MEND MANUAL

VOLUME 1 – SUMMARY

MEND 5.4.2a

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MEND MANUAL

VOLUME 1

SUMMARY

ABSTRACT

The Mine Environment Neutral Drainage (MEND) Program was a cooperative research initiative between the Canadian mining industry, non-governmental organizations, and federal and provincial government departments. MEND researched ways to reduce the environmental impact and financial liabilities of acidic drainage from tailings, waste rock and mine openings. The original MEND Program extended over a nine-year time frame ending in December 1997, with technology transfer activities continuing to December 2000 under the MEND 2000 Program.

More than two-hundred technical reports were produced under MEND. The MEND Manual fills the need to assimilate MEND information into a manageable compendium. The objective of the manual is to provide practitioners in Canadian industry, government and non-governmental organizations with a comprehensive single reference document focused on acidic drainage. The MEND Manual includes a summary volume and five technical volumes, which address: sampling and analyses; prediction; prevention and control; treatment; and monitoring.

AUTHORS OF THE MEND MANUAL

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

Volume 1:		
		SENES Consultants Limited
Volume 2:		
	Section 2.1 to 2.3	SENES Consultants Limited
	Section 2.4	URS Norecol Dames & Moore
		EVS Environment Consultants
	Section 2.5	SENES Consultants Limited
	Section 2.6	BC Research Inc.
Volume 3:		
	Section 3.1 to 3.3	URS Norecol Dames & Moore
		SRK Consulting
		BC Research Inc.
	Section 3.4	SENES Consultants Limited
		URS Norecol Dames & Moore
		SRK Consulting
Volume 4:		
	Section 4.1	SENES Consultants Limited
	Section 4.2	SENES Consultants Limited
		SRK Consulting
	Section 4.3	SENES Consultants Limited
	Section 4.4	O'Kane Consultants Inc.
	Section 4.5	SENES Consultants Limited
	Section 4.6	URS Norecol Dames & Moore
		SRK Consulting
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		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
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	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 in the preparation of Volume 1 of the Manual.

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

Finally, the tremendous contribution of Gilles Tremblay of the MEND Secretariat in overseeing the production of this Manual, and for assisting in its organization, writing, editing and promotion, is greatly appreciated. We thank him sincerely for his hard work, tenacity and good humour in seeing this complex project through to completion.

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: MEND Secretariat at Natural Resources Canada (CANMET), 555 Booth Street, Ottawa, Ontario, K1A 0G1.

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DISCLAIMER

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

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

PREAMBLE

The Mine Environment Neutral Drainage (MEND) Program was a cooperative research initiative that was financed and managed by a partnership between the Canadian mining industry, the Government of Canada, and the Provinces of British Columbia, Manitoba, Ontario, Québec and New Brunswick. MEND researched ways to reduce the environmental impact and financial liabilities of acidic drainage from tailings, waste rock and mine openings. The original MEND Program extended over a nine-year time frame ending in December 1997, with technology transfer activities continuing to December 2000 under the MEND 2000 Program.

This manual is intended to serve as a single source reference to the diverse and complex research undertaken by the MEND Program from 1989 to 2000, and selected complementary work completed outside of MEND. This manual includes a summary volume (Volume 1) and five technical volumes, which respectively address: sampling and analyses; prediction; prevention and control; treatment; and monitoring.

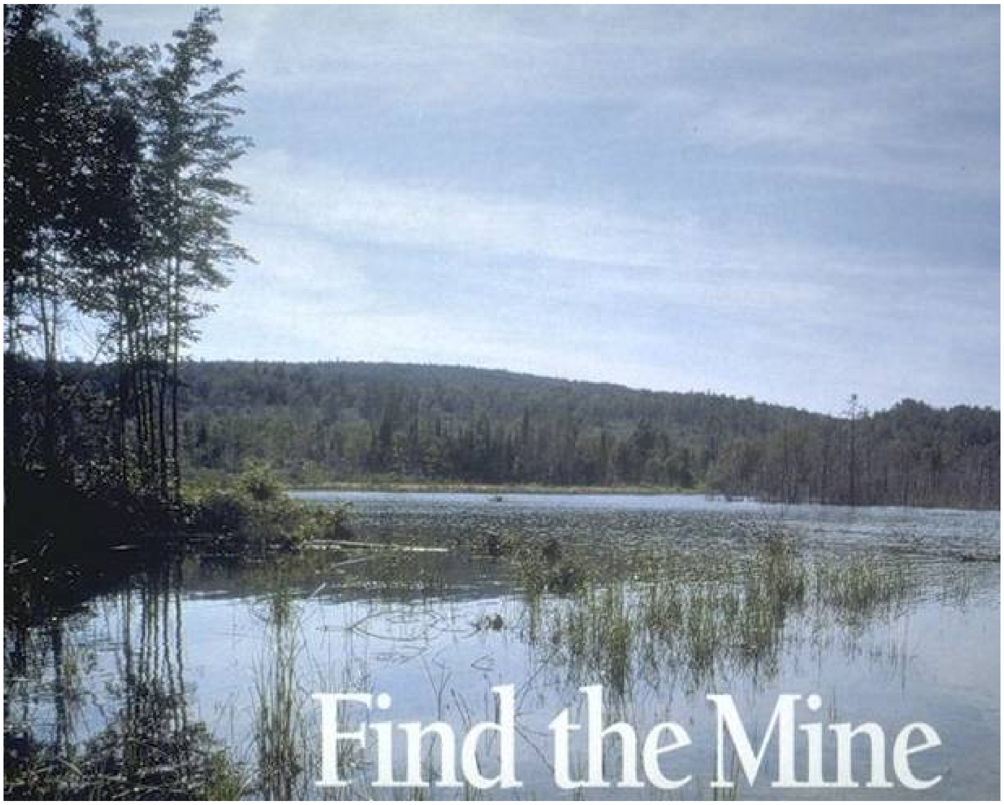
As a result of MEND, the knowledge base on acidic drainage has grown considerably to include: a fundamental understanding of the acid generation process; methods for its prediction; measures to prevent and control its generation; and treatment processes, should it occur. MEND focused the acidic drainage effort, and developed a toolbox of technologies that is now available to all stakeholders. And while the knowledge base can be generally described as reasonable and adequate, there is a need for additional research to: add to the present state of understanding; confirm the performance of technologies through large- scale applications and long-term data; and continue the search for more efficient and affordable technologies. As such, readers are encouraged to think of acidic drainage research as a work in progress where future work is likely to add to the present state of knowledge.

Acidic drainage is a technically complex area and one that typically requires the involvement of experts from numerous technical disciplines. Site-specific factors and conditions add to this complexity, and often necessitate site-specific research. As such, acidic drainage technologies are not universally applicable. Research to date and the application of the new technologies have provided practical experience in their use. In this light, the discussions in the manual also note aspects to consider when evaluating the potential use of these technologies.

Many acidic drainage related decisions are subject to a range of considerations including, but not limited to, the technical basis, the regulatory framework, costs and risks. The MEND Manual, and the majority of the MEND reports referred to in the manual, focused on acidic drainage technical subjects. For the benefit of the reader, the manual includes references to non-MEND documents that address issues such as the management of tailings disposal facilities, treated effluent quality and effluent toxicity requirements, environmental management systems, *and risk assessment. Readers may find it best to use the manual as a key reference document that allows follow-up with listed references in areas of interest. As such, the MEND Manual is not a "how to" document.*

This manual would not be complete without a word of thanks to the many researchers who undertook projects under the auspices of the MEND Program, and to the expert advisors and reviewers who constructively contributed to MEND projects and reports including this manual. MEND is also grateful to the many volunteers and their organizations for their contributions of time, expertise, funding, and participation in the various MEND committees, as well as to those people who assisted in the preparation of this manual by way of their contributions of updated/new material and expert review and in the process encouraged the MEND Manual writing team in its review and synopsis of MEND-sponsored reports, conferences and workshop notes, and related work by others. Appendix A provides an overview of the acidic drainage process. A listing of MEND contractors and the titles of their reports are included as Appendix B. In Appendix C, Bibliography, readers will find a listing of various papers on MEND projects published in conference and workshop proceedings, and in publications. This listing is by no means complete. MEND reports, available at time of printing, are listed in Appendix D. Appendices A, B, C and D are included in each volume of the manual (paper copy).

The MEND Secretariat, comprised of a dedicated group working from the CANMET offices in Ottawa, played a key role in co-ordinating activities, management and administration, reporting, and leading technology transfer. The efforts of Marcia Blanchette, Grant Feasby, Michel Filion, Charlene Hogan, Karen Mailhiot, Leslie McMillen, Carl Weatherell, Gilles Tremblay and the MEND administration staff were instrumental to MEND's success.



(Courtesy of Cambior)

Plate 1. The Flooded Solbec Tailings Impoundment.

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1.0 INTRODUCTION

The Canadian Mine Environment Neutral Drainage (MEND) Program was created in 1988 to develop scientifically-based technologies to reduce or eliminate the liability associated with acidic drainage. This program established Canada as the recognized leader in acidic drainage research and development for metal mines. Canadian industry reports that a significant reduction in acidic drainage related liability has been confidently predicted. MEND 5.9 concluded that the estimated liability was reduced by $340 million for five Canadian sites alone. It is acknowledged that the overall reduction in liability is significantly higher than this quoted value, with a minimum of $1 billion commonly accepted when the mining industry as a whole and the federal and provincial governments are included. This represents an impressive return on the $17.5 million investment in MEND over nine-years.

More than two-hundred technical reports were produced under MEND. This manual fills the need to assimilate MEND information into a single information source. The objective of the manual is to provide practitioners in Canadian industry, government and non-governmental organizations (NGOs) with a manageable single reference document that is focused on acidic drainage. It is not a "how to" manual for reasons outlined in this volume.

Acidic drainage is also commonly known as acid rock drainage and acid mine drainage. In general terms, acidic drainage is the result of the natural oxidation of sulphide minerals that have become exposed to air and water. However, sulphide exposure by itself does not necessarily lead to acid generation. When it does occur, acidic drainage can be generally characterized as having a depressed pH, and elevated levels of dissolved metals and sulphate. At some sites, conditions allow metal leaching and result in a neutral pH or alkaline drainage with elevated dissolved metal and sulphate concentrations. A brief synopsis of acidic drainage is given in Appendix A.

Canada's leadership role in acidic drainage technologies is the result of a long process that cumulated with the MEND Program. When acid drainage research was in its infancy, some twenty to thirty years ago, the focus of the research was to develop methods of revegetating acid sources. These early efforts were successful in developing revegetation methods, particularly for tailings areas, but made next to no headway in preventing or controlling acidic drainage. By the mid-1980s, it had become widely apparent that acidic drainage was a serious concern that had to be addressed, and it was recognized that coordinated scientific research efforts were required. To accomplish this, in 1986 the Canadian mining industry initiated the Reactive Acid Tailings Stabilization (RATS) Task Force which comprised a Steering Committee and a Technical Working Group (TWG) with representation from the mining industry, CANMET, Environment Canada, and the Provinces of British Columbia, Manitoba, Ontario, Québec and New Brunswick. The TWG's recommendations vis-a-vis the use of a coordinated and scientific approach were

a)

b)

c)

Plate 2. Typical Acidic Drainage a) Tailings b) Waste Rock c) Pit Walls

subsequently implemented through the initiation of a tripartite consortium called the Mine Environment Neutral Drainage (MEND) Program in 1989. MEND's objectives were 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
- Establish techniques to enable the operation and closure of acid generating tailings and waste rock disposal areas in a predictable, affordable, timely and environmentally acceptable manner.

