DRAFT ACID ROCK DRAINAGE TECHNICAL GUIDE

VOLUME II

Canada

BC

DRAFT ACID ROCK DRAINAGE TECHNICAL GUIDE VOLUME II

BRITISH COLUMBIA ACID MINE DRAINAGE TASK FORCE REPORT

Prepared for the:

British Columbia Acid Mine Drainage Task Force. Volume 1 was funded by Energy, Mines and Resources Canada and the British Columbia Ministry of Energy, Mines and Petroleum Resources under the Canada/British Columbia Mineral Development Agreement (1985-90). Volume II was funded by Environmental Protection, Environment Canada, West Vancouver Contract KA601-8-3976.

Prepared by:

Steffen Robertson and Kirsten (B.C.) Inc.
801 - 1030 West Georgia Street
Vancouver, B.C. V6E 2N7

In Association With:

Norecol Environmental Consultants
700 - 1090 West Pender Street
Vancouver, B.C. V6E 2N7

Gormely Process Engineering
612 - 1200 West Pender Street
Vancouver, B.C. V6E 2S9

May 1990

Canadian Cataloguing in Publication Data

Main entry under title:
Draft acid rock drainage technical guide

Vol. 2 has added caption title: Summary guide.
Co-published by: Government of British Columbia.
Includes bibliographical references.
ISBN 0-7718-8953-4

1. Acid mine drainage - British Columbia.
2. Mines and mineral resources - British Columbia - Waste disposal.
3. Sulphides - British Columbia.

I. British Columbia Acid Mine Drainage Task Force.
II. Steffen Robertson and Kirsten (B.C.) Inc.
III. Norecol Environmental Consultants.
IV. Gormely Process Engineering.
V. Canada.
VI. British Columbia.
VII. Canada. Environmental Protection Directorate.
VIII. British Columbia Acid Mine Drainage Task Force report.

TD899.M5D73 1990 622'.509711 C90-092147-1

DISCLAIMER

The purpose of this guide is to provide the user with an understanding of the process of acid rock drainage and to provide guidance and recommendations in the application of currently available technology. This guide is issued as a draft document with the intention of being updated as technology progresses. The user of this guide assumes full responsibility for the design of facilities and for any action taken as a result of the recommendations contained in this guide. Neither the Province of British Columbia Acid Mine Drainage Task Force nor the consultants who prepared this document may be held liable for the outcome of any action taken by the user.

REPORT 66002/2

ACID ROCK DRAINAGE
DRAFT TECHNICAL GUIDE
VOLUME II - SUMMARY GUIDE

Prepared for the
British Columbia AMD Task Force

Prepared by:

STEFFEN ROBERTSON AND KIRSTEN (B.C.) INC.
801 - 1030 West Georgia Street
Vancouver, B.C. V6E 2Y3

In Association with

NORECOL ENVIRONMENTAL CONSULTANTS
700 - 1090 West Pender Street
Vancouver, BC V6E 2N7

and

GORMELY PROCESS ENGINEERING
612 - 1200 West Pender Street
Vancouver, BC V6E 2S9

December 1989

TABLE OF CONTENTS
VOLUME II - SUMMARY GUIDE

LIST OF TABLES

LIST OF FIGURES

1.0 INTRODUCTION

1.1 Objective of this Summary Guide

In December 1988 the Province of British Columbia Acid Mine Drainage Task Force commissioned the preparation of a draft technical guide on acid rock drainage (ARD). The objectives of the guide are to provide the user with an understanding of the process of ARD and to provide guidance and recommendations in the application of state-of-the-art technology in prediction, control and monitoring of ARD. The guide consists of two volumes; Volume I being a more detailed technical guide, and this document which is the Volume II - Summary Guide.

The objective of this volume of the guide is to present a "stand-alone" summary and recommendations for prediction, control and monitoring of ARD. This summary guide refers the user to Volume I for technical detail and published literature wherever applicable. Volumes I and II of the Draft Technical Guide have been prepared for the Province of British Columbia Acid Mine Drainage Task Force by Steffen Robertson and Kirsten (B.C.) Inc. in association with Norecol Environmental Consultants and Gormely Process Engineering.

