contaminated soils were collected in a lined holding pond. A system consisting of a combination of chemical treatment and membrane filtration was implemented to treat the contaminated discharge.

The system consisted of three chemical pretreatment steps followed by membrane filtration. The study does not provide detailed information on the membrane step but from the results it seems that RO or a tight NF membrane was likely used.

The first two steps involved the precipitation of the radioactive elements, uranium and radium and the removal of arsenic and selenium using reduction and co-precipitation followed by settling. In the third pretreatment step, the remaining metals were precipitated by lime addition. The stream was further polished and treated by membrane filtration. The treatment system consistently met the discharge limits of the time and a flux of 250 US gal ft^{-2} membrane area per day (425 L m^{-2}) was maintained for a 200 US gpm unit design. Table 8.10 provides the concentrations of the different species in the three membrane streams. No capital or operating cost data were reported in the study.

Table 8.10. Maximum groundwater contaminant levels and membrane treatment results at Canonsburg, UMTRA site (Tiepel and Shorr, 1985).

Metals and other Assays	Concentration (mg/L)				
	Groundwater	Feed	Concentrate	Permeate	Discharge Limit*
Ra	690	1.00	3.60	0.6	3.00
U	13	6.40	2.60	0.001	2.00
Ag	-***	0.03	0.03	0.01	0.01
Cd	12	0.076	0.012	0.01	0.20
Cr	5.5	4.60	5.40	0.06	0.05
Cu	16	2.00	2.00	0.03	0.20
Fe	-	14.80	350	0.04	3.00
Mn	-	1.61	1.70	0.02	4.00
Ni	18	0.21	0.13	0.06	0.20
Pb	12	1.00	1.0	0.10	0.20
Zn	2	0.16	6.80	0.008	0.40
Se	36	-	-	-	-
As	10	-	-	-	-
pH	6-8	6-8	10	6-9	6-9
TSS	20-3,000	-	-	-	-
TOC	13	-	-	-	-

*Monthly average discharge limit; ** pCi/L; *** data not reported

8.5. Black Hawk Colorodo Pilot

Ultrafiltration ceramic and polymeric membranes were used to clean-up the acidic drainage/heavy metal contamination (Stewart *et al.*, 1997).

Site description

Since the late 1850's, the areas around the towns of Black Hawk and Central City, Colorado, have been mined for gold, silver, lead, zinc and copper. In the late 1980's, the area was classified as a Superfund site by the US Environmental Protection Agency. Early placer mining, followed by underground mines resulted in the disposal of large volumes of waste rock and tailings over a large and wide area. This resulted in the discharge of heavy metals from the waste rock and mine tailings stored at the area into the surface water streams. Over 800 abandoned mines and tunnels still exist in the area and many are still discharging acidic mine water containing high concentrations of heavy metals.

Process description

The goal of the study was to identify an efficient and cost-effective treatment system for the removal of heavy metals without the expense of a clarifier system. Due to the site constraints, a system with a minimized footprint was also required. A comparison was made between a conventional clarifier, a ceramic membrane system and a polymeric membrane system. The cost data from the study were normalized to a 250 US gpm sized system for the purposes of comparison.

The first system consisted of a general clarification step with pH adjustment followed by flocculation and sedimentation in a rectangular clarifier. This system was able to remove approximately 70-80% of the heavy metals but required a large land area in order to accommodate the required retention times for coagulation/flocculation and sedimentation.

The second system was a polymeric membrane system that had a footprint of only 10% of that required for the conventional system. This system had significantly better performance than the first system with removal rates of over 90%. After several months of operation the polymeric membranes became brittle and failed. The system throughput was 10 US gpm and the trans-membrane pressure was 35-40 psig. No information was provided on the system maintenance requirements. Any pH adjustment was made prior to the membrane skids and the concentrate stream was neutralized and the sludge was pressed and landfilled.

The third system was a tight ceramic MF membrane system developed by BASX systems with a pore size of 0.2 μm. The system was more robust than the polymeric system and yielded heavy metals removal of over 99% in most cases, and the operating costs were reduced by 30%. The system throughput was 10 gpm and the trans-membrane pressure was 35-40 psig. Table 8.11 shows the heavy metal removal efficiencies of the three described processes.

Process economics

The capital costs calculated and presented here were calculated over a 10-year life of the system. The reported values are the present value for 1997 and the cost data as mentioned earlier were normalized to represent a 250 US gpm system. It should be noted that the capital and operating costs could vary widely based on the effluent stream conditions and compositions as well as the site conditions. Table 8.12 provides the capital and operating costs of the three systems that were tested.

Table 8.11. Heavy metal removal efficiencies of the processes tested at Black Hawk, Colorado.

Process	Metal	Removal Efficiency (%)
Clarifier	Cadmium	0-85
	Chromium	> 99
	Lead	90-95
	Manganese	0-3
	Zinc	0-90
Polymeric Membrane System	Cadmium	85-95
	Chromium	>99
	Lead	>99
	Manganese	50-80
	Zinc	85-95
Ceramic Membrane System	Cadmium	90-99
	Chromium	>99
	Lead	>99
	Manganese	70-90
	Zinc	90-95

Table 8.12. Comparative capital and operating costs for treatment of AD at Black Hawk, Colorado.

Capital Costs ($US)			
Cost Item	**Ceramic Membrane System**	**Polymeric Membrane System**	**Conventional Treatment (coagulation/flocculation/ sedimentation) System**
Estimated capital costs for a 250 gpm treatment plant	1,900,000	1,800,000	4,200,000
Annual Operating Costs ($US)			
General building and equipment maintenance	20,000	20,000	100,000
Treatment chemicals	60,000	78,000	255,000
Sludge disposal	20,000	20,000	25,000
Operator labor	30,000	90,000	120,000
Monitoring costs	18,000	18,000	18,000
Power costs for pumping	80,000	80,000	0.0
Membrane replacement cost	0.0	100,000	0.0
Contingency (15%)	34,200	60,900	77,700
Total costs	262,200	466,900	569,800
Present value annual costs (1997) for the 10 year life of the plant	1,611,105	2,868,898	3,660,319

The cost data show that even if an investment had been made in a conventional system, a switch to ceramic membrane system would result in a lower cost over the 10 year life of the system.

8.6. Debiensko Coal Mines, Katowice, Poland

Mine water treatment and recovery for zero liquid discharge at Polish mines were described in detail by Solomon *et al.* (1989), Bostjancic and Ludlum (1996), and Sikora and Szyndler (2004).

A brief summary of the integrated treatment process extracted from the above publications is provided below.