MEND involved the participation of a consortium of volunteers including regulators, mine managers and engineers, government officials, scientists, and non-governmental organizations that freely contributed their time and expertise to the program.

A budget of $12.5 million over five years was established for MEND research in five areas:

- Prediction – where the objective was to develop improved analytical techniques to predict acidic generation, and create mathematical models to simulate the acid generation processes in tailings and waste rock;
- Prevention and Control – where the objective was to develop techniques to prevent or at least minimize acid generation, and demonstrate these disposal, management and closure techniques in the field;
- Treatment – where the objective was to develop and demonstrate chemical and passive treatment systems, and examine lime treatment sludge stabilization methods;
- Monitoring – where objectives were to improve site monitoring, develop field sampling methods and reference standards, assess new monitoring techniques, and develop closure criteria; and
- Technology Transfer – where the objective was to promote the transfer of information both on a national and international scale, and develop information banks.

In 1992, MEND revised its research plan to narrow its focus, solicit research on a competitive basis, increase its technology transfer and international liaison roles, and encourage innovation and the testing of new ideas (MEND 5.7.1). The plan extended MEND to a nine-year program, with an expanded budget of $18,000,000 (Table 1).

Table 1
MEND Program Budget

Research Area	RATS Budget	Revised MEND Research Plan Budget
Prediction	$4,140,000	$4,203,000
Prevention and Control	$6,280,000	$9,281,000
Treatment	$1,410,000	$1,729,000
Monitoring	$420,000	$1,125,000
Technology Transfer	$250,000	$362,000
New Ideas		$1,300,000
Total	$12,500,000	$18,000,000

1.1 THE MEND MANUAL

The objective of the manual is to summarize the work completed under MEND in a format that would provide practioners in Canadian industry and government with a manageable reference document. The document is not a "how to" manual. It is a set of comprehensive working references for the sampling and analyses, prediction, prevention, control, treatment and monitoring of acidic drainage. The manual 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 describes the MEND-developed technologies and their applicability in terms of cost, site suitability and environmental implications – a “toolbox” of techniques and options.

The manual is organized into six volumes. The content of the volumes and other aspects of the manual are reviewed below.

1.1.1 USING THE MANUAL

The manual is intended to serve as a single reference document for practitioners in Canadian industry and government with regards to acidic drainage. It also contains information that could be of interest to students, NGOs, and other members of the public who are interested in learning about what has been done to address liabilities associated with acidic drainage. The following general comments are meant to assist readers in making best use of the manual.

1. Volume 1 (this volume) is intended to serve as the stand-alone detailed summary for the manual. It also introduces readers to the MEND program.

- Readers are encouraged to read Volume 1 in order to get a good sense of the content of the entire manual. Following a review of Volume 1, the approach is likely to differ depending on the information requirements of the reader.

- People who want to learn about research developments in acidic drainage including techniques available to prevent and control acid generation, or treat drainage may find Volume 1 sufficient for their needs. Additional sources of general information (i.e. MEND videos on acidic drainage, Internet site) are also identified in Volume 1.

2. Volumes 2 to 6 respectively review the five main subject areas: sampling and analyses, prediction, prevention and control, treatment, and monitoring. The volumes review related theory, research completed by MEND and others, as well as available techniques, limitations and costs. A comprehensive list of MEND and other references is also included.

   - The manual summarizes the present state of technical knowledge in acidic drainage. In addition, it makes reference to other aspects (i.e. practical and regulatory considerations). Given that acidic drainage is a technical area, where site-specific influences are likely to be paramount and necessitate site-specific investigations and evaluations, this manual is not, and should not be used as, a "how to" type document.

   - People interested in specific technical aspects are encouraged to review the applicable MEND Manual volume as well as any of the related documents. As an example, a reader interested in learning about the collection and analyses of tailings pore water and seepage could review Volume 2 – Sampling and Analyses for core information, as well as Volume 6 – Monitoring for additional insight. If the pore water and seepage were to be to collected from a tailings area that had been capped using an engineered dry cover, the reader may also want to review the section of Volume 4 – Prevention and Control that deals with dry covers.

   - Readers who require additional data and technical information beyond that presented in the volumes are encouraged to obtain and review the technical references of interest to them, and to follow-up on current research projects referred to in the manual. The MEND reports, conference proceedings, and workshop notes referenced in the manual are available from Natural Resources Canada, MEND Secretariat in Ottawa. The list of MEND reports is included in Appendix D.

3. Readers interested in extracting other information (i.e. regulatory aspects, cost information) will find that this information is disseminated throughout the manual. Selected regulatory aspects are typically addressed when applicable, in the introductory subsections of Volumes

2 to 6 inclusive. As an example, a range of issues including regulatory aspects associated with the acidic drainage monitoring is discussed in Volume 6 Monitoring.

1.1.2 OTHER IMPORTANT MINE WASTE MANAGEMENT ISSUES

Readers are reminded that many other factors aside from acidic drainage need to be considered when managing mine wastes. A *Guide to the Management of Tailings Facilities* (MAC 1998) provides overall guidance in this regard. The MAC (1998) guide stresses that tailings management facilities are site-specific, with each site having its unique setting both physically and environmentally. Industry is strongly encouraged to ensure that their mine waste management facilities, including the waste containment structures, water management and control programs, and monitoring and facility audit systems, are confidently designed, constructed, operated and monitored with qualified technical personnel. Martin and Davies (2000) discuss recent initiatives in the stewardship of tailings facilities by the Mining Association of Canada, Canadian Dam Association, International Committee on Large Dams, United Nations Environmental Program/International Council on Metals and the Environment, and others. The trend is to apply stewardship practices to the management and operation of tailings impoundments commencing, at the concept stage through to closure.

As indicated in Volume 6 of the MEND Manual, mine waste management programs should be an integral and important part of an overall environmental management system for the organization. An effective environmental management system addresses all environmental activities within an organization, including the organizational structure, planning activities, responsibilities, procedures, processes, and a commitment to provide required resources. The ISO 14001 International Standard (ISO 1996) is a useful reference in this area.

Recent developments affecting acidic drainage monitoring include environmental effects monitoring and the Metal Mining Effluent Regulations – these issues are reviewed in Volume 6, Section 6.3. Useful references include the *Synthesis Report on Monitoring Methods* issued by the Aquatic Effects Technology Evaluation Program (AETE 4.1.4 1999), and the notes for MEND's risk assessment workshops held in Vancouver in 1998 (MEND BC.01) and in Sudbury in 1999 (MEND ME.01).

While MEND research was focused on acidic drainage issues, it also assessed related issues such as risk assessment. Specifically, MEND 2.11.9 reviewed the risk assessment process as it applies to the subaqueous (underwater) disposal of tailings in engineered or man-made impoundments. The main objective of the MEND-sponsored risk assessment workshops held in Vancouver (MEND BC.01) and Sudbury (MEND ME.01) was to communicate the application of risk management techniques to mine waste management. The workshops included expert presentations on risk assessment principles, examples of qualitative assessments, consideration of risk in regulations, and case study examples of risk assessment and management for proposed projects.

All activities and actions undertaken by individuals and groups in society have associated levels of risk. A risk, in general terms, represents the possibility of an unfavourable condition or event occurring. From an engineering or environmental perspective, risk can be defined as the mathematical product of the probability of an event occurring and the consequences of that event should it actually occur. Risk assessment has become an important component of mine waste management facility planning and operation.

In recent years, risk assessment approaches have evolved to be more comprehensive and viewed as the risk management component of decision-making processes (SENES 2000). Probabilistic methods can be used to assess and present a range of confidence for the various elements (i.e. hazards, likelihood, and consequences) in the risk assessment process. These techniques can be applied to identify impacts or benefits associated with proposed actions, and determine the sensitivity of outcomes with respect to the underlying assumptions. Risk assessment techniques used by industry range from screening level studies to detailed and sophisticated modelling studies.

Risks associated with acidic drainage extend from the risk of acid generation, to the risk of adverse impacts to the receiving environment and related liabilities. Considerable work has been completed in the area of characterizing mine wastes to determine whether or not a waste will become acid generating. The regular sampling of mine wastes as they are produced, and the monitoring of waste management facilities represent some of the methods that are used to address uncertainty in the net acid generation potential of wastes.

Technologies and practices are now available to prevent or control acid generation. Risk assessment of options to mitigate acidic drainage concerns have largely focused on external drivers related to acid generation and potential impacts to the environment. Risk assessment tools provide a framework to identify and communicate risks associated with a particular acidic drainage prevention or control initiative. As an example, a risk assessment of the use of a water cover over tailings should ask: what could potentially go wrong (i.e. loss of tailings containment dam, seismic events, storm events, effects of droughts, etc.)?; how often are these events likely to happen?; and, if they were to occur, what would the consequences be? This example again indicates that acidic drainage is only one component of mine waste management.

Communicating risk, the act of communicating unwelcome information to affected parties, can cause initial alarm (Boswell *et al.* 2000). Effective risk communication, however, also presents valuable opportunities for consultation. Aziz *et al.* (2000) discusses environmental risk from the perspective of the mine operator, management and an environmentalist, which altogether point to the need for co-operative and enduring relationships founded on a common willingness to listen, learn and respond. In addressing the global context, the Chairman/CEOs of a number of the industry's largest companies have initiated the Global Mining Initiative (GMI) that aims to ensure that the mining, metals and minerals industry will be responsive to global challenges (ICME 2000). The GMI is an ambitious leadership and change program, that implicitly brings to focus the need to do more to earn public trust.

SENES (2000) reports that the selection of an appropriate level of risk can be weighed, as is the case with the U.S. EPA, against the size of populations exposed and what is reasonably achievable. However, risk acceptance will vary with an individual's background (e.g. technical, social, etc.). A risk assessment will not necessarily identify the "best" option for all attributes. As an example, a waste management option having a low probability of acidic drainage release may also be cost prohibitive or otherwise unreasonable. In such as case, the "best overall approach" may be the most appropriate.

1.2 MANUAL STRUCTURE AND CONTENT

1.2.1 STRUCTURE

The technical volumes (Volumes 2 to 6) of the manual present information using a format that typically comprises a review of theory; MEND research; applications and limitations; base method; variations; information on cost; and a listing of MEND and relevant publications.

The vast majority of the information presented in the volumes is based on MEND reports. References are included to indicate sources of data and information including well-worded parts of MEND reports and other documents that are reproduced in the manual.