1.2 Definition of Acid Rock Drainage

Acid rock drainage is the term used in this Guide to define drainage that occurs as a result of natural oxidation of sulphide minerals contained in rock which is exposed to air and water. This phenomenon is often referred to as acid mine drainage (AMD), however it is not necessarily confined to mining activities but can occur wherever sulphide-bearing rock is exposed to air and water. Some natural springs are acidic, usually in the vicinity of outcrops of sulphide-bearing rocks. Not all operations that expose sulphide-bearing rock will result in acid drainage. Acid drainage will not occur if either the sulphide minerals are non-reactive or if the rock contains sufficient natural potential to neutralize the acid.

For practical purposes, the principal ingredients in the ARD process are; reactive sulphide minerals, oxygen and water. The oxidation reactions are often accelerated by biological activity. The chemical and biological reactions yield low pH water that has the potential to mobilize any heavy metals that may be contained in the rock. If alkaline material is available in the rock waste, the pH may be raised as a result of neutralizing reactions as the drainage passes through the waste. If water is available as a transport medium, the resultant drainage can contain products of the acid generation process, typically elevated metal levels and sulphate. This drainage can cause a detrimental impact on water quality in the receiving environment.

1.3 Acid Rock Drainage In British Columbia

The history of ARD in BC is referred to in Chapter 1.0, Section 1.4.1 of Volume I of the Draft Guide. The results of the B.C. Acid Mine Drainage Task Force questionnaire are contained in a report issued in June 1988 (Steffen, Robortson and Kirsten, 1988) and are summarized below:

1.3.1 Coal Mining

There are seven operating coal mines in British Columbia, none of which is presently generating acid rock drainage. All of these mines are located in the Rocky Mountain regions (south-east and north-east regions). Although the Rocky Mountain coal deposits appear to be non-acid generating, proposed coal mines in central B.C. and on Vancouver Island appear likely to encounter potentially acid generating strata. While a geographical trend in acid generation potential from coal mines may be suggested, definite conclusions cannot be drawn due to insufficient information from mines in those areas where ARD is a potential problem.

The coal deposits of the Rocky Mountain regions have relatively low sulphur contents (<0.6%). Proposed coal mines in central B.C. and Vancouver Island have encountered sulphur levels ranging from 0.6% to 4.2% (Errington and Ferguson, 1987). However, low sulphur contents in themselves are not sufficient to ensure that acid generation will not occur. One pcoposed mine in central B.C. has experienced low pH leachate from a coal waste pile (according to the response to the AMD Task Force questionnaire) even though it reports a sulphur content of only 0.4% (Steffen Robertson and Kirsten, 1988).

1.3.2 Metal Mining

There are sixteen operating metal mines in British Columbia, of which six generate acid rock drainage (based on the responses to the AMD Task Force questionnaire). At least five abandoned mines are also known to generate ARD. In addition, many new properties under active exploration have the potential for acid generation (Errington and Ferguson, 1987; Steffen Robertson and Kirsten, 1988). Acid rock drainage flows from underground workings, tailings, open pits and waste rock dumps. Acid producing mines are spread throughout widely separated regions of the province and include a variety of geological environments.

1.4 Sources of Acid Rock Drainage

Acid rock drainage may occur from a number of sources as a result of metal and coal mining activities as follows:

- Underground workings.
- Open pit mine faces and pit workings.
- Waste rock dumps from metal mines and spoil piles from coal mining.
- Tailings deposits.

- Ore stockpiles and spent ore piles from heap leach operations.

These sources are described in more detail in Chapter 1.0, Section 1.7 in Volume I of the Draft Technical Guide.

1.5 References and Suggested General Reading

ERRINGTON, J.C. and FERGUSON, K.D., 1987. Acid Mine Drainage in British Columbia: today and tomorrow. Proceedings of the Acid Mine Drainage Seminar/Workshop, Halifax, Nova Scotia, March 23-26, p.67-87. Environment Canada Catalogue En 40-11-7/1987.