Polish mines discharge a massive amount of contaminated mine water each day, an estimated 2,500 m^3/min or approximately $3.6x10^6$ m^3/d. The water contains approximately 600 mg/L to 120,000 mg/L total dissolved solids, which is mostly common salt (NaCl). About 60% of this drainage can be recovered and used for drinking water or in agriculture and/or other industries. The remaining, approximately $1.44x10^6$ m^3/d, are saline waters that are discharged directly to local rivers causing substantial damage to Polish water reservoirs.

At the Debiensko Coal Mines a plant was constructed to treat this brackish water. It was designed by Polish engineers and scientists using water treatment technologies from the U.S. and Sweden. The plant recovered 10,500 m^3/d of drinking and process water, ~ 4,500 m^3/d of distilled water, 250 tonnes/d of pure sodium chloride for sale, and ~ 25 tonnes of calcium sulphate.

The water purification was conducted in the following five stages: pretreatment, membrane filtration using reverse osmosis (RO), brine concentration, salt crystallization and purge treatment. The cost for the entire desalination plant was about $60 million USD. The pretreatment system accounted for about 40% of the cost. Table 8.13 shows the products and costs of production of the desalination plant at Katowice.

Table 8.13. Products and cost of production from mine drainage at Katowice, Poland. The prices are in U.S. Dollars (adapted from Sikora and Szyndler, 2004).

Product	Quantity per day	Price
Products from mine drainage		
Distilled water	4,500 m^3	\$0.8 per m^3
Drinking water	9,800 m^3	\$0.2 per m^3
Salt tablets for water softening	150 tonnes	\$40 per tonne
Bag and bulk salt	250 tonnes	\$40 per tonne
Products from crystallizer purge		
Lower quality salt (animal feed)	30 tonnes	\$15 per tonne
Iodine to chemical industry	54 kg	\$4 per kg
Bromine to chemical industry	280 kg	\$0.3 per kg
Carnallite for fertilizer	12.5 tonnes	\$90 per tonne
Magnesium chloride for bricks	13 tonnes	\$60 per tonne

The pretreatment section prevented the fouling of the RO membranes in the reverse osmosis section. It consisted of the following components:

- Feed water dosing with an algaecide;
- Sedimentation with polymer dosing;
- Disinfection, chlorination and intermittent shock treatment with sodium bisulphate;
- Flocculation with alum and acid dosing for pH control;
- Filtration in dual media sand, anthracite and granular activated carbon filters; and
- Sludge thickening and disposal.

The pretreated water was purified in a reverse osmosis system consisting of the following stages.

- A two-stage microfiltration section containing 50 μm washable / reusable steel baskets and 5 μm disposable cartridge filters;
- A RO system consisting of spiral wound RO membranes contained in more than 500 vessels and pressurized to approximately 6-7 MPa (870 – 1000 psig). The RO system concentrated the saline water to ~ 80,000 – 90,000 mg/L total dissolved solids (TDS);
- The permeate was used as drinking water after de-carbonation, chlorination and lime treatment; and

- The RO membranes were cleaned periodically with a prepared acidic solution, which was neutralized after washing.

The concentrate or reject from the RO section was concentrated further in brine concentrators, which were vertical tubes with falling film evaporators driven by vapor compressors. The falling film design gave a high heat transfer coefficient. The feed water was concentrated to near the point where sodium chloride would normally precipitate. Calcium sulphate crystals were added as seeds to the input feed solution at the startup, which gave the precipitating salt a place to attach and remain in suspension without crystallizing.

In the crystallizer circuit, about 60% of the saturated brine from brine concentrators, concentrated to approximately 260,000 mg/L total dissolved solids (TDS) and 3000 mg/L total suspended solids (TSS) was sent to the pre-heater of a forced-circulation, submerged-tube crystallizer. The remaining 40% of the feed was sent to the elutriation leg of the crystallizer. The salt was allowed to crystallize and the circuit is purged periodically.

The crystallizer purge treatment, using chemical and thermal methods, was used for the recovery of chemicals and distilled water. The following technologies were used to recover chemicals from the crystallizer purge:

- Calcium sulphate precipitation;
- Thermal pre-concentration and additional sodium chloride crystallization, iodine and bromine desorption and adsorption;
- Final stage thermal concentration and sodium chloride crystallization;
- Carnallite crystallization; and
- Magnesium chloride crystallization.

Using these integrated water treatment processes, the following products were recovered from the mine water:

- Distillate – approximately 65 m^3/d;

- Sodium chloride – approximately 30 tonnes/d;
- Carnallite – approximately 4,200 tonnes/year;
- Magnesium chloride – approximately 4,400 tonnes/year; and
- Iodine and bromine – approximately 110 tonnes/year.

8.7. Newmont - Gold Leaching Operation in Peru

Another example of a membrane application in mining operations is a full-scale plant operated by Newmont Mining Corporation in Yanacocha, Peru.

The gold mine produces approximately 3 Millon oz. gold per year. It utilizes a cyanide heap leaching process for gold and silver recovery. The company faces tight environmental discharge criteria which were deemed to be too costly to meet individually using chemical treatment options for excess water from the gold leaching operation during the wet season. Additional constraints for the company were limitations in cyanide concentrations which could be chemically treated prior to discharge of excess water, which resulted in reduced gold and silver production and gold lost during release of the treated water. Newmont commissioned a 1500 US gpm membrane plant, manufactured by Harrison Western Group, in 2004 that allowed the company to meet its discharge requirements, contain gold losses and significantly reduced its water treatment costs. The membrane system also increased precious metal recovery.

The feed to the membrane plant is from the Merrill-Crowe barren solutions, which is a diatomaceous earth filtered feed. The permeate contains some residual free cyanide, which is treated by alkaline chlorination and neutralization of the effluent and the membrane concentrate returns some of the free cyanide, the bulk of the metal cyanide complexes, metal oxyanions and nitrates to the leaching process. Some preliminary problems with fouling, due to a mercury amalgam forming on the surface of the membranes from trace residual gold precipitate passing through the filters, were solved utilizing a cyanide washing protocol. The plant is fully automated and has run unattended at the site during road blockage incidents.

Due to the success of the process, the company installed an additional 6000 US gpm capacity in 2005 (Newmont, 2007; Harrison Western, 2007). Detailed information on the process and its economics was not available.