1.2.2 VOLUME 2 – SAMPLING AND ANALYSIS

The techniques that are now used to predict, prevent and control, and treat acidic drainage represent a vast improvement over those available only a decade ago. Science-based techniques are now effectively applied as a matter of course across Canada and internationally. MEND has shown that acidic drainage technologies require reliable, representative data. As data is subject to sampling and analyses methods and procedures, there is a need to ensure that good practices are followed. Volume 2 is intended to serve as a general reference for readers with regards to the methods that are used to collect a variety of samples for acidic drainage-related purposes. However, given the complexities that are inherent in the collection of samples for scientific purposes under diverse conditions, the volume cannot specifically indicate all the topics that need to be considered when planning a sampling program or in the actual sampling. This volume provides general guidance by identifying sampling methods and discusses selected, relevant sampling issues.

While the collection and analysis of samples was not a primary focus of MEND, it did make important contributions in this area. Relevant MEND projects have involved the sampling and analysis of tailings, ore and waste rock, pore waters and gases, treatment sludges, sediments, surface and groundwater, and fish and benthic organisms.

Surface and Groundwater Sampling, and Chemical Analyses:

Water quality data for samples of surface water and groundwater are used to monitor and assess changes in the drainage (i.e. runoff, seepage, and stream flow) from a source. The values of, and changes in, water quality parameters (i.e. pH, sulphate, total and/or dissolved metals) can be interpreted based on acidic drainage theory and in some cases used to assess the state of the acid generation process. As examples, data could be used to: 1) monitor for the onset of acid generation, or 2) monitor the quality of drainage from a closed-out mine waste management area to demonstrate the performance of measures taken to prevent or control acid generation. MEND 4.5.4 *Guideline Document for Monitoring Acid Mine Drainage* and *Appendix A - Technical Summary Notes* are useful guides for the design and implementation of monitoring programs for new mines.

Established methods and procedures were typically used in groundwater sampling in MEND projects. MEND 4.8.2 evaluated the innovative use of an electrical-conductance, bottom-contacting probe that can be used to identify locations of groundwater discharge on the bottom of lakes and rivers.

For the benefit of readers, Volume 2 of the manual provides technical discussions of pH, acidity, alkalinity, sulphate, redox potential, total dissolved solids, conductivity, metal concentration analyses, carbonate, and quality assurance/quality control in analyses.

Solids Sampling:

Tailings are sampled for a variety of reasons, including the collection of samples for acid generation potential characterization and to investigate conditions *in situ*. Important sampling objectives are to obtain representative samples and avoid unacceptable sample disturbance/alteration during collection and handling. MEND projects in this area include the preparation of a field sampling manual for tailings (MEND 4.1.1), which contains charts to guide readers in selecting methodologies for tailings solids, liquids and pore gas sampling. The charts address the phase of the sample, the position of the sample relative to the water table, field power requirements, the required degree of isolation of the sample from sources of contamination, and the acceptable degree of sample disturbance. The sampling of tailings solids, and sampling program design, sample size and important quality assurance/quality control issues are also addressed under an associate MEND report titled *Field Quality Assurance/Quality Control (QA/QC) Protocols for Monitoring and Predicting Impacts of Acid Rock Drainage* (MEND 4.5.2).

Plate 3. Surface Water Sampling

Plate 4. Sediment Core Sample.

Volume 2 stresses the need to have a well-developed procedure in hand prior to sampling. A meaningful sampling strategy should have clear sampling objectives, and incorporate a sampling strategy that meets those objectives. Sampling objectives and strategies should be reviewed periodically to assess their performance. Volume 2 also reviews the sampling of tailings to investigate the presence of sulphate-reducing bacteria, *in situ* geotechnical and geochemical measurements including sampling for mineralogical assessments, the use of tailings lysimeters, oxygen consumption, and the sampling of pore water in submerged tailings.

Waste Rock Sampling:

Waste rock is typically sampled to assess the potential for acidic drainage through a variety of analyses including mineralogy, particle size distribution, hardness/weathering, chemical composition, and acid-base accounting. Volume 2 discusses the challenges faced when sampling waste rock including the potential for wide variations in waste rock, approaches that can be taken to sample waste rock on a geological unit basis, and the number of samples that may be required. MEND 4.5.1-1 *Review of Waste Rock Sampling Techniques*, and MEND 4.5.1-2 *Handbook for Waste Rock Sampling Techniques* are useful references. Numerous MEND studies have involved waste rock sampling including the MEND 1.14 series reports that are related to the characterization of acid waste rock at La Mine Doyon near Rouyn-Noranda, Québec, and at the Whistle Mine (MEND 1.41.4) located nearby Sudbury, Ontario.

Mine Surfaces:

MEND, in co-operation with the British Columbia Acid Mine Drainage Task Force (BC AMD Task Force), completed a number of studies under the MINEWALL project (MEND 1.15.2). The studies were undertaken to better understand and predict water chemistry in and around mines. The work involved a literature review, geochemical assessment, and the development and assessment of a computer code to predict pit-water chemistry. The computer code, MINEWALL 2.0, was further refined and applied at the Placer Dome's Equity Silver Mine, Main Zone Pit, BHP Canada's Island Copper Mine and Noranda's Bell Mine (MEND 1.15.2c).

Treatment Sludge:

Treatment sludge is a by-product of the chemical treatment of acidic drainage. Sludge sampling and analyses are undertaken to provide data regarding the metal content of sludge and sludge stability and provide a scientific basis for sludge management. MEND 3.42.2a, *Characterization and Stability of Acid Mine Drainage Treatment Sludges,* and other studies (e.g. Zinck 1997; 1999; Zinck and Aubé 1999) are likely to serve as useful references for readers planning a sludge sampling and analysis program.

Drainage Sediments:

The sampling of sediments in the environment downstream of an acidic drainage source can assist in understanding the effect (if any) of contaminants on the aquatic ecosystem. Sediments are of interest as they can in some cases act as contaminant sinks, and biologically toxic concentrations of contaminants in sediments may not be detected through surface water sampling. MEND 4.5.4, *Guideline Document for Monitoring Acid Mine Drainage*, which includes comprehensive information on sediment sampling, is reviewed in Volume 2.

Biological Sampling:

Sampling and monitoring programs are used to establish baseline environmental data, and later to detect changes (if any) in aquatic systems. A number of MEND projects were conducted using well-established biological sampling methods and protocols. MEND did not, however, sponsor the development of any aquatic biology sampling procedures. For the reference of readers, Volume 2 reviews the sampling of periphyton (algae attached to hard substrates along shorelines), phytoplankton and zooplankton, benthic invertebrates, and fish.

Geophysics and Remote Sensing:

The principal applications for geophysics in the environmental monitoring of acidic drainage are to: 1) locate and define conductive acidified groundwater plumes, and 2) characterize the sulphide content of rock destined to become waste rock. MEND 4.6.1, *Applications of Geophysical Methods for Monitoring Acid Mine Drainage*, presents detailed information on available geophysical methods as well as case studies. MEND 4.6.1, *Application of Remote Sensing and Geophysics to the Detection and Monitoring of Acid Mine Drainage* provides a compendium of information on methods in use at present, and tabular lists to assist readers in assessing the applicability of available techniques to detect and monitor acidic drainage.

Chemical Analysis:

The chemical analysis of elements and compounds is an essential part of static and kinetic test programs undertaken to assess the weathering process. Numerous labour intensive analyses have been advanced to rapid instrument determinations which have lowered cost and improved accuracy. MEND projects were conducted using well established standard chemical analytical methods and, as such, did not involve the development of analytical procedures. Volume 2 reviews the analyses for water (i.e. pH, acidity, alkalinity, sulphate, total dissolved solids, conductivity, metals) and solids (carbonate). The importance of quality assurance and quality control is also presented.

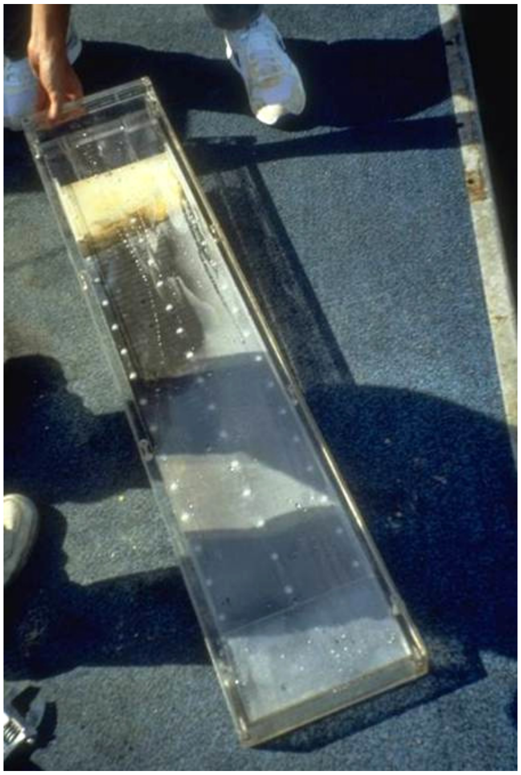


Plate 5. Pore Water Sampling using Dialysis Arrays (Peepers).

Plate 6. Sludge Sampling.

1.2.3 VOLUME 3 – PREDICTION

The geochemical behavior of mine wastes can be predicted using a number of methods. For example, prediction studies can be used to identify mine wastes that are likely to be acid generating, potentially acid generating, or otherwise susceptible to metal leaching. Prediction studies can also be used to estimate when acidic drainage may commence, and predict the quality of drainage over time. In addition, predictive numerical geochemical models can be applied to predict the effects of closure strategies (e.g. use of a dry cover, or a water cover).

Laboratory Static and Kinetic Geochemical Test Methods:

Laboratory static and kinetic geochemical tests are extensively used to characterize mine wastes from an acidic drainage potential perspective. A range of references are available in this area including MEND 1.16.1b, *Acid Rock Drainage Prediction Manual* for the application of chemical evaluation procedures for the prediction of acid generation from mining wastes.

Acid-base accounting (ABA) is a two-part analytical procedure that is used to determine, as a minimum, the acid potential (AP) and neutralizing potential (NP) of the waste. Variations of the acid-base accounting tests exist, but in general, AP is most often based on sulphur concentration due to iron sulphide minerals, as in most cases these are the main source of acid. The NP is determined by reacting a known weight of finely ground sample with a mineral acid. Typically, both the AP and NP values are reported in equivalent kilograms of calcium carbonate per tonne of waste, so that an "account" can be made to express the net potential for acid generation. The net potential of a waste to generate acid is determined from the difference between the AP and NP. This difference is commonly referred to as the net neutralization potential (NNP) as shown in Equation 1, which assumes that all available acid generating and acid neutralizing materials are available to react.

$$NNP = NP - AP \qquad (1)$$

Alternatively, the neutralization potential ratio (NPR) can be calculated as shown in Equation 2.

$$NPR = NP / AP \qquad (2)$$

The main limitations of ABA testing are that the data do not distinguish between the types of minerals responsible for NP and AP. ABA results need to be carefully interpreted taking into consideration the characteristics of the waste. To assist readers, Volume 3 includes discussions of ABA test procedures, total inorganic carbon, mineralogy, metals, and the physical characteristics of wastes.