PAINE, P.J., 1987. Historic and geographic overview of acid mine drainage. Proc. Acid Mine Drainage Seminar/Workshop, 23-25 March, 1987, Halifax, Nova Scotia, 1-47 pp. Environment Canada Catalogue En 40-11-7/1987.

PROVINCE OF BRITISH COLUMBIA, ACID MINE DRAINAGE TASK FORCE, 1989. Acid Rock Drainage Draft Technical Guide - Volume I. Prepared by Steffen Robertson and Kirsten, in association with Norecol Environmental Consultants and Gormely Process Engineering.

ROBERTSON, A. MacG., 1987. Alternative Acid Mine Drainage Abatement Measures. Proc. of the 11th annual B.C. Mine Reclamation Symposium, Campbell River. April 8, 9.

SKOUSEN, J.G., SENCINDIVER, J.C. and SMITH, R.M., 1987. A Review of Procedures for Surface Mining and Reclamation in Areas with Acid-Producing Materials. W. Virginia Surface Mine Drainage Task Force, W. Virginia Energy and Water Research Centre, W. Virginia and Reclamation Assoc. Morgantown, W.V.

STEFFEN, ROBERTSON AND KIRSTEN, 1988. Acid Mine Drainage in British Columbia. Analysis of Results of Questionnaire from Acid Mine Drainage Task Force. Report 66001/1.

2.0 THE ACID GENERATION PROCESS

2.1 Acid Generation and Neutralization

When sulphide minerals are exposed to the atmosphere they come into contact with water (as a vapour or liquid) and oxygen. Under these circumstances, the reactive minerals are unstable and will weather to new minerals, some of which readily dissolve in water to produce a strongly acidic solution, for example:

$$FeS_2 + 15/4\ O_2 + 7/2\ H_2O \rightarrow Fe\ (OH)_3 + 2SO_4^{2-} + 4H^+$$

The speed or rate of this reaction is important. If it occurs very slowly, with production of acidity spread over a wide time interval, the effect on the environment may be unimportant. However, rapid acid generation is likely to be a problem. The rate at which the reaction proceeds is dependent on several factors, as described in Volume I, Chapter 2.0, and summarized here.

Although the majority of metal sulphides are iron-bearing, certain varieties are more reactive than others. For example, marcasite which has the same chemical formula as pyrite (FeS_2), is very unstable and will rapidly generate acidic waters. Sulphides of other common metals (for example lead, zinc and copper) are generally far less reactive than the iron sulphides, partly due to the greater stability of their crystal structures and partly due to the formation of low solubility minerals which encapsulate them preventing further weathering.

The size and exposure of sulphide grains and the development of crystals controls the rate of breakdown. Fine grained, poorly crystalline varieties weather more rapidly than coarse crystalline grains. For example, a form of pyrite which develops in low temperature conditions such as swamps may quickly produce acid whereas the large masses of sulphides which occur in high temperature deposits may weather relatively slowly as a result of the small surface area to volume ratio.

Since water and oxygen are essential components of the reaction, exclusion of one or the other will stop the reaction. However, much larger quantities of oxygen are needed compared to water. For example, submerging the sulphide in water almost stops the reaction because the rate of diffusion of oxygen in water is very low. However, air containing a small amount of moisture will induce weathering. Temperature (that is, climate) is also an important control, typically, cooler conditions will reduce the rate of reaction.

The production of new minerals by the acid generation reaction may change the rate of the reaction as the process progresses. In the case of iron sulphide weathering, the products may further react with pyrite, accelerating the rate of weathering. On the other hand the reaction products may coat the sulphide, thereby preventing further weathering. The resultant chemistry of the waters will determine if the minerals precipitate or remain in solution.

Certain bacteria are known to accelerate the rates of reaction. The effect of bacteria is strongly dependant on pH conditions, temperature and the presence of critical concentrations of elements such as molybdenum which can be toxic to the bacteria.