10. CONCLUSIONS

The information presented in this review shows that membrane separation is an efficient and cost-effective technology for acidic drainage and mine effluent treatment. Comparison with conventional treatment technologies has also shown that membrane separation, if properly designed and operated, can provide superior discharge water quality and much improved treatment results while offering lower capital and operating costs. Membrane separation, however, cannot completely replace conventional treatment technologies and is not a stand-alone treatment option. Membranes can be a powerful tool for volume reduction and waste minimization, allowing for the recovery and recycle of water and other potentially valuable by-products from AD and other effluents such as acid, gypsum, heavy metals and sulphur. Because of the volume reduction that membrane separation offers, the footprint and capital costs of the accompanying conventional treatment options such as clarifiers and other chemical treatments could be substantially reduced.

Due to the composition of AD and other mining streams that require treatment, the most significant issue encountered with membrane separation in mining applications is membrane fouling and brine disposal. Some of the technical issues that drive membrane research and technology development, with the goal of improving the performance and reducing cost, are as follows:

- Membrane fouling – lowering membrane replacement costs, maximizing recoveries;
- Pretreatment as a measure of fouling control;
- Maximizing water recoveries; and
- Brine disposal or treatment and minimizing its associated costs.

The Global Acid Rock Drainage Guide, Version 0.8

Chapter 1

From GARDGuide

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1.0 The Global Acid Rock Drainage Guide

The GARD Guide

1.1 Introduction

Development of this Global Acid Rock Drainage Guide (GARD Guide) was sponsored by the International Network for Acid Prevention (INAP) with the support of the Global Alliance. It is the property of INAP. Access and use of the GARD Guide is granted by INAP under certain conditions.

This GARD Guide deals with the prediction, prevention, and management of drainage produced from sulphide mineral oxidation, often termed "acid rock drainage" (ARD), "saline drainage" (SD), "acid mine drainage" or "acid and metalliferous drainage" (AMD), "mining influenced water" (MIW), and "neutral mine drainage" (NMD). The GARD Guide also addresses metal leaching caused by sulphide mineral oxidation. While focused on mining, the technology described will be helpful to those practitioners that encounter sulphide minerals in other activities (e.g., rock cuts, excavations, tunnels). Some of the approaches in the GARD Guide are also relevant to issues arising from reactive non-sulphide minerals.

This Version of the GARD Guide

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- Last Updated: December 13, 2010
- Property of the International Network for Acid Prevention (INAP)
- For further information or to provide comments and contributions to updates of the Guide, please contact: INAP at terrence.chatwin@inap.com.au (mailto:terrence.chatwin@inap.com.au)

The GARD Guide is intended as a state-of-practice summary of the best practices and technology to assist mine operators, excavators, and regulators to address issues related to sulphide mineral oxidation. The GARD Guide will be of interest to the following:

- Mining and mining service companies
- Governments (national regulatory or land management agencies, IFC, World Bank, regional development agencies etc.)
- Consultants
- Researchers/Educators/Academia
- Community/Communities of interest
  - Bankers
  - Non-governmental organizations (NGOs)
  - Indigenous Peoples

The GARD Guide is a technical document designed primarily for a scientist or engineer with a reasonable background in chemistry and the basics of engineering with little specific knowledge of ARD. The target audience is adapted from a model developed by the PIRAMID Consortium (2003).

> "The document assumes the reader to be a scientist or engineer with a reasonable background in chemistry and the basics of engineering, albeit with no specific knowledge of acid rock drainage. The underlying science and technology of ARD are discussed in sufficient detail that the reader can understand their application, but the discussion stops short of being a formal scientific treatise on the relevant aspects of, for example, geochemical kinetics and solute transport hydrodynamics. Rather, the document guides the reader through the logical framework of ARD management enabling them to quantify the nature of the problematic drainage, and the potential for management that exists on the site, leading to the selection of the most appropriate form of prevention and remediation."

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1.1.1 Acid Rock Drainage

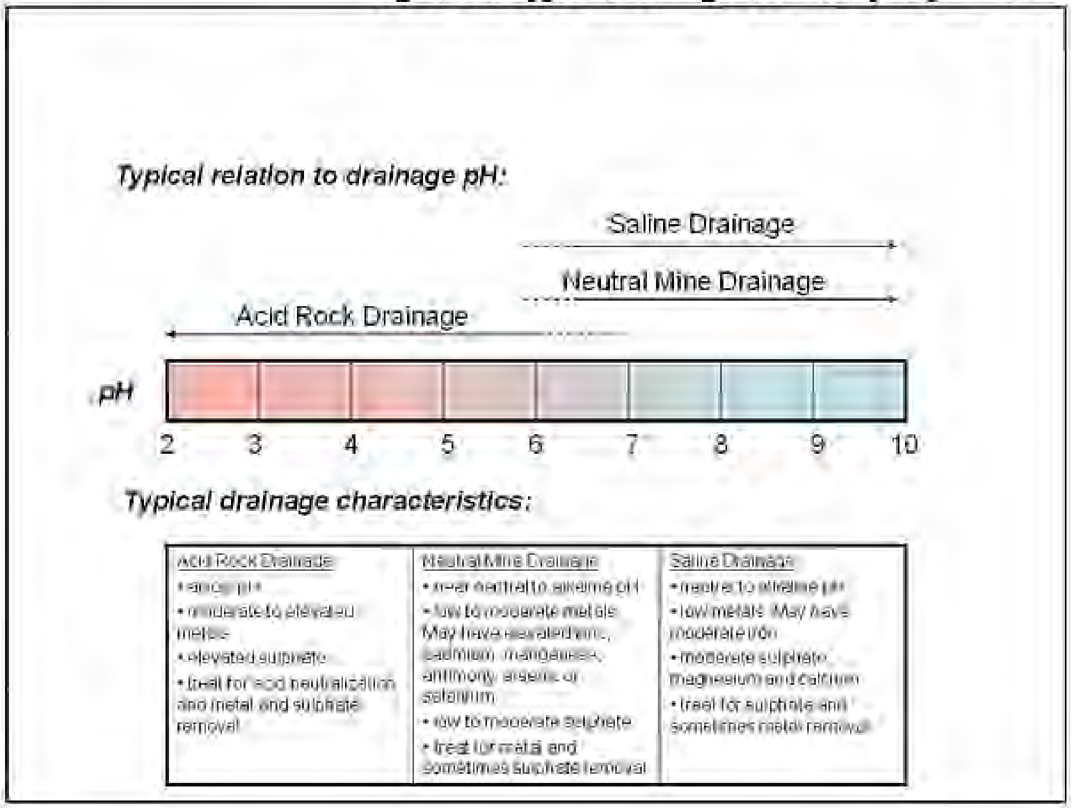
(http://www480.pair.com/sturner/gardwiki/index.php/Chapter_1#1.1.1_Acid_Rock_Drainage)
Acid rock drainage is formed by the natural oxidation of sulphide minerals, together with reactions of the base minerals in the rock, which are exposed to air and water. Activities that involve the excavation of rock with sulphide minerals, such as mining, accelerate the process because such activities increase the exposure of sulphide minerals to air, water, and microorganisms. The drainage produced from the oxidation process may be neutral to acidic, with or without dissolved heavy metals, but such drainage always contains sulphate.