Kinetic tests are widely used to simulate weathering and to obtain data on characteristics such as sulphide oxidation rates, carbonate depletion rates, acid generation lag times and metal leaching rates. The tests include humidity cell tests, and column tests.

Humidity cells provide a means to measure acid generation and acid consumption under fully oxygenated conditions. In a typical humidity cell test, a mine waste sample is placed in a chamber and allowed to oxidize through aeration, drying, and rinsing cycles. Though this method does not accurately simulate field conditions, it does provide an oxidation rate for the whole sample. There are numerous variations of this test as indicated in Volume 3.

Column tests are used to evaluate leaching processes under a variety of conditions, such as fully oxygenated to oxygen deprived. Column tests are typically used to investigate metal concentrations rather than acid and metal release rates for disposal conditions. Examples include; unremediated, placement of an engineered cover or water cover, and co-disposal of waste rock and tailings, waste blending, etc.

Many MEND projects have involved the use of kinetic tests. Volume 3 reviews the design considerations and the use of kinetic tests in MEND projects.

Field Methods:

Field tests are carried out to evaluate the behavior of sulphidic wastes under field conditions, and can allow calibration of the results of kinetic testing completed in the laboratory. They usually involve field measurements and observations of an application of interest, with *in situ* monitoring including oxygen consumption measurements, pore gas measurements, runoff and groundwater monitoring, waste characterization, and other sampling and analyses.

The geochemical and physical characteristics of a waste rock pile, from its origin in underground workings to its placement underwater in a lake, were assessed under MEND 1.44.1 *History of Eskay Creek Mine's Waste Rock Dump from Placement to Disassembly*. This study provides qualitative and quantitative information on mass transport and water infiltration within a waste rock pile, and demonstrated that geochemical processes are dependent on physical factors such as channeling or stratification within a dump. An important observation from field studies of waste rock piles is that accumulated quantities of oxidation products and acidity can be progressively released to the environment (MEND 1.14.3; MEND 1.41.4).

Numerical Modelling:

Computer modelling is often used to assess waste management options. The simulation of scenarios, such as the subaqueous disposal of fresh tailings or the use of an engineered cover, can be beneficial and assist in identifying a cost-effective management option for acid generation or prevention or control. The modelling approach that is best suited to a site will depend on factors

Plate 7. Column Test.

Plate 8. Field Test Cell – Dry Cover.

such as the particular question to be addressed, the availability of data taking site-specific conditions into account, and the required reliability of the prediction. Numerical models are often used to estimate the acidity and the quality of drainage over time. In general, models are limited by a lack of site-specific data, or by highly variable data.

A number of advances in the prediction of drainage quality for waste rock, tailings and open pit mines were made under MEND including a tailings model (RATAP) and a geochemical model (MINEWALL). MEND 1.42.1 is a useful reference document in that it reviews geochemical processes and geochemical models adaptable for the prediction of acidic drainage from waste rock. Numerical models (i.e. WATAIL, SOILCOVER) are available in the public domain, along with propriety models, to predict the performance of remediation strategies such as the use of engineered covers on tailings and waste rock.

1.2.4 VOLUME 4 – PREVENTION AND CONTROL

Volume 4 describes the research completed under the auspices of MEND, and by others, in acid generation prevention and control. MEND made significant contributions in this area, and spent just over half of its total budget of $18 million on projects related to prevention and control. This substantial expenditure was beneficial as it led to the development and application of numerous technologies.

While a tremendous amount of work has been completed in this area, there is a need for further research and development to address areas of uncertainty and reduce costs, which in some cases can be excessive and unaffordable. Long-term monitoring has been commenced on full-scale applications at a number of sites to assist in confirming the performance of available technologies. Experience in the closure of acid-generating mine waste sites has shown that the prevention of acidic drainage should be a first objective when this is achievable and affordable.

The prevention and control of acidic drainage is a technically complex area and one that typically requires the involvement of experts from numerous technical disciplines. Site-specific factors and conditions add to this complexity, and often necessitate site-specific research. As a result, acidic drainage technologies are not universally applicable. The application of a particular technology to a site may be negated by prohibitive cost or other factors that affect mine waste management.

The various prevention and control technologies are described in Volume 4 under eight subject headings that are briefly outlined for the benefit of the reader.

<u>Water Covers:</u>

MEND research demonstrated that the oxidation of sulphide minerals can be inhibited by the presence of a water cover, as the water acts as a barrier to the diffusion of oxygen from the atmosphere to the submerged sulphides. Potential disposal options include: 1) the subaqueous disposal of unoxidized sulphidic wastes under a water cover; and 2) the flooding of oxidized wastes.

In Canada, the use of water covers and underwater disposal are being confirmed as the preferred prevention technology for unoxidized sulphide-containing wastes. These aspects were addressed through initial investigations of historically submerged tailings in natural basins with extensive and detailed geochemical investigations. A total of 25 reports and/or scientific papers have been prepared on subaqueous disposal (MEND 2.11), and a generic design guide (MEND 2.11.9) is available. 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 impoundments and operating and closure plans.

Underwater disposal of unoxidized mine wastes (tailings and waste rock) in constructed or man-made lakes is presently an option favoured 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 that parallel the full-scale operation and evaluate closeout scenarios have been investigated (MEND 2.12.1).

The underwater disposal of mine wastes can be challenging and may not be an acceptable disposal method at some sites. MEND addressed a range of issues related to the subaqueous disposal of mine wastes including the effects on the sulphide oxidation process, and concerns for aspects such as: the effect of water depth, oxygenated water, currents, waves; impacts to/from pore water; biological influences; water cover quality; and potential benefits of diffusion barriers at the waste/water cover interface.

The key challenge for flooding oxidized wastes is that contaminated pore water and soluble mineral phases can be released, resulting in unacceptable contaminant concentrations and loadings to the water cover and to the receiving aquatic environment. The flooding of oxidized wastes can also necessitate the treatment of excess pond water prior to its release.

Both the Quirke (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-

a)

b)

Plate 9. Quirke Tailings Impoundment
a) Before Flooding b) After Flooding. (Courtesy of Rio Algom)

(Courtesy of Rio Algom)

Plate 10. Aerial View of Flooded Quirke Tailings Impoundment.

(Courtesy of Aur Resources)

Plate 11. Aerial View of Active Louvicourt Engineered or Man-Made Tailings Impoundment.

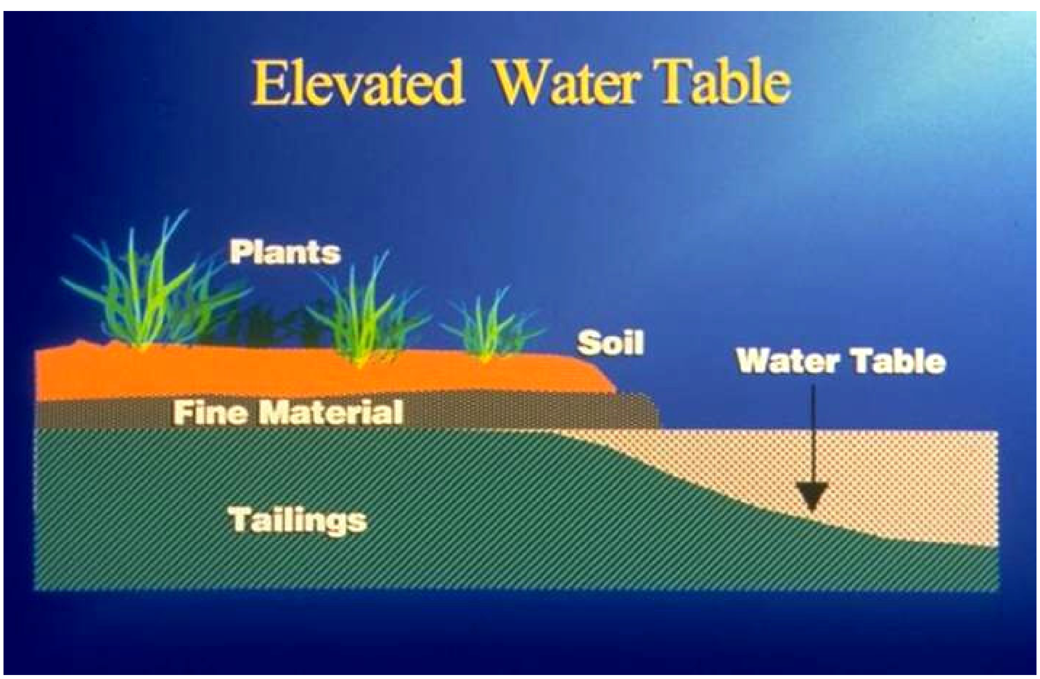


Plate 12. Sketch of Elevated Water Table Concept.

rich layer over the sulphide-rich materials can prevent or retard diffusion of soluble oxidation products into the water column.

Water covers have been applied at many sites, but are not universally applicable. Related issues, such as the ability to maintain a water cover over the long term, the integrity of the containment structures, locality and site-specific potential risks due to seismic events, severe storm events, etc., can negate the use of this technology. However, under suitable conditions, the present state of knowledge is sufficient to allow for the responsible design, operation and closure of waste management facilities using water covers for both fresh and oxidized tailings and waste rock.

<u>Saturation:</u>

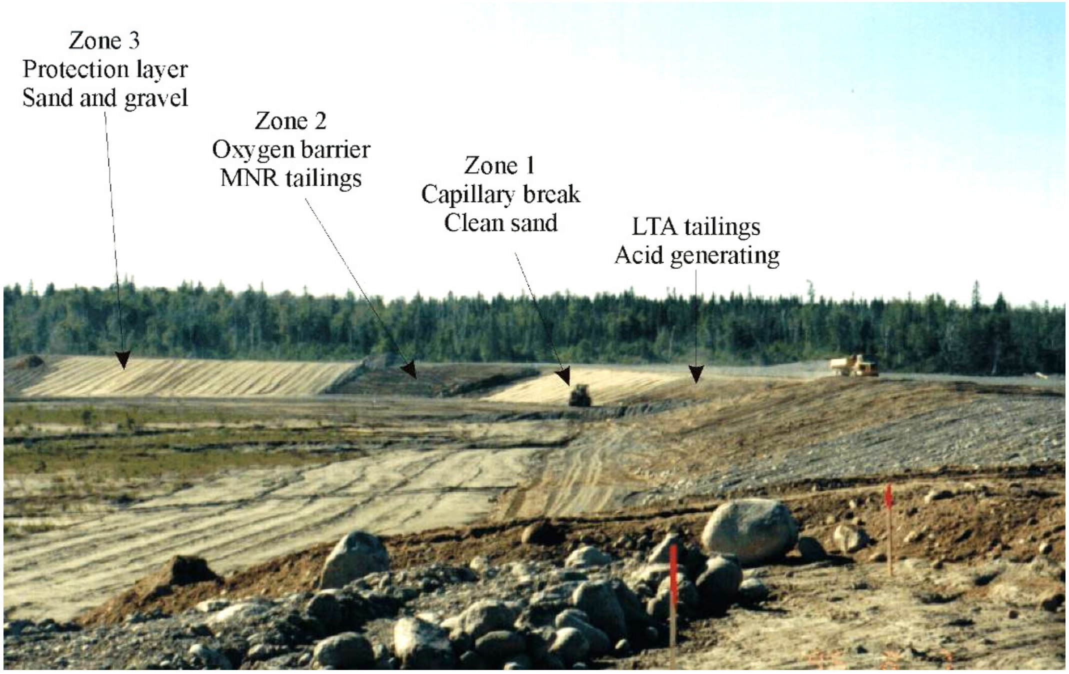
Saturation refers to the moisture saturation of tailings pore spaces to make good use of the low rate of oxygen diffusion through water-filled pore spaces in comparison to those that are gas-filled. In this light, MEND investigated the innovative use of elevated water tables in tailings as a means of saturating the tailings while eliminating the need to maintain a water cover (MEND 2.17.1). The use of an elevated water table by itself does not prevent acid generation, as there may be zones of near-surface exposed and unsaturated tailings that remain available for oxidation. The use of an elevated water table can, however, significantly reduce the inventory of sulphide tailings available for oxidation. Technologies that can be applied to make use of elevated water table conditions, including the use of thickened or paste tailings, have been reviewed by MEND. The use of elevated water concepts may be cost advantageous when applied in tandem with other approaches to prevent and control acid generation.

