 624-646. 2.21.2
2.31.1
- Yanful, E.K., Woysner, M. and Bell, A. 1996. *Design of a Composite Soil Cover for an Experimental Waste Rock Pile near Newcastle, New Brunswick*. Colloque sur le programme de Neutralisation des eaux de drainage dans l'environnement minier. Rouyn-Noranda, Québec. 29 et 30 octobre. Vol 1, pp. 59-70. 2.31.1

-
- Yanful, E.K., Woyshner, M. and Riley, M. 1996. *Construction and Monitoring of a Composite Soil Cover on an Experimental Waste-Rock Pile near Newcastle, New Brunswick*. Colloque sur le programme de Neutralisation des eaux de drainage dans l'environnement minier. Rouyn-Noranda, Québec. 29 et 30 octobre. Vol 1, pp. 71-84. 2.31.1
- Zinck, J.M. 1997. *Acid Mine Drainage Treatment Sludges in the Canadian Mineral Industry: Physical, Chemical, Mineralogical and Leaching Characteristics*. In: Proceedings of the 4th International Conference on Acid Rock Drainage. Vancouver, British Columbia. 31 May to 6 June. Vol 4, pp. 1691-1708. 3.42.2
- Zinck, J.M. and Aubé, B. 1999. *Optimization of Lime Treatment Processes*. In: Proceedings of the 31st Annual Meeting of the Canadian Mineral Processors Conference. Ottawa, Ontario. 19 to 21 January. pp. 75-93. 3.42.2
- Zinck, J.M., Hogan, C.M. and Griffith, W.F. 1998. *Effect of Process Parameters and Aging on Sludge Density and Stability*. In: Proceedings of Waste Processing and Recycling in Mineral and Metallurgical Industries II. Calgary, Alberta. August. 16 to 18. pp 419-434. 3.42.2

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 étude 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

-
- 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

-
- 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

-
- 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

TECHNOLOGY TRANSFER/TRANSFERT DE LA TECHNOLOGIE

- | | |
|--------|---|
| 5.4.2a | MEND Manual. Volume 1 – Summary. March 2001. \$25 |
| 5.4.2b | MEND Manual. Volume 2 – Sampling and Analysis. January 2001. \$25 |
| 5.4.2c | MEND Manual. Volume 3 – Prediction. December 2000. \$25 |
| 5.4.2d | MEND Manual. Volume 4 – Prevention and Control. March 2001. \$25 |
| 5.4.2e | MEND Manual. Volume 5 – Treatment. December 2000. \$25 |
| 5.4.2f | MEND Manual. Volume 6 – Monitoring. December 2000. \$25 |

Individual volumes of the MEND Manual are \$25.00 each or \$100.00 for the complete set of six volumes.

- 5.4.2CD CD ROM: MEND Manual, July 2001. \$100
- 5.5.1 Reactive Acid Tailings Stabilization (RATS) Research Plan, July 1988. \$15
- 5.6.1 Proceedings - Second International Conference on the Abatement of Acidic Drainage, Montréal, September 16, 17 and 18, 1991 (4 Volumes). \$150
- 5.7.1 1992 Revised Research Plan/Plan de recherche révisé 1992, August 1992. Complimentary
- 5.8 E Report of Results of a Workshop on Mine Reclamation. Toronto, Ontario, March 10-11, 1994. \$20
- 5.8 F Résultats de l'atelier sur la réhabilitation des sites miniers. Toronto, Ontario, les 10 et 11 mars, 1994. \$20
- 5.8.1 Economic Evaluation of Acid Mine Drainage Technologies (includes diskette), January 1995. \$20

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

NEW IDEAS/NOUVELLES IDÉES

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

INTERNATIONAL/E

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

MEND WORKSHOP NOTES/NOTES DES ATELIERS \$10.00 ea.

- 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

**ICARD WORKSHOP NOTES/NOTES DES ATELIERS DE LA CONFÉRENCE
(VANCOUVER, MAY/JUNE 1997) \$25.00 ea.**

- 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.