ARD results from a series of reactions and stages that usually progress from near neutral to more acidic pH conditions (see Chapter 2). In addition to ARD, neutral mine drainage or saline drainage may result from the oxidation process where there are sufficient base minerals to neutralize the ARD. NMD is characterized by elevated metals in solution at near neutral pH. SD contains high levels of sulphate at neutral pH without significant metal concentrations and saline drainage's principal dissolved constituents then are sulphate, magnesium, and calcium ions.

Although the water quality resulting from sulphide mineral oxidation does not lend itself to precise compartmentalization, the accompanying chart illustrates the various types of drainage (Figure 1-1). Neutral mine drainage and saline drainage can occur together (i.e., near neutral pH with elevated metals and sulphate).

The GARD Guide addresses ARD, NMD, and SD where contaminants are released from solid to liquid phase by the oxidation of sulphide minerals. For simplicity in the GARD Guide, drainage produced by sulphide mineral oxidation is referred to simply as ARD except where specific aspects of ARD, NMD, and SD formation or drainage characteristics are important to the application of a particular technology or management approach. In those cases, the specific terms NMD and SD are used.

Figure 1-1: Types of Drainage Produced by Sulphide Oxidation



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1.2 Acid Rock Drainage Management - The Business Case

ARD formation is difficult to stop once initiated because it is a process that, if left unchecked, will continue (and may even accelerate) until one or more of the reactants (sulphide minerals, oxygen, water) is exhausted or no longer available for reaction. The process can continue to produce contaminated drainage from mining and other sulphide bearing rock wastes for decades or even centuries after mining has ceased. In temperate or tropical climates with high rainfall, large volumes of ARD can be produced requiring large and expensive collection systems, treatment plants and civil works (e.g., covers on mine wastes).

The cost of ARD remediation at primarily abandoned and "orphaned" mines in North America has been estimated in the tens of billions of U.S. dollars. Individual mines can face post-closure liabilities of tens to over a hundred million dollars for ARD remediation and treatment if the sulphide oxidation process is not properly managed during the mine's life.

Put simply, ARD can make a mine project uneconomic and present mine owners with technically challenging and expensive long-term management issues.

Failure to address ARD can impact a company's "social license to operate" through financial, political, and management issues such as the following:

- Unbudgeted reclamation costs with little or no internal resources (i.e., manpower, equipment, infrastructure, utilities and management) at the time of closure
- Contaminated water resources with adverse impacts on human health, flora, and fauna
- Unbudgeted increases of environmental remediation
- More stringent regulatory requirements which evolved over time
- Loss of corporate image, public acceptance, and stakeholder trust
- Loss of future mining opportunities
- Commitment of corporate resources to a mine that has long since ceased to provide economic value

> "Treating acid drainage once it has occurred, or mitigating environmental impact after it has occurred, is usually an admission that something has gone wrong either in the characterisation, planning, design or operation of a mine. It is Newmont's belief that acid drainage can be prevented if some key principles are followed throughout the life of a mine, from exploration through to closure." Paul Dowd, former Managing Director, Newmont Australia (Dowd, 2005)

Proper mine characterization, drainage quality prediction, and mine waste management can prevent in most cases, and minimize in all cases, ARD formation. However prevention of ARD must begin at exploration and continue throughout the mine-life cycle. The mining industry recognizes that continuous ARD planning and management is imperative to successful ARD prevention. Proper planning and management of ARD can prevent environmental impacts from occurring.

Many mines will not produce ARD because of the inherent geochemical nature of their mining wastes or very arid climatic conditions. Also, mines that have implemented well founded prediction and, where required, prevention and monitoring programs should also be able to avoid significant ARD issues. For example, Placer Dome Inc., a large gold and copper mining company, published information on the ARD and metal leaching potential and management plans for its 22 operating and closed mines (Placer Dome Inc, 1998 and 2003). Of the 22 mines, eight (36%) exhibited a potential for ARD and five others (23%) a potential for NMD (metal leaching), requiring that prevention and monitoring plans be developed and implemented. Only three (14%) mines actually produced ARD or NMD where water treatment of drainage was necessary; none of those mines had implemented ARD prevention measures from the start of operations.

A comprehensive approach to ARD management, as promoted by the GARD Guide, will reduce environmental risks and subsequent costs for the mining industry and governments, reduce adverse environmental impacts, and build public support for mining. The extent and specific elements of the ARD management approach that should be implemented at a particular mine or project will vary based on the potential to produce ARD and other site-specific factors.

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1.3 Scope and Objectives of the Global Acid Rock Drainage Guide

1.3.1 Scope

The potential for acidic drainage to form from mining has been known since at least 1556 and ARD was observed as early as 1698 associated with coal mining in Pennsylvania (BC Acid Mine Drainage Task Force, 1989).

Research into the process of ARD formation and methods to minimize its impact have been ongoing for more than 50 years. Much progress has been made, in the last 20 years in particular, through a number of research consortiums. As such, there is a considerable scientific and engineering guidance available on ARD through organizations such as INAP, MEND, the British Columbia AMD Task Force (BC AMDTF), the British Columbia Ministry of Energy, Mines and Petroleum Resources (BC MEMPR), ADTI, the Australian Centre for Minerals Extension and Research (ACMER), the South African Water Research Commission (WRC), The South African Department of Water Affairs and Forestry (DWAF), the Partnership for Acid Drainage Remediation in Europe (PADRE), and other programs. However, this research is generally available through disparate references and is not easily accessible. The research tends to be issue, commodity, or geographically (climate) centred. The objective of this GARD Guide is to consolidate and summarize the current information and to use global thinking on ARD management.

Many examples and case studies of ARD prediction and mitigation have been studied for the last 20 years that buttress and corroborate the more fundamental scientific research. The knowledge gained from both positive and negative field results contributes greatly to current and future ARD management plans and enhances the credibility of consultation processes on ARD. Also, application of ongoing science and engineering research supports continual improvement in ARD management.

This GARD Guide focuses on mining and pertains to ores, wastes (overburden, waste rock and residues/tailings), and mine workings (including in situ mining). The GARD Guide applies to the entire mining industry and all commodities produced by mining, including base metals, coal, iron ore, precious metals, diamonds, and uranium where the ores contain sulphide minerals[1]. The GARD Guide is applicable to the complete mine life cycle and to existing and historical ARD issues as well as future mines.