<u>Dry Covers:</u>

Dry cover systems are commonly used to decommission waste rock piles and tailings impoundments at sites around the world. The key objective of dry cover systems is to provide a barrier that minimizes the influx of atmospheric oxygen to the mine waste, and limits moisture infiltration. Apart from these functions, dry covers are expected to be resistant to erosion, and provide media for vegetation.

Dry covers can range from a single layer of earthen material to several layers of different material types, including native soils, non-reactive tailings and/or waste rock, geosynthetic materials, and oxygen consuming materials. Multi-layer cover systems utilize the capillary barrier concept to keep one (or more) of its layers near saturation under all climatic conditions. This creates a “blanket” of water over the reactive waste material, which reduces the influx of atmospheric oxygen and subsequent production of acidic drainage.

MEND research on dry covers commenced in 1988. Multi-layer soil cover systems for tailings and waste rock were extensively investigated (e.g. Waite Amulet (MEND 2.21.2 – tailings), Les Terrains Aurifères (MEND 2.22.4 – tailings) and Heath Steele (MEND 2.31.1 – waste rock)). A



(Courtesy of Barrick)

Plate 13. Dry Cover Placement at Les Terrains Aurifères (LTA) using Tailings as the Oxygen Barrier Layer.

(Courtesy of Placer Dome)

Plate 14. Soil Cover at Equity Silver Mine.

review of soil cover technologies (MEND 2.21.3) is available, while a design guide for earthern covers is in preparation (MEND 2.21.4). These MEND reports are likely to serve as useful references as they address cover design, selection of cover materials, construction issues, and instrumentation. They will also review the performance monitoring of covers that are exposed to Canadian climatic conditions.

Supplying suitable and sufficient quantities of cover materials can be challenging and cost prohibitive at some sites. MEND addressed this issue through evaluations of the use of alternate cover materials, such as sulphide-free tailings and organic waste materials, instead of natural soils.

Laboratory studies have shown that sulphide-free fine tailings offer promising characteristics for use in dry covers (MEND 2.22.2). Barrick's tailings site in Northwest Québec, Les Terrains Aurifères, provided the first full-scale demonstration project of using tailings in a cover system (MEND 2.22.4). A second site, Québec crown-owned Lorraine, was also rehabilitated using the same closure technique.

Innovative dry cover research has noted that a range of materials, including low cost waste materials from other industries (i.e. crude compost, lime stabilized sewage sludge, paper mill sludge), may provide excellent potential for generating oxygen-reducing surface barriers (MEND 2.20.1). This approach would see the application of one waste material to solve the disposal problem of another waste material

MEND 2.20.1 evaluated the use of alternate materials, including geomembranes, in constructing dry covers. The first full-scale application in Canada of a geomembrane liner for close-out was completed in 1999 at La Mine Poirier in Northwest Québec. Performance monitoring of the close-out scenario to evaluate the liner is ongoing (Lewis and Gallinger 2000).

<u>The Co-Disposal of Tailings and Waste Rock:</u>

As its name implies, co-disposal refers to the combined disposal of waste rock and tailings. MEND investigated this concept with a study into the possibility of injecting tailings into waste rock piles.

Co-disposal is expected to remain an active area of interest for a number of reasons including: the potential to minimize the footprint of mine waste management areas; potential opportunities to establish and create elevated water table conditions within waste rock piles; and the possible elimination of tailings containment structures at some sites.

Blending and Layering:

The blending and layering of waste rock is an approach founded on the geochemistry of sulphide oxidation. In concept, a net acid generating waste could be blended with, or layered between, alkaline material to produce a non-acid generating waste that has seepage water quality acceptable for discharge without additional measures (MEND 2.37.1; MEND 2.37.3). This is a challenging area that continues to be under development given the potential benefits.

Separation and Segregation:

MEND had an important role in sulphide tailings separation research where a key driver was to identify techniques to separate sulphide solids for disposal, or produce reduced sulphur content tailings for use in site rehabilitation. MEND has identified suitable methodologies in this regard, however, high cost remains a major drawback.

Laboratory and field tests are showing that depyritized tailings have excellent potential for use in dry covers. Flotation has been shown to be an effective, albeit costly, method of reducing the sulphide content of tailings prior to their discharge. The extent to which tailings sulphur levels need to be reduced to prevent acidic seepage has also been investigated under MEND. Economic analyses indicate that the hydraulic placement of desulphurized tailings would be more cost effective in comparison to mechanical placement (MEND 2.22.3).

Permafrost:

The potential to best utilize cold climatic conditions and permafrost has been investigated under MEND. The research has shown that the sulphide oxidative process slows considerably as the temperature of the waste drops and approaches 0ºC. MEND projects have also assessed the effects of freezing on metal leaching, and conceptual acid control strategies for use in cold climatic conditions.

Permafrost in both continuous and discontinuous forms is present across Northern Canada, and covers about 40% of the country land mass. A reasonable and sufficient knowledge base exists with regards to the construction of a variety of structures over permafrost. However, knowledge and experience in the use of permafrost, including the natural and assisted freezing of sulphide wastes, is an area that continues to be developed.

MEND 6.1, *Preventing AMD by Disposing of Reactive Tailings in Permafrost*, reviews concepts for the prevention of acidic drainage through the disposal of tailings in permafrost conditions. This report would serve as a useful introduction for readers. Volume 4, Section 4.8 of the manual provides an overview of MEND research in permafrost, and a discussion on the general approach that is being taken in planning mine waste disposal in permafrost.

(Courtesy of Cambior)

Plate 15. In-Pit Disposal of Waste Rock at Solbec.

(Courtesy of Cambior)

Plate 16. Solbec Pit, Several Years Later.

Backfilling:

In recent years, sulphide tailings and waste rock have been disposed in mined-out open pits with the specific objectives of preventing or controlling acid generation. While this practice has been extensively applied and there is a sound technical base for in-pit disposal programs, few sites provide scientific databases that can be used to assess the performance of these technologies.

MEND 2.36.1 investigated the backfilling of open pits and identified a range of approaches for the in-pit disposal of mine wastes. The project determined that not all pits are suitable for in-pit disposal. In addition, while in-pit disposal has been used on many occasions, there have been few scientifically monitored pits. However, this approach is proving to be effective and affordable under suitable conditions.

The backfilling of mines has been extensively practised internationally. Only recently, however, have backfilling programs been designed specifically for the disposal of sulphide tailings or waste rock to inhibit acidic drainage.

1.2.5 VOLUME 5 – CHEMICAL AND PASSIVE TREATMENT

The key objective in treating acidic drainage is to neutralize the free acidity and reduce the concentrations of contaminants of concern (e.g. dissolved metals) to low levels to ensure that the treated effluent quality is acceptable for recycle or release.

MEND expenditures related to the treatment of acidic drainage totalled about $1,500,000. MEND added to the state of knowledge and expanded the understanding of technical and other issues that need to be considered in the responsible selection, operation and management, and decommissioning of treatment systems. In the chemical treatment area, MEND completed assessments of acidic drainage characteristics, available treatment methods, metal recovery/recycling methodologies, and treatment sludge management. MEND also assessed passive treatment processes including anoxic limestone drains, aerobic wetland treatment systems, passive anaerobic treatment systems, biosorption treatment methods, passive *in situ* treatment methods, and hybrid active/passive treatment systems.

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

Chemical Treatment:

In Canada, acidic drainage is most often treated using lime-based chemical processes (MEND 3.32.1). In these treatment processes, lime is added to raise the pH to an appropriate level to enable dissolved metals removal by precipitation/co-precipitation. Lime-based processes result in the formation of a by-product: gypsum/metal hydroxide/carbonate sludge. Other alkalis (i.e. limestone, sodium hydroxide and sodium carbonate) are also used along with metallic salts to remove specific contaminants (i.e. iron and barium salts for arsenic and radium removal respectively).

MEND 3.32.1 investigated chemical treatment and sludge management practices. This involved the comprehensive review of available treatment processes; the implications of long-term acidic drainage treatment; sludge disposal; and capital and operating costs for chemical treatment facilities. The report would be a useful reference for chemical treatment processes, including, the batch treatment of ponded acidic water, conventional lime treatment, and the high density sludge (HDS) type lime-based treatment process.

The 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.
- A conventional treatment plant is most appropriate for continuous treatment where sufficient space and suitable conditions are available for the disposal of the low density sludge.
- 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. The use of HDS-type plants can be cost beneficial because of long-term cost savings in lime usage and sludge disposal. Over the past decade, the trend for long-term treatment has been HDS-type plants.

MEND 3.32.1 also showed that a treatment system has to be compatible with site-specific conditions, including the acidic drainage collection and storm water management system, and allowable limits on the timing and quality of treated discharge. 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.

Sludge management presents two potential issues: metal leaching, and sludge volume. For metal leaching, studies conducted to date support the view that sludge will remain stable if properly

(Courtesy of Cominco)

Plate 17. Cominco's High Density Sludge (HDS) Plant in Kimberly, B.C.