Fortunately, many rocks contain minerals which will naturally consume the acidity produced by the weathering of sulphides. This process is referred to as neutralization. An example of a neutralizing reaction is:

$$H^+ + CaCO_3^- \rightarrow Ca^{2+} + HCO_3^-$$

The most common acid consuming mineral is calcium carbonate (calcite), the major constituent of limestone. Although several minerals are capable of removing acidity, including carbonates of iron and magnesium and hydroxides of iron and aluminum, a limited number will increase the pH from relatively low values, such as around 3, to an acceptable, approximately neutral level. Whether the drainage from a mine is acidic depends on a number of factors and site-specific conditions. The most important criterion is probably the balance between sulphide and neutralizing minerals and their relative reactivities. The rate at which the neutralizing reactions occur is dependant on a number of physical and chemical factors. An important consideration is the susceptibility of carbonates, particularly calcite and dolomite, to form coatings of precipitates, such as gypsum and iron salts, which can cause "blinding" of the mineral and result in a decrease in reaction rates. Generally. if there is an excess of sulphides in the waste, all acid-consuming minerals may eventually be removed allowing the mine drainage to become acidic.

2.2 References and Bibliography

KNAPP, R., 1987. "The Biogeochemistry of Acid Generation in Sulphide Tailings and Waste Rock". Proc. Acid Mine Drainage Seminar/Workshop. Halifax, Nova Scotia, March 23-26. Environment Canada Catalogue En 40-11-7/1987.

LOWSON, R.T., 1982. "Aqueous Oxidation of Pyrite by Molecular Oxygen". Chemical Reviews, Vol. 82, No. 5, October.

PROVINCE OF BRITISH COLUMBIA, ACID MINE DRAINAGE TASK FORCE, 1989. Acid Rock Drainage Draft Technical Guide - Volume I, Chapters 2.0 & 3.0. Prepared by Steffen Robertson and Kirsten, in association with Norecol Environmental Consultants and Gormely Process Engineering.

3.0 ACID ROCK DRAINAGE MIGRATION

3.1 Natural Controls

The quantity and quality of acid rock drainage is dependent on chemical, physical, and biological properties of the waste through which the drainage migrates. A number of reactions may occur along the route as the water, initially of low pH, migrates from the source to the receiving environment. The mobilization of metals and the type of reaction products generated are principally controlled by the geochemistry of the waste material and the pore water. With decreasing pH the dissolved metal load generally increases, however, a combination of chemical conditions could occur where metals are mobilized at neutral or even alkaline conditions. During neutralization of low pH drainage, precipitation of many of the soluble metals may occur and the resultant drainage will contain the residual metals and products of the buffering reactions.

Physical properties of the waste material such as permeability, availability of pore water, pore water pressure, and the mechanism of movement, i.e., whether by stream flow or diffusion, influence the rate of migration and the reactions that occur along the route of migration. These factors control the rate of movement of contaminant fronts, the amount of dilution, and the degree of mixing that occurs as the contaminants move from the source to the receiving environment. The processes of acid generation and ARD migration are shown schematically in Figure 3.1 using a waste rock pile as an example.

Biological activity, other than that of sulphide oxidizing bacteria, along the route of migration may influence the quality of ARD. Biological species may attenuate the metal concentrations by absorption or possibly precipitation, particularly if the drainage passes through wetland conditions with anaerobic zones.

3.2 Impact on the Environment

The environment has a certain capacity to naturally treat acid rock drainage through neutralization, dilution and biological activity which can result in some improvement in water quality. Acid rock drainage leaving the waste facility passes over or through soils or rock which have a limited neutralization capacity. ARD also mixes with surface and ground water which dilute and may neutralize the ARD.

Therefore, for all waste deposits there is a level of ARD release that can be sustained by the environment without significant impact. However, this natural treatment or neutralizing capacity is usually limited. The environmental impact of ARD is dependent on baseline conditions, drainage quality, and the natural dilution and neutralizing capacities of the environment. The impact of ARD on the environment may change with time if the natural neutralization capacity of the environment is depleted. The objective of ARD prevention and abatement measures is to reduce ARD releases to below the level that can be assimilated by the environment without significant impact.