While much of the science in the GARD Guide is more broadly applicable, it does not specifically address the following:

- Acid sulphate soils, although reference is made to approaches and technologies from the acid soil literature where relevant to the management of sulphide mineral oxidation
- Dissolution of sulphate salts (e.g., jarosites and other hydroxyl-sulphates) that are produced by pyrometallurgical or hydrometallurgical processes (However, jarosites or other salts produced as intermediate products during sulphide oxidation under ambient conditions are considered.)

The technology described in the GARD Guide may be of value to those encountering or managing acid sulphate soils and pyrometallurgical or hydrometallurgical sulphate salts.

Additional Web links for organizations:

- MEND http://www.nrcan-rncan.gc.ca/mms-smm/tect-tech/sat-set/med-ndd-eng.htm
- the British Columbia Ministry of Energy, Mines and Petroleum Resources (BC MEMPR) http://www.gov.bc.ca/empr/
- ADTI http://inside.mines.edu/adti/ADTIMAIN.html
- the *Australian Centre for Minerals Extension and Research (*ACMER) http://www.acmer.uq.edu.au/index.html
- the South African Water Research Commission (WRC) http://www.wrc.org.za/
- The South African *Department of Water Affairs and Forestry* (DWAF) http://www.dwaf.gov.za/
- the Partnership for Acid Drainage Remediation in Europe (PADRE) http://www.padre.imwa.info/
- West Virginia Coal Mine Drainage Task Force - http://wvmdtaskforce.com/

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1.3.2 Objectives

The overall objective of the GARD Guide is to collate and facilitate worldwide best practice in prediction, prevention, and mitigation of ARD. It is a reference document for stakeholders involved in sulphide mineral oxidation and related waste management issues.

The GARD Guide has been prepared as a road map through the process of evaluating, planning, design, and management of ARD over the life cycle of mining. The GARD guide has also been prepared as a compendium of the concepts, the techniques, and the processes to be considered in successful ARD management over the mine-life cycle. It provides a broad, but not highly detailed, understanding of ARD technologies and management. However, a comprehensive approach to ARD management will be created where the concepts and guidance in the GARD Guide are translated into site-specific actions.

The GARD Guide is also a "compass" to identify more detailed information on ARD as it lists references for those looking for specifics on ARD technologies and approaches.

The GARD Guide will assist the reader to monitor the evolution of the sulphide oxidation process in mine wastes and identify when involvement of more experienced ARD practitioners is required to address a particular issue.

The GARD Guide is not a design document; design requires a high level of understanding and site-specific knowledge of a particular project or mine. Detailed design of ARD mitigation techniques will continue to be conducted by knowledgeable practitioners.

The following are specific objectives of the GARD Guide:

- Articulate the issues associated with sulphide mineral oxidation
- Improve the understanding of best global practice, customized where necessary for special geoclimatic conditions
- Promote a risk-based, proactive, consistent approach by encouraging planning for and implementation of reduction and control of ARD at the source
- Leverage the world's ARD expertise and share expertise with developing countries
- Support the 'Equator Principles' developed by a consortium of lending institutions and the International Council of Mining and

Metal's (ICMM's) objectives by achieving 'global best practice' in future mining projects

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1.4 Relation to Other Guides

There is a considerable body of knowledge on ARD management in the scientific and engineering literature. Many technical documents and guidelines have been produced that summarize certain aspects of the state-of-knowledge and in some cases provide guidelines for managing ARD. In addition, the series of International Conferences on Acid Rock Drainage (ICARD), BC MEND, ACMER, and other conferences regularly review ARD research and management. The ICARD proceedings in particular are valuable summaries of ARD technology and the reader is encouraged to review these proceedings, especially case studies.

Some Existing ARD Compendia

- Acid Rock Drainage At Enviromine, Enviromine http://technology.infomine.com/enviromine/ard/home.htm
- ARD Test Handbook, AMIRA International, May 2002 http://www.amira.com.au/
- MiMi – Results and Synthesis Report for Phase 1 1998-2001, MiMi, April 2003
- MiMi – Performance Assessment Main Report, MiMi,, December 2004
- Guidelines for Metal Leaching and Acid Rock Drainage at Minesites in British Columbia, Ministry of Energy and Mines, August 1998
- Draft Guidelines and Recommended Methods for Prediction of Metal Leaching and Acid Rock, Ministry of Energy and Mines, 1998
- Draft Acid Rock Drainage Technical Guide Volume 1, British Columbia Acid Mine Drainage Task Force Report, August 1989
- MEND Manuals, MEND, January 2001
- List of Potential Information Requirements in Metal Leaching/ Acid Rock Drainage Assessment and Mitigation Work, MEND Report 5.10E, January 2005 PDF http://www.mend-nedem.org/reports/files/5.10E.pdf
- Environmental Regulation of Mine Waters in the European Union, ERMITE http://www.ncl.ac.uk/environment/research/Ermite.htm
- Field and Laboratory Methods Application to Overburdens and Minesoils, Industrial Environmental Research Laboratory Office of Research and Developments U.S. Environmental Protection Agency, March 1978 www.techtransfer.osmre.gov/nttmainsite/Library/hbmanual/fieldlab/back.pdf
- Risk Assessment Framework For the Management of Sulfidic Mine Wastes, Australian Center for Mining Environmental Research, September 1999
- Industry Liaison Officer Report for the Management of Sulfidic Mine Wastes Project, Australian Center for Mining Environmental Research, February 2000 http://www.acmer.uq.edu.au/publications/handbooks.html
- Management of Sulfidic Mine Wastes and Acid Drainage, Australian Center for Mining Environmental Research, September 2000
- Manual of Techniques to Quantify Processes Associated with Polluted Effluent Form Sulfidic Mine Wastes, Australian Center for Mining Environmental Research, February 2000
- Comparison of Oxidation Rates of Sulfidic Mine Wastes Measured in the Laboratory and Field, Australian Center for Mining Environmental Research, February 2000
- Management of Sulfidic Mine Wastes – Current Australian Practice and Available Knowledge and Techniques, Australian Center for Mining Environmental Research, May 2000 http://www.acmer.uq.edu.au/publications/handbooks.html
- Determining the Toxicity Potential of Mine Waste Piles, USGS, June 2003 http://pubs.usgs.gov/of/2003/ofr-03-210/
- Acid Drainage Technology Initiative, ADTI Workbook Chapters: Introduction (in draft), Mitigation (in draft), Sampling and Monitoring, Pit Lake and Prediction (in preparation)
- On-site and Laboratory Investigations of Spoil in Opencast Collieries and the Development of Acid-Base Accounting Procedures, Usher BH, Cruywagen LM, de Necker E, Hodgson FDI, South African Water Research Commission Report Number 1055/1/03, 2003 http://www.wrc.org.za/Pages/DisplayItem.aspx?ItemID=7585&FromURL=%2FPages%2FAllKH.aspx%3F
- Acid –Base Accounting, Techniques and Evaluation (ABATE), Usher BH, Cruywagen LM, de Necker E, Hodgson FDI, South African Water Research Commission Report Number 1055/2/03, 2003 http://www.wrc.org.za/Pages/DisplayItem.aspx?ItemID=7586&FromURL=%2FPages%2FAllKH.aspx%3F
- Engineering guidelines for the passive remediation of acidic and/or metalliferous mine drainage and similar wastewaters.