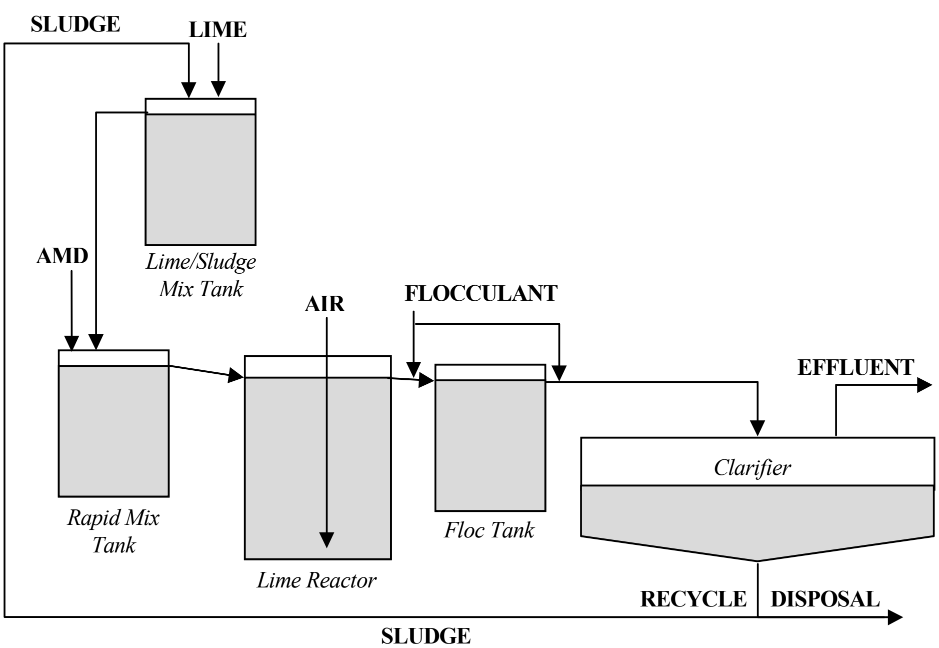


Plate 18. Schematic of High Density Sludge (HDS) Process.

disposed (MEND 3.42.2). The volume of sludge requiring disposal can be significant at some mine properties. In extreme conditions, the volume of sludge that can be produced over the long term from a conventional lime-based chemical treatment process may exceed the volume of the acid source. As such, provisions need to be made to provide for adequate and suitable sludge storage space, or to reduce sludge volume. In this regard, increasing the solids content of sludge through the use of an HDS-type process rather than a conventional chemical treatment process is likely to be beneficial.

<u>Passive Treatment:</u>

Passive treatment processes rely on a variety of abiotic (non-biological) and biologically mediated processes. These processes include oxidation and reduction, biological alkalinity production, metals mineralization as hydroxides and sulphides, plant uptake, and filtering and sedimentation. Passive treatment techniques include the use of constructed wetlands, passive anaerobic treatment systems, and anoxic limestone drains. The use of passive treatment systems is technically feasible; however, the Canadian experience indicates that they do have specific and limited applications for acidic drainage treatment. Applications range from complete systems for treating small seeps to secondary treatment systems such as effluent polishing ponds. Large-scale passive systems capable of handling low winter temperatures, high metal loads, and fluctuations in flow rates associated with the spring freshet have yet to be implemented.

MEND 3.14.1 investigated the state-of-the-art of passive treatment technologies, and presents a thorough summary of design parameters, operating requirements, and performance data and cost information for anoxic limestone drains, constructed wetlands, microbial bioreactor systems, and biosorption treatment systems. Some key findings include:

- An anoxic limestone drain (ALD) usually consists of a subsurface limestone rock filled trench that is capped to exclude air and the infiltration of oxygenated water. ALDs gradually release alkalinity, through limestone dissolution, as the acidic water passes through the drain. ALDs need to remain saturated and operated under anoxic conditions to prevent the oxidation of iron and the precipitation of ferric hydroxide precipitates in the drain. ALDs are often used for the treatment of acidic drainage at coal mines;
- Aerobic wetland systems are effective in treating net-alkaline drainage and in the process oxidizing iron, aluminum and manganese. Natural acidic drainage treatment processes that occur in wetlands are abiotic, chemical and physical processes. Biological processes include plant intake of metals, plant mediated oxidation, and biosorption. Constructed aerobic wetlands are not universally applicable due to the necessity for a long hydraulic retention time, and an extensive surface area. Wetland treatment systems could be used downstream of an anoxic limestone drain;

Plate 19. Wetland Passive System.

(Courtesy of Rio Algom)

Plate 20. Panel Wetland.

- In passive anaerobic treatment systems, an organic source is introduced and replaced as required, or plants are used to provide a sustained source of organic matter. These systems rely on sulphide reducing conditions, sulphide precipitation, and biogenic alkalinity production to treat net-acidic drainage. The key to these systems is the ability of self-sustainability;
- Biosorption is not presently considered to be effective as a stand-alone method for acidic drainage treatment. The capacity of a biosorption system relies on the capacity of the biosorbents, residence time, and influent water quality and temperature. Once saturated, biosorbents need to be regenerated or replaced;
- Other *in situ* biological treatment systems include reactive walls, which consist of a trench filled with an organic substrate and limestone. Field testing has shown that reactive walls are capable of transforming acidic groundwater flow to net-alkaline with significant reductions in iron and sulphate concentrations;
- At some sites, passive treatment can be accomplished using chemical dosing systems which add alkali to a metered acidic drainage flow; and
- Bioreactor treatment systems are hybrid engineered systems that make use of passive anaerobic, biological treatment processes within the framework of an active treatment process. The use of bioreactors holds promise, however, their relatively high cost remains a key impediment.

Other useful MEND reports include MEND 3.12.2, which investigated the mechanisms that mitigated the effects of acidic drainage in a natural wetland ecosystem containing submerged uranium tailings at the Panel waste management area near Elliott Lake, Ontario. The report presents information and data relevant to understanding the passive treatment processes that occur in wetland systems. In another project, MEND 3.11.1 presented the results of a four-year investigation into the potential use of wetland ecology and microbiology to treat acidic drainage from metal mines. A major outcome of this initiative was the development of design parameters for the acid reduction using microbiology (ARUM) process.

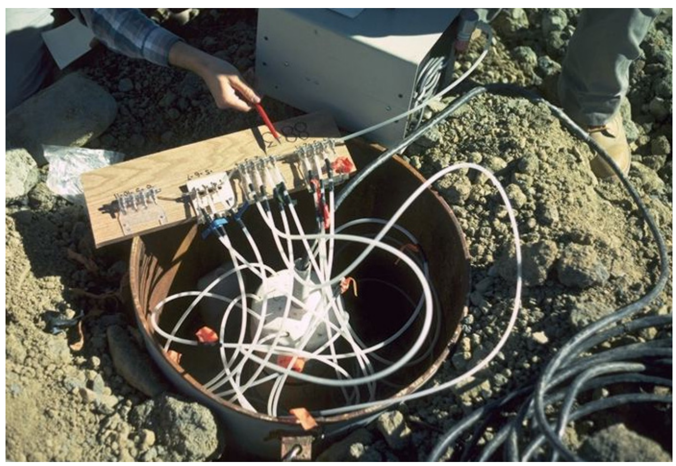
1.2.6 VOLUME 6 – MONITORING

Monitoring refers to the strategies, collection, and assessment of data relevant to the prediction, prevention, control, and treatment of acidic drainage. Several guides are available to assist in the development of acidic drainage monitoring programs, including reports completed under the auspices of MEND and the BC AMD Task Force. Strategies applicable to the monitoring of acidic drainage can also be applied to the monitoring of neutral pH/metal leaching contaminated drainage, and drainage from potentially acid generating materials.

a)

b)

c)



d)

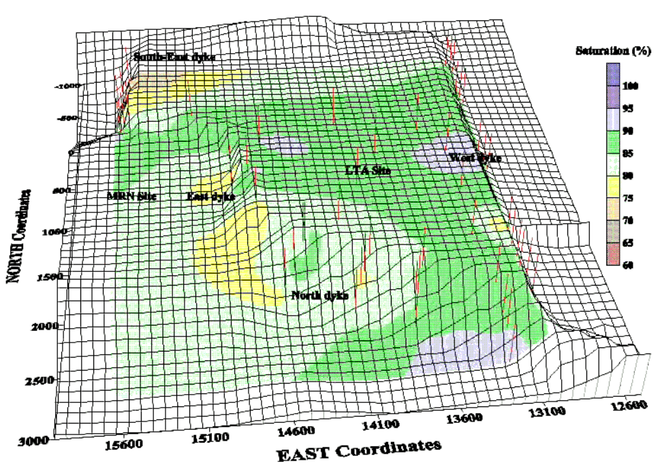


Plate 21. Monitoring Tools a) Sampling Wells b) Microelectrodes for pH and Dissolved Oxygen Profiles c) Sampling in Borehole d) 3D Saturation Plot of Fine Layer at LTA.

The objective of Volume 6 is to familiarize readers with the work completed by MEND and others in monitoring and related areas. About $1.1 million was spent on twenty-five monitoring related projects under MEND.

MEND monitoring projects have included the preparation of manuals, reference materials, and reports on emerging monitoring technologies. A key MEND deliverable on acidic drainage monitoring is MEND 4.5.4 *Guideline Document for Monitoring Acid Mine Drainage.* This document is a single source introductory guide to acidic drainage monitoring, and provides 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 for freshwater systems.

Other guideline type 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 presented in MEND 4.5.1-1, and available sampling techniques for waste rock are presented in MEND 4.5.1-2.

Volume 6 provides diverse information regarding acidic drainage monitoring and sampling techniques and environmental monitoring programs in general. However, acidic drainage monitoring represents only one component of an overall environmental monitoring program. Environmental monitoring programs vary from site to site as they are developed taking into account the type and scope of operations, site-specific issues, and environmental protection requirements and objectives. In addition, monitoring requirements are likely to change over the life of a mine. For reference, the general objectives of monitoring during the baseline/exploration phase, the operational phase, and the decommissioning phase are outlined in Volume 6. A discussion of other related topics is included, such as recent developments in regulatory requirements respecting effluent quality, effluent toxicity testing, and use of environmental management systems.

1.3 THE MINE ENVIRONMENT NEUTRAL DRAINAGE (MEND) PROGRAM

1.3.1 BACKGROUND

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 and it was believed that this technology would also address acidic drainage and allow the sites to be abandoned without future liability. Successful revegetation methods were developed, and many sites were revegetated. However, after several years, the quality of water draining from vegetated sites had not significantly improved, and mine site operators were faced with the prospect of operating 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, CANMET, 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 through the initiation of a tripartite consortium called the Mine Environment Neutral Drainage (MEND) program. Provincial groups also worked with MEND to coordinate research. Provincial initiatives included the:

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

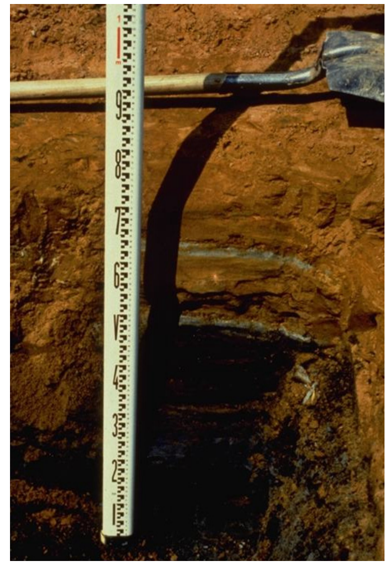
The initial MEND research plan was based on a five-year budget of $12.5 million (MEND 5.5.1). Three years into the program, the original "RATS" plan was re-evaluated and a "Revised Research Plan" was produced. This plan extended MEND to a 9-year program and the partners agreed to an expanded budget of $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 the provincial governments. When MEND ended in December 1997, the two levels of government together with the Canadian mining industry had spent over $17 million (Table 2) to find ways to reduce the estimated liability caused by acidic drainage (Appendix A).