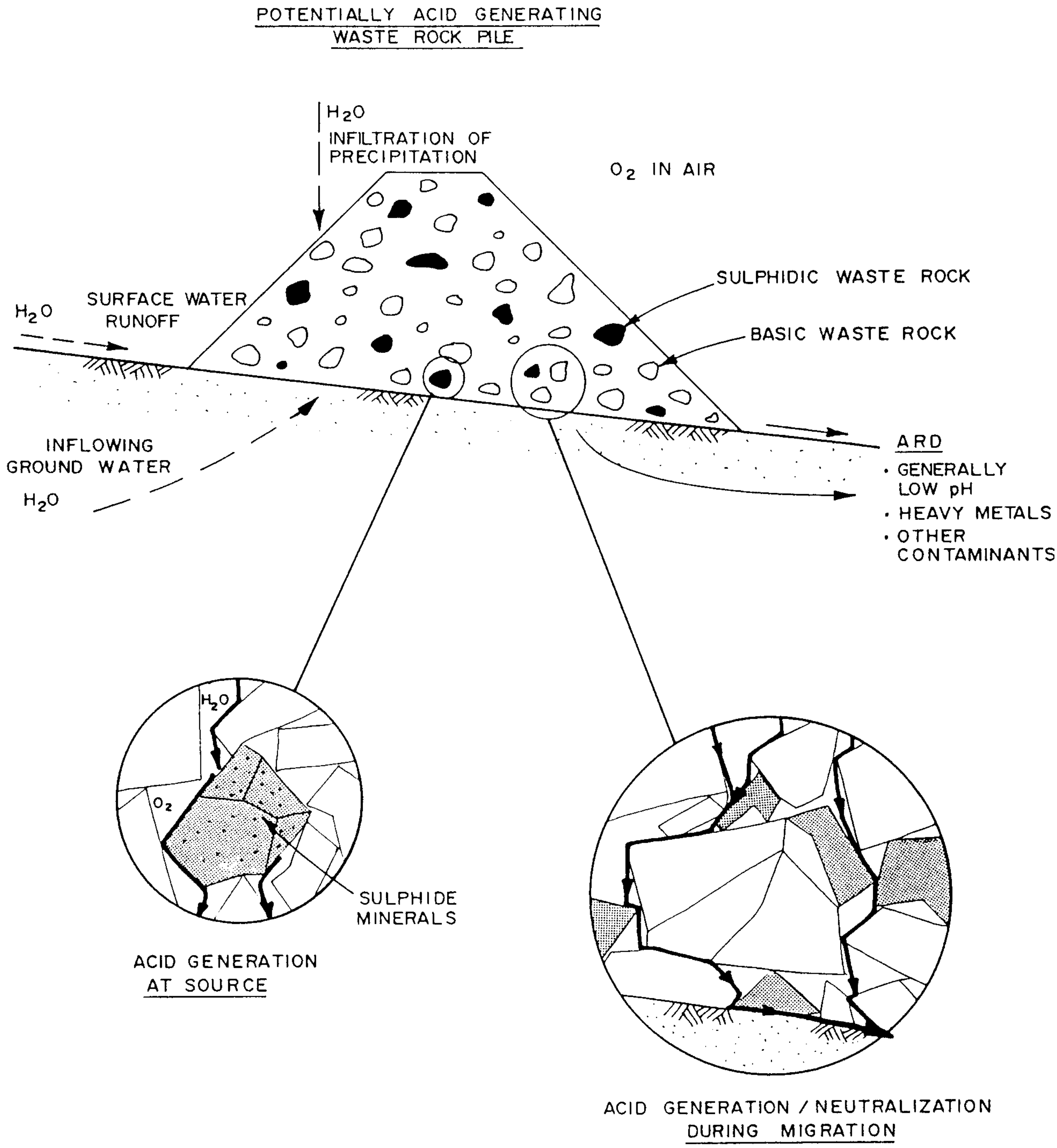


FIGURE 3.1
SCHEMATIC SHOWING CONCEPT OF ACID GENERATION AND ARD MIGRATION

4.0 PREDICTION OF ACID GENERATION AND ACID ROCK DRAINAGE

4.1 Introduction

It is extremely important to be able to predict the potential for waste to generate acid rock drainage, for both economical and environmental reasons. Accurate prediction of the acid generating potential of wastes is essential to optimize the requirements for ARD control. It is important to be able to predict the potential for ARD under ideal conditions for the reactions as well as for conditions imposed by different control techniques. This enables the limits set by the worst case scenario and the controlled scenario to be established.