European Commission 5th Framework RTD Project no. EVK1-CT-1999-000021 "Passive in-situ remediation of acidic mine / industrial drainage" (PIRAMID). University of Newcastle Upon Tyne, Newcastle Upon Tyne UK. 166pp.) (PIRAMID Consortium (2003) http://www.ncl.ac.uk/environment/research/PIRAMID.htm

- ASTM Method E-1915 Standard Test Methods for Analysis of Metal Bearing Ores and Related Materials by Combustion Infrared Absorption Spectrometry, Annual Book of ASTM Standards volume 03.06 (also standard method for humidity cell testing, SPLP (vol 11.04) and MWMP (vol 03.06)) http://www.astm.org/Standards/E1915.htm
- Best Practice Guideline Series, South Africa Department of Water Affairs and Forestry, 2006
- Managing Acid and Metalliferous Drainage, Australian Government Department of Industry Tourism and Resources, 2007

Some existing compendia of ARD technology are listed above. The GARD Guide summarizes and references these and other key literature and compendia on the assessment, prediction, control, and management of ARD. It refers the reader to more specialized state-of-the-art guides and summaries where they already exist. INAP has commissioned a separate review of the ARD literature (Wolkersdorfer, 2008).

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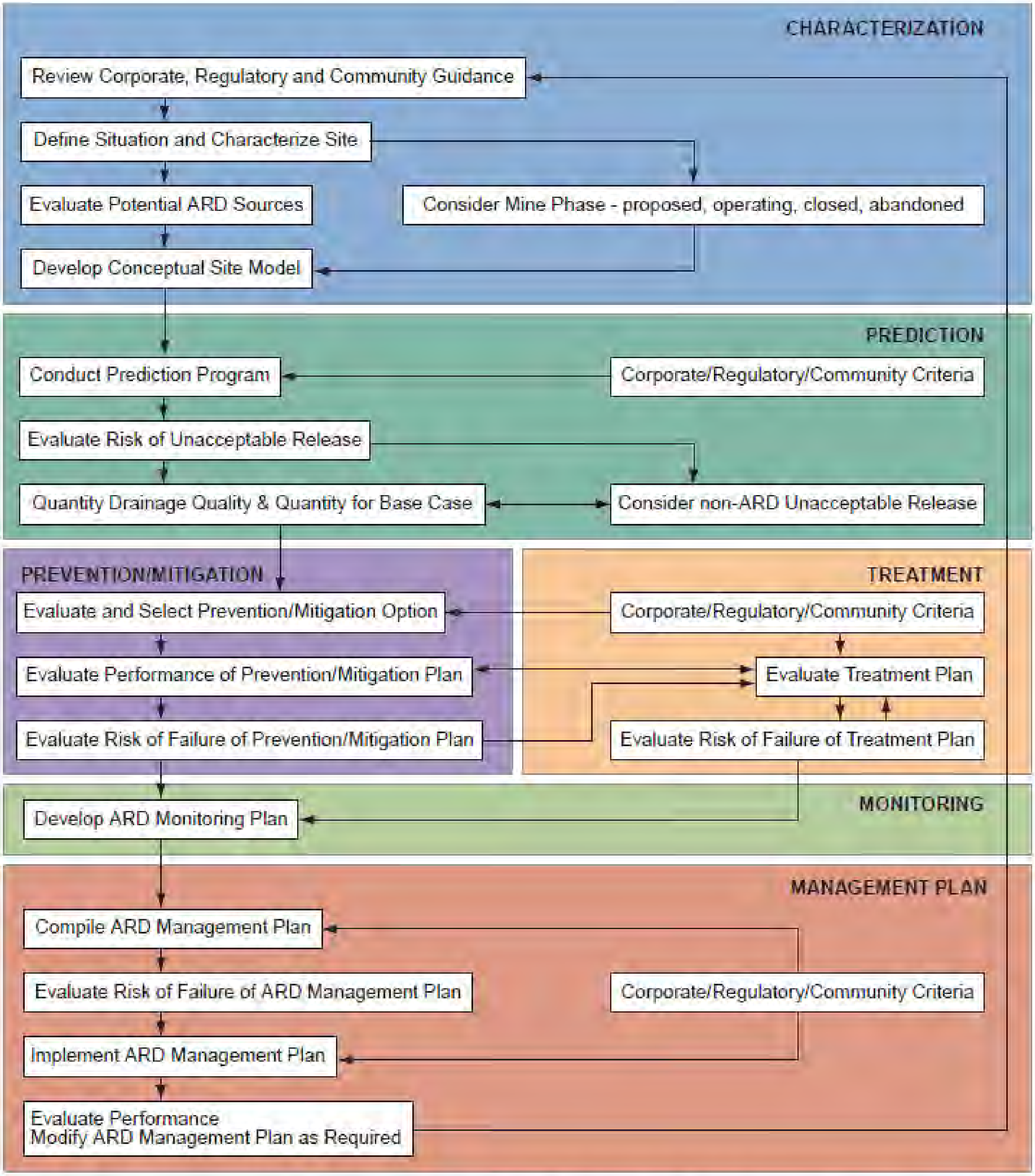
1.5 Approach of the Global Acid Rock Drainage Guide

The GARD Guide is based on a systematic approach to ARD management as shown in Figure 1-2. The approach proceeds from site characterization to preparation, and ultimately implementation of an ARD management plan. It includes a loop for verification and calibration of predictions and assessments as part of evaluating the performance of the ARD management plan.

Figure 1-2: Overall ARD Management Plan



Specific elements of the approach and appropriate technologies are described in more detail in this GARD Guide.