Table 2
Funding Contribution by MEND Partners

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

a)

b)



c)

d)

e)

f)

Plate 22. Sustainable Vegetation and Acidic Drainage – Common Misconception of the 1970s a) Simple Vegetation Cover b) Oxidized Surface Layer of Tailings below Cover c) Toe of Tailings Dam d) Acidic Drainage e) Treatment Plant f) Lime Treatment Sludge Pond

1.3.2 KEY MEND OBJECTIVES

The two main MEND program objectives were to:

1. 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.
2. Establish techniques to enable the operation and closure of acid generating tailings and waste rock disposal areas in a predictable, affordable, timely and environmentally acceptable manner.

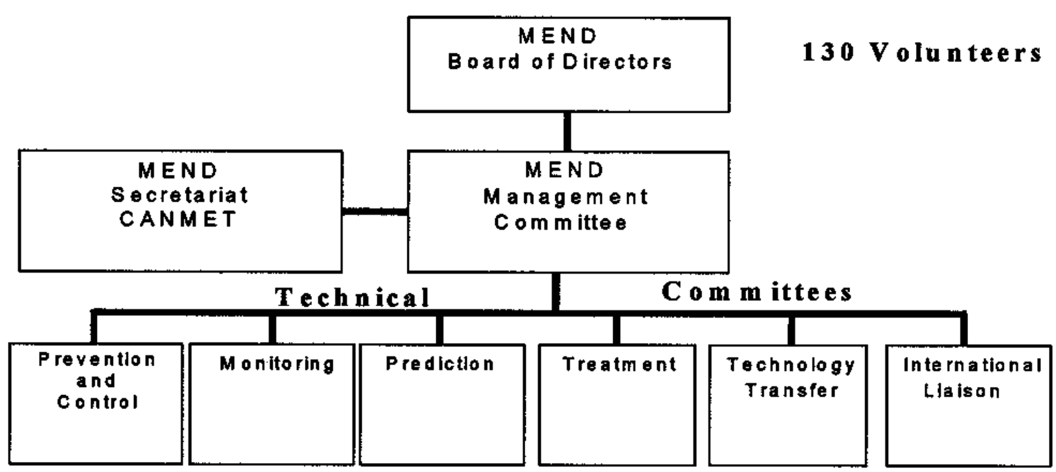
1.3.3 MEND ORGANIZATIONAL STRUCTURE AND RESEARCH

MEND's organizational structure 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.
- The technical committees addressed technological issues and solutions.

The MEND Secretariat was a small-dedicated group that coordinated the activities, managed the accounting, the reporting and technology transfer, and was the "glue" which held the program together.

Figure 1 **MEND Organization**



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

MEND relied heavily on the 130 volunteer representatives of the different participating agencies: regulators, mining company managers and engineers, NGOs and government officials and scientists. These volunteers freely contributed their time and expertise to the program. Their emphasis was on technology development needed for MEND to be successful rather than individual organizational needs.

Research and development on acidic drainage sponsored by MEND produced some important and successful technology improvements. When MEND started in 1989, it was widely believed that:

- If mine wastes or mine walls were not now acid generating, they never would be;
- Acidic drainage was a temporary, short-term issue; and
- Reclamation and revegetation were the solutions.

Tremendous progress has since been made. MEND focused the acidic drainage effort and developed a toolbox of technologies that is available to all stakeholders. We now know that:

- Acid generation may not start for decades or more;
- Acidic drainage is not a short-term issue, once it starts it is very difficult to stop; and
- Reclamation and revegetation are only part of the solution – prevention is the key.

There is now a common understanding of acidic drainage issues among MEND participants. Technologies are in place to open, operate and decommission a mine property in an environmentally acceptable manner. MEND is presently used as a model for technology development programs to advance environmental management in the mining industry. Decisions are taken based on sound science principles.

1.3.4 NEW IDEAS PROJECTS

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

MEND developed and distributed a two-page proposal format across Canada. One-hundred and thirty-five proposals were received, of which 18 were funded. Up to $10,000 was provided for the review and the development of a concept. The new ideas projects are listed in Table 3.

Table 3
Listing of New Ideas Projects

Project Title
Status of AMD Research in the U.S.
Permafrost to Prevent AMD
Low Cost Wax Cover
Chemically Modified Clay Cover
Ferric Phosphate Coating of Pyrrhotite
State-of-the-art of Japanese Technology
Formation of Hardpan in Pyrrhotite Tailings
Passivation of Sulphide Minerals
Selective Ion Exchange Resin
Chelating Ribbons
Comingled Waste Disposal
Chelating/Membrane Filtration
Sprayed Polyurethane Covers
Literature Review: Foam Flotation
Limestone Precipitation Layer in Coal Wastes
Ion Flotation for Zinc Recovery

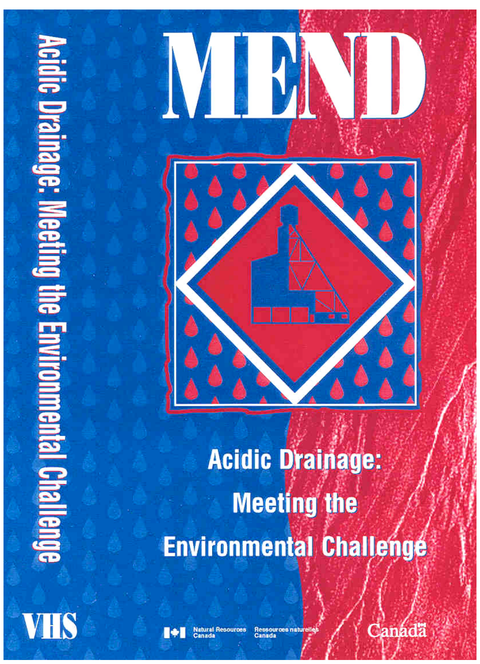
The investment in the 18 New Ideas project totalled approximately $230,000. Although most of the new ideas were innovative and applicable and provided useful information, they did not achieve the objective of providing a solution to the problem of acidic drainage. At least three had potential applications (sprayed polyurethane, modified clay and permafrost) and three yielded useful state-of-the-art reviews (U.S. research, foam flotation and Japanese technology).

1.3.5 TECHNOLOGY TRANSFER

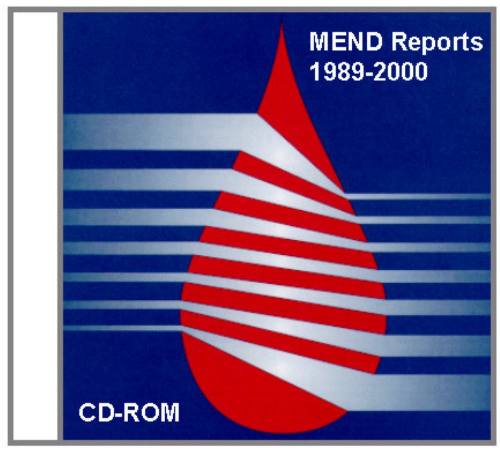
Technology transfer activities were expanded in the later years of the program, when the dissemination of information on developed technologies to the partners and the public became a major function of MEND. A MEND 2000 Internet site (**http://mend2000.nrcan.gc.ca**) was established and is updated with current information on technology developments. The site provides report summaries, the MEND publication list, information on liabilities, case studies, and conference and workshop announcements.

a)

b)



c)



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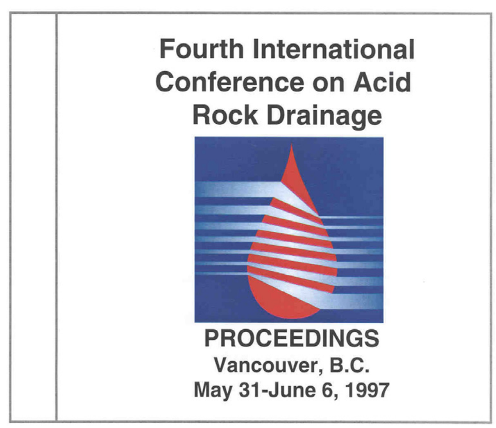


Plate 23. MEND Technology Transfer Initiatives
a) MEND Internet Site b) MEND Video
c) CD-ROM of MEND Reports d) CD-ROM of 4th ICARD

MEND and MEND 2000 hosted several workshops per year at locations across Canada. Proceedings for 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 (2^{nd} Montréal), 1994 (3^{rd} Pittsburgh), 1997 (4^{th} Vancouver), and 2000 (5^{th} Denver). In addition, many technical papers detailing work carried out under the auspices of the MEND Program were presented at various conferences and forums. Other important technology transfer initiatives included:

- MEND videos - available in English, French, Spanish and Portuguese. These videos describe technological advances relating to the prediction, prevention and treatment of acidic drainage from mine sites. These can been ordered directly from the Internet site;
- This MEND Manual, which 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 on CD-ROM;
- More than 200 reports completed during MEND and MEND 2000;
- A selection of over 110 MEND reports on two CD-ROMs; and
- National case studies on acidic drainage technologies.

1.3.6 THE MEND MODEL FOR COOPERATIVE INITIATIVES

MEND has been described as a model way for governments, industry and NGOs to cooperate in technology development for advancing environmental management in the mining industry, and allowing more decisions to be based on scientific research findings. 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;
- MEND has demonstrated that technology transfer is critical. Research results must be effectively communicated to industry, government agencies, NGOs and the public if a program is to achieve desired results;
- The Secretariat 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 has been 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 the MEND subaqueous tailings disposal technology and has been able to progress from the exploration phase to an operating mine within five 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 also fostered working relationships with environmental groups, ensuring that they are an integral part of the process.

1.3.7 MEND 2000

When MEND ended on December 31, 1997, 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. Increased technology transfer was also emphasized.

This resulted in MEND 2000, a three-year program that officially ended in December 2000. The program was funded equally by the Mining Association of Canada (MAC) and Natural Resources Canada (CANMET). The MEND 2000 objectives 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.