4.2 Prediction Techniques

The potential for waste to generate acid rock drainage may be evaluated using techniques described in detail in Volume I, Chapter 4.0, and summarized as follows:

1) Geographical, paleoenvironmental, and geological comparisons with nearby mine sites where the potential for ARD has been demonstrated through experience.

2) Sampling and geochemical static testing to determine the relative quantities of acid generating minerals and acid neutralizing minerals for different geological units.

3) Sampling and geochemical kinetic testing to determine the rates of acid generation and drainage quality under controlled laboratory or on-site conditions.

4) Mathematical modelling to extrapolate the results of static and kinetic testing over time to predict the long-term trend in acid generation rates and drainage quality.

4.3 Recommended Approach to Prediction

As part of the regulatory approval process for mines in British Columbia, the government requires testing to identify potentially acid generating materials. Prior to final mine plan approval, the government will require assurance that all sources of potential acid generation have been identified and that prevention or control measures have been incorporated in mine plans where appropriate. It is important to the mining company as well as to government to do sufficient tests to ensure that problems have been addressed since remedial measures and treatment of acid drainage can be costly, with long term liabilities. The key to a successful approach to ARD testing is to do sufficient testwork to enable prediction to be carried out with a degree of confidence compatible with the cost of sampling, risk of failure (probability and consequence) and potential cost of remediation.

The initial steps in prediction should be made during the exploration stage of a project when the mineral development prospects of a property are being investigated. The next stage in the process occurs during Prospectus and Stage I phases with the development of a mine plan, definition of the location, size, and management of each mine component. From the perspective of acid generation, the primary environmental components of a mine are: the mine workings, waste/rock or spoil piles, overburden dumps, ore stockpiles, the millsite, and tailings impoundment. These components have different potential impacts as a consequence of differences in physical conditions, geochemical characteristics, and exposure to climatic conditions. As a result, the environmental impact of a proposed minesite must be determined on the basis of the potential impact of each component evaluated in terms of anticipated site specific conditions.

The overall procedure for evaluating the potential for acid generation at a minesite required for each stage of the Mine Development Review Process is outlined in Figure 4.1-1. This figure depicts the importance of a reliable sampling program in the overall process. The level of sampling and testing increases for each stage of the process.

During the exploration stage, the geology of the ore depesit end host rocks should be mapped and the potential ore zone identified. The project geologist should gather all available data pertinent to acid generation potential, such as type of sulphide minerals present and content in ore and waste rock, carbonate content, etc. This data may give a preliminary indication of acid generation potential.

At the Prospectus level, testing of the types of material encountered at the site should be conducted such that tests are carried out on at least three samples from each of the geological units to be exposed. These samples should first be subjected to static predictive tests in order to evaluate the chemical balance between acid-producing and acid-consuming minerals. This is done by measurement of total sulphur concentrations and measurement of total neutralization potential. Static test procedures are discussed in Volume I, Section 4.4. The results of static tests are expressed in terms of the Net Neutralization Potential (NNP), or similar descriptions of net values. Prior to analysis the descriptive mineralogy of the samples should be determined to allow better interpretation of the results of the static tests. Since not all sulphur is reactive or available to produce acid, and minerals other than carbonates can neutralize acid, the tests may indicate the worst likely acid generation scenario. On the other hand, the acid-base account does not consider the relative rates of the acid-generation and acid-neutralization reactions and assumes that the neutralization capacity is available at the same rate as the generation of acid. Analytical error may contribute to inaccurate results and incorrect interpretation. The consequence of these factors is that the acid-base account test may lead to an underestimate of acid generation potential.

At Stage I, the project geologist should supervise the detailed identification of homogeneous geologic units of ore and wasts rock based on lithelogy, mineralogy, and continuity of units. Geographical, geological and paleoenvironmental characteristics are compared with similar or nearby mines whenever possible. This comparison may indicate whether the proposed mine has a potential to produce acidic drainage though this approach is very limited in its uses.