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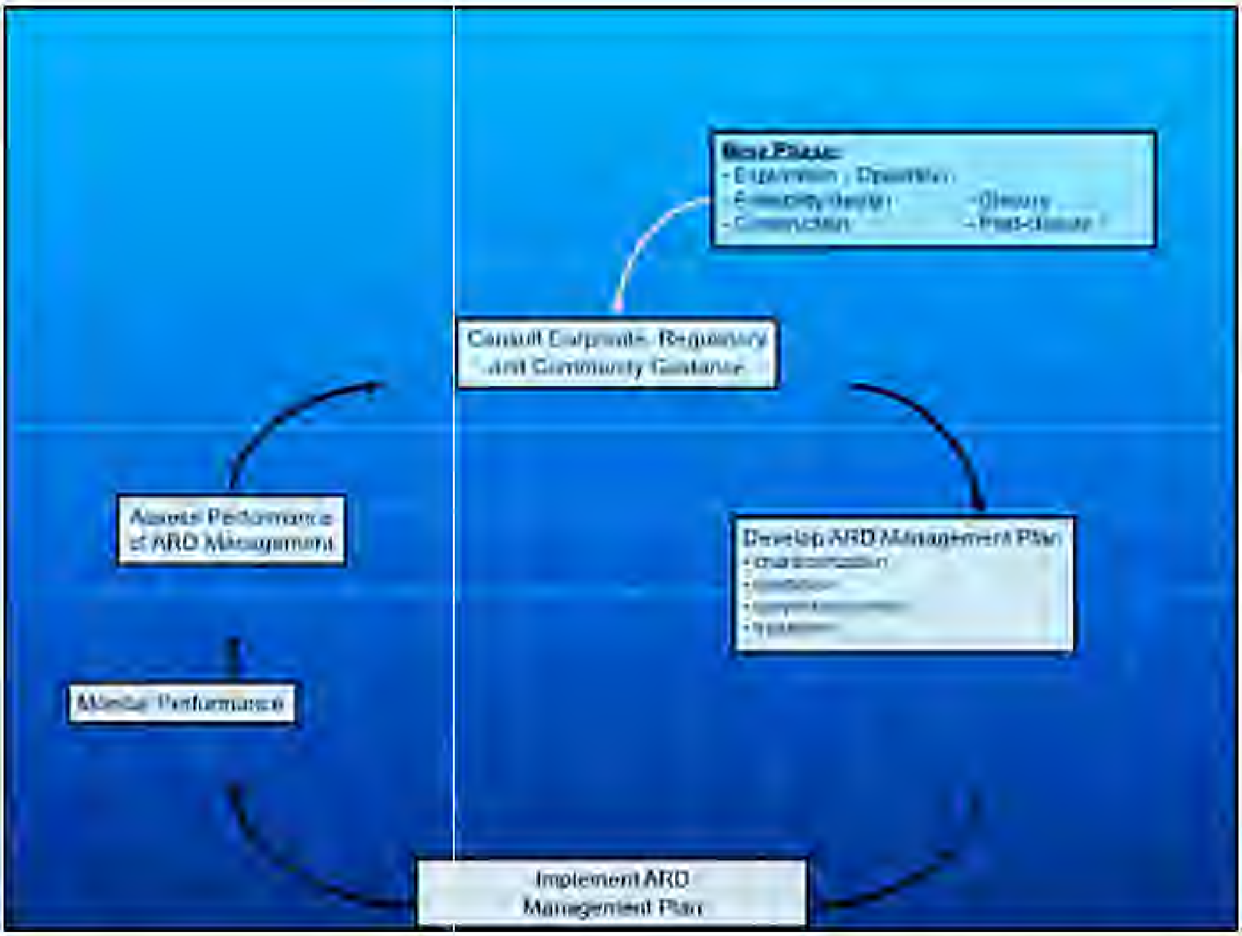
1.6 Application to Mine Phase

ARD management is applied at all phases of a mine from "cradle to cradle" as part of an environmental management system (EMS), which includes a continuous improvement process (Figure 1-3). (The term "cradle to cradle" characterizes the objective to return land used for mining to biologically productive use after mining is finished.)

Figure 1-3: Applying an Environmental Management System to ARD



The ARD management plan is based on technical understanding and knowledge but is defined within corporate policies, government regulations, and community expectations. The ARD management plan is based on site characterization and ARD/NMD/SD prediction science and incorporates engineering measures aimed at ARD prevention and control. Water treatment may be included in the plan as a contingency, or as a necessity for existing mines.

Implementation of the ARD management plan requires the use of management systems and communication between stakeholders. The plan's performance is monitored through a range of metrics usually based on evaluation of mine water quality. The overall performance of ARD management is evaluated against site-specific environmental requirements and the criteria established by corporate policies, government standards, and community expectations. In this way, the ARD management process is a continuous loop.

The level of assessment and planning for each phase of mining varies based on the degree of information available and the extent of rock excavation and the potential environmental impact. For example, relatively little disturbance and excavation of rock containing sulphide minerals usually occurs during exploration. However ARD management plans are required for exploration drilling, bulk samples, and test pits/underground workings. A poorly planned exploration drilling program could cause long-term ARD problems through disturbance of the natural groundwater conditions and provision of new vertical flow paths. In addition, site characterization, including ore and waste characterization and ARD prediction, must begin at the start of mineral exploration.

The approach to ARD management during the phases of mine development is discussed in more detail in Chapter 9.

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1.7 The Sustainable Development Approach

With its potentially wide-ranging and multigenerational consequences, ARD is an important "sustainable development" or "sustainability" issue. Environmental impacts of ARD can be serious and enduring. Depending on where a mine operates, ARD can also impact the well-being of people surrounding the mine, now and in the future. Poor management of ARD can not only harm the environment but also the mining industry's reputation and communities' acceptance of individual mining operations. Applying the concept of sustainable development, on the other hand, offers an opportunity to involve multiple stakeholders in ARD management, improve risk management, and optimize the socioeconomic and business benefits of a mining operation.

The Minerals, Mining and Sustainable Development (MMSD) Project, an effort initiated by nine of the world's largest mining companies, describes sustainable development as a goal to:

> "maximize the contribution to the well-being of the current generation in a way that ensures an equitable distribution of its costs and benefits, without reducing the potential for future generations to meet their own needs" (MMSD, 2002).

In practice, sustainable development requires an integrated, balanced, and responsible approach that accounts for short-term and long-term environmental, social, economic, and governance considerations. The economic benefit derived from mining can be an essential contributor to sustainable development. Environmental and social consequences of ARD detract from this significant benefit unless managed appropriately.

Sustainable development requires that the mining company engage stakeholders and find optimal solutions that minimize risk, maximize benefits to multiple stakeholders, and manage trade-offs. Fundamentally, the company must exercise socially responsible practices. As a particular mining project presents an ARD risk, how can the mining company best limit the risk and satisfy the needs of its stakeholders? Sustainable development requires the following:

- Looking for solutions to ARD issues from a whole-society perspective
- Applying proactive pollution prevention rather than reactive mitigation and treatment
- Implementing ARD prevention and mitigation throughout the whole mine-life-cycle perspective

Application of sustainable development principles to ARD management is discussed further in the GARD Guide (Chapters 10 and 11).

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1.8 Layout and How to Use the Guide

1.8.1 Layout

The GARD Guide is based on a "Wiki" model. Chapters and subchapters are constructed as pages. Internal links are provided for topics where more detail is available. Links to external websites are included to organizations and other more detailed or specific topic references. The application of management technologies is based on the ARD formation process described in Chapter 2. Chapters 3 to 8 build on elements in the 'knowledge map' presented in Figure 1-2. Each chapter is "stand alone" with key references and guidance. A **Glossary** of common terms and description of **Acronyms** is available. Each chapter contains tools (e.g., lists, tables, and figures) to assist the reader to apply the knowledge.

Most of the technologies and approaches in the GARD Guide are applicable to generic ARD issues. However, the technologies and approaches may need to be modified to address particular aspects of ARD, such as those related to the following:

- Commodities (coal or hard rock)
- Stage in mine life cycle
- Exploration
- Mine planning, feasibility studies, and design (including environmental impact assessment)
- Construction and commissioning
- Operation
- Decommissioning
- Post-closure
- Mine sources (e.g., in situ leaching, open pit, underground, tailings, waste rock etc.)
- Climate (wet or dry, temperate or hot or cold)
- High/moderate/low technology applications
- Types of drainage – ARD, NMD, or SD
- Sensitive community issues

Information on these special technologies or approaches is provided in the text, side bars, and tables, as appropriate.

Chapter 9, Acid Rock Drainage Assessment and Management, brings the technologies together and discusses their application while describing in more detail the risk approach, engineering design process, and management systems to ARD. The chapter describes how to prepare and implement the ARD management plan. Chapter 10, Communication and Consultation, describes how to communicate ARD issues within and outside an organization. ARD management must be fully incorporated into geological programs, mining, and milling, so effective communication between disciplines is critical. The chapter also describes the importance of knowledge management given the potential long life of ARD issues. Regulators and local communities must have a clear understanding of the risks of ARD and the effectiveness of approaches proposed to manage it.

Differences in approaches to sustainable development might affect how ARD technologies and management are applied. Sustainable development aspects are briefly discussed in most chapters of the GARD Guide and in more detail in Chapter 11 with respect to the possible future of ARD management. Chapter 11 also identifies research needs and a possible path forward to increase our understanding of ARD genesis, best practice, and management.

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1.8.2 How to Use the Global Acid Rock Drainage Guide

The GARD Guide contains 11 chapters, including this one. Readers are encouraged to, in the first instance, progress from one chapter to the next because the approach to ARD management is step-wise. Chapter 4, Characterization, in particular is an important step in implementing the ARD management approach because the application of technology must be based on a thorough knowledge of site conditions.

The tools provided in the GARD Guide will help the reader compile information for use by ARD specialist practitioners. The GARD Guide will also support the reader's participation in more detailed scientific investigations and engineering studies at a particular mine site (e.g., identify and collect rock and water samples and review the results of analyses). With the help of the GARD Guide and a site-specific ARD management plan, for example, an environmental coordinator will be able to work with other functional groups at a mine site (e.g., mine, mill, and plant services departments) to assist them in implementing the management plan within the overall mine operations and to monitor the plan's performance.

In general, readers are encouraged to apply the flowcharts and to use the tools in the GARD Guide to address a particular ARD issue. However readers must exercise caution and fully assess the relevance of a tool to their particular situation because ARD issues are often multifaceted and complex; a simple tool, therefore, may not fully apply. References and links in the GARD Guide should be used to access more detailed information on a specific aspect of ARD management relevant to a particular mine project or ARD management issue. An expert ARD practitioner or a suitably qualified person should be consulted in complex cases.

The GARD Guide is also a resource for teaching environmental aspects of mining to science and engineering students.

Finally the GARD Guide is a "living document" and will be updated periodically to reflect the results of ongoing research and advancing knowledge of ARD management technologies. The reader is encouraged to revisit the INAP website to access the most recent version of the GARD Guide and to provide INAP with comments on how the GARD Guide could be improved.

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1.9 Chapter References

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1. ↑ Although coal is not strictly "ore" as the term is used in hard rock mining, the reader should consider that the term "ore" also applies to coal where found in the GARD Guide.

Chapter 7

From GARDGuide

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7.0 Drainage Treatment

7.1 Introduction

This chapter contains an overview of the following topics related to mine drainage treatment:

- Objectives of and approach to mine drainage treatment
  - Risk-based approach
- Drainage sources, collection and management
- Treatment technologies including:
  - Active treatment
  - Passive treatment
  - Active/passive hybrids
  - In situ treatment
- Treatment residues and waste
- Recovery of useful byproducts
- Drainage treatment during mine closure and post closure
- Selection of appropriate treatment technology

The objectives and approach to treatment of the different mine water types depend on the category of mine water and the degree of treatment required.

The consideration of drainage treatment technologies covers the range of applications to the following:

- Different commodities, including coal, diamond, iron, gold, uranium, and precious and base metals
- Different phases of mining, including exploration, feasibility (assessment and design), construction, operation, decommissioning, and post closure

7.1.1 Risk-based approach

A risk assessment should evaluate all aspects of the treatment process using a standard Failure Modes and Effects Analysis (FMEA) approach, which evaluates risk based on consequence and likelihood.

There are five main areas that should be assessed: influent, treatment system, effluent, byproduct management, and site conditions.

Risks to be assessed for the influent can include, for instance, influent flow rates (excessively high and/or variable), contaminant concentrations (exceed type and concentration predicted), and influent pH. The treatment risks to be evaluated can include mechanical failure, power failure, plugging of substrate, piping or ditches, armouring of reactants, failure of reagent delivery system, failure of process control components, inadequate design volume of holding ponds, scaling of plant components, and shutdown due to labour disruption. Effluent management risks may include failure to meet compliance (total or dissolved metals, pH, etc.), effluent toxicity test failure, change in permit requirement, and inability to meet receiving environment water quality.