1.3.8 MEND3

In 2000, members of the MEND 2000 Steering Committee, together with their representative constituencies, reviewed the current and future needs of Canadian stakeholders in addressing acidic drainage. They recommended that a renewed national ARD research initiative called "MEND3" be launched in 2001. The overall mission of MEND3 is to provide leadership and guidance in ARD research on Canadian priority issues, within an international context. MEND3

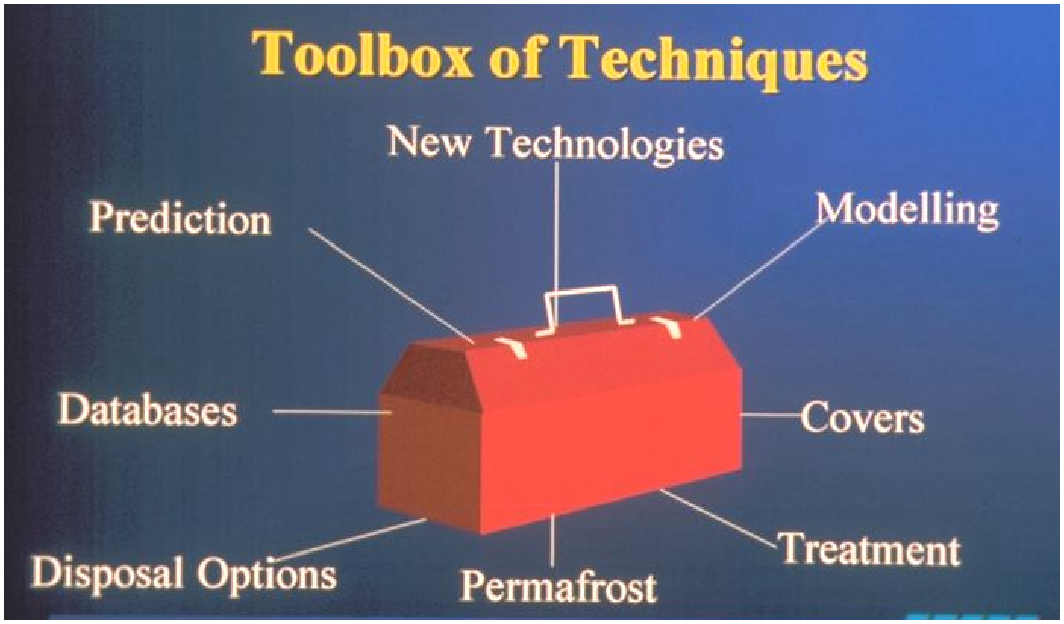
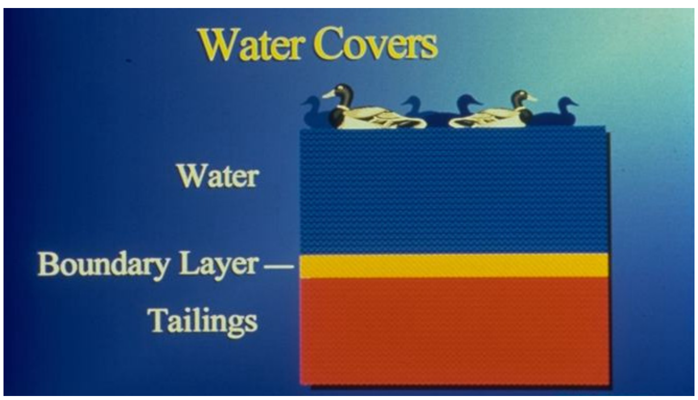


Plate 24. Toolbox of MEND Technologies

a)



b)

Plate 25. Examples of MEND-Developed Technologies.
a) Water Covers b) Dry Covers

is intended to be a phased research program, carefully focused on prioritized Canadian national and/or regional needs, with modest administration costs. This is a proactive program that will maximize value from scarce resources, involve many stakeholders and provide a regional link to international efforts. The first year, 2001, will be used to lay the initial groundwork for a possible future multiyear program.

1.3.9 CONCLUSIONS

The benefit of the MEND and MEND 2000 programs has come through the sharing of experiences, the 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). The study concluded that:
    - There is 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 program has been recognized as a model for industry-government cooperation.

MEND is thus a good example of a successful, multi-stakeholder initiative addressing a technical issue of national importance, and has been a model for cooperation among industry, various levels of government and NGOs. The program has significantly advanced environmental management practices and thus contributed to the long-term sustainability of the mining industry.

1.4 MEND AND RELEVANT PUBLICATIONS

MEND Reports are cited in Appendix D.

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Boswell, J., Hattingh, N. and de Waal, D. 2000. *Communication with the Public about Tailings Projects.* In: Proceedings of the 7th International Conference on Tailings and Mine Waste '00. Fort Collins, Colorado. 23-26 January. pp. 381-391.

ICME - International Council on Metals and the Environment 2000. The Global Mining Initiative. Key Article Contributed by Sir Robert Wilson, Chairman Rio Tinto. ICME Newsletter Vol 8, No. 3.

ISO – International Organization for Standardization. 1996. ISO 14001, Environmental Management Systems – Specification with Guidance for Use. First Edition. 1 September.

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.

MAC – The Mining Association of Canada. 1998. A Guide to the Management of Tailings Facilities. September.

Martin, T.E. and Davies, M.P. 2000. *Trends in the Stewardship of Tailings Dams.* In: Proceedings of the 7th International Conference on Tailings and Mine Waste '00. Fort Collins, Colorado. 23-26 January. pp. 393-407.

SENES Consultants Limited 2000. State-of-the-Art of Risk Assessment Application to ARD. Report prepared for INAP - The International Network of Acid Prevention. April.

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

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

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.

APPENDIX A – ACIDIC DRAINAGE

A.1 ACIDIC DRAINAGE

Detailed descriptions of the theoretical basis for sulphide oxidation are given in MEND reports and in the technical volumes of the MEND Manual. The following is a general overview of the acid generation process, treatment, and acidic drainage liability.

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. Key anthropogenic sources include waste rock and tailings produced as by-products of mining, quarrying and mineral processing; exposed rock faces in road cuts and road fill; and other rock fill used in construction.

Mines are the major source of acidic drainage because sulphide minerals are often concentrated in the geological environments that host 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 which increases 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 pyritic slates.

A.1.1 SULPHIDE MINERAL OXIDATION

Sulphide minerals can, under suitable conditions, react with water and oxygen to produce an acid by-product. The oxidation of pyrite (FeS_2), a predominant sulphide mineral, is shown by Equation A.1. The reaction can be catalyzed by bacterial (e.g. *Thiobacilli*) activity under acidic conditions.

$$FeS_2 + \frac{15}{4} O_2 + \frac{7}{2} H_2O \rightarrow Fe(OH)_3 + 2\ SO_4^{2-} + 4H \qquad \text{(A.1)}$$

The sulphide oxidation process is subject to a range of variables including, but not limited to, mineral surface area, solution pH, temperature, the availability of oxygen and water, and the presence and availability of sources of alkalinity (e.g. carbonate and silicate minerals). Uncontrolled acid generation leads to acidified runoff and seepage. Under controlled conditions, the availability of oxygen or water can be reduced to very low levels such that the oxidation process can, for practical purposes, be brought to a stop.

Acidic drainage can 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 elements such as Zn, Cu, Cd, Pb, Co, Ni, As, Sb and Se. Rainfall and snow-melt flush leachate from the waste sites. Acidic drainage, if not treated prior to release from the mine site, can adversely impact the receiving environment.

Naturally occurring alkalinity, such as carbonate minerals and carbonate ions in solution, can partially or completely neutralize acidity *in situ*. When this situation occurs, the resulting non-acidic leachate is likely to have low iron concentrations[1] but may contain elevated concentrations of sulphate, calcium and magnesium. Natural neutralization through 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, hydroxides and oxyhydroxides in the pH 6 to 7 range.

There can be a time lag between the beginning of the sulphide oxidation process and the appearance (if at all) of acidic drainage. Acid may be generated and released by high sulphur wastes having small amounts of carbonate minerals a few days after exposure. In contrast, low sulphur (< 2%) wastes with some carbonate may not release acid for years or decades.

Once the oxidation of iron sulphide minerals is initiated, the rate of oxidation tends to increase until a peak rate is reached. Then, the general trend is for a long-term decrease in acidity release. As readily accessible mineral-grains are consumed, the reactive mineral surfaces shrink and oxidation product coatings limit the reactivity of the remaining sulphide solids. The rate of decrease is determined by numerous factors but is mainly due to the reactivity of the sulphide minerals, the size of particles, and the availability of other reactants (i.e. oxygen and other oxidants). A decrease in oxidation rates may not be readily apparent in the mine waste drainage because oxidation products can be stored and released over a long period of time, and/or during flushing events, at a rate that is controlled by the solubility of the oxidation products. At some sites where sulphidic wastes were disposed without the benefit of recently developed technologies to prevent and control acid generation, acid generation will likely persist for hundreds of years.

<u>Seasonal Effects:</u>

The release of acidity from mine wastes is controlled to varying degrees by seasonal precipitation (e.g. transport medium). It has been observed that:

- Base flow conditions develop during dry spells. 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-melt 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 loadings decrease 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.

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

Treatment:

Acidic drainage can be treated using chemical or passive processes. Chemical treatment is most often accomplished using a limestone-derived alkali. Equation A.2 shows the neutralization of sulphuric acid to produce gypsum ($CaSO_4 \bullet 2H_2O$). Additional lime is typically required to raise the solution pH and precipitate dissolved metals in hydroxide form.

$$H_2SO_4 + CaCO_3 + H_2O \rightarrow CaSO_4 \cdot 2H_2O + CO_2 \tag{A.2}$$

Passive treatment options include constructed wetlands, alkalinity producing systems, microbial reactor systems, biosorption systems and reactive barrier walls. The application of passive systems in Canada is limited by climatic conditions. However, the use of passive systems, or hybrid active-passive systems, can be beneficial when conditions are suitable (e.g. as a secondary treatment).

At active mine sites (and many inactive mine sites), systems are operated to collect and treat effluents and seepage, and prevent downstream environmental impacts. 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 in the long term from the acidic drainage effluent can exceed the volume of tailings and/or waste rock *in situ*. Storage capacity could become an issue for decommissioned mine sites.

A.1.2 ACIDIC DRAINAGE LIABILITY

Acidic drainage is the largest environmental liability facing the Canadian mining industry, and to a lesser extent, the public through abandoned mines.

In Canada:

Estimates for Canada in 1986 showed that acid generating waste sites totalled over 12,000 hectares of tailings and 350 million tonnes of mine waste 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 A-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 A-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 A-1
Estimated Quantities 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 A-2
Estimated Quantities of 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 A-3. The assumptions made to calculate the reclamation and maintenance costs for the various options are presented in MEND 5.8e.

Table A-3
Estimated Liability for Acidic Drainage from Mine Wastes

Waste	Options	$Billions
Tailings	Collect and Treat	1.5
	Water Cover	1.5
	Dry Cover	3.2
Waste Rock	Collect and 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-and-treat water for a very long time, but such practice raises concerns about treatment by-product disposal and sustainability of the process.

<u>Outside of Canada:</u>

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 U.S.$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 (U.S. EPA). The U.S. EPA estimated total rehabilitation costs at approximately U.S.$175 million;
- More than U.S.$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 U.S.$500-U.S.$1,200 million (Murray *et al*. 1995);
- The Mineral Policy Center in the U.S. has estimated that there are 557,000 abandoned mines in 32 states, and that it will cost between U.S.$32 - $72 billion to remediate them (Bryan 1998); and
- The 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 U.S.$100 billion.

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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, WV. pp. 13-14.

APPENDIX B – 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 étude 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.
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APPENDIX D – 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 revisé 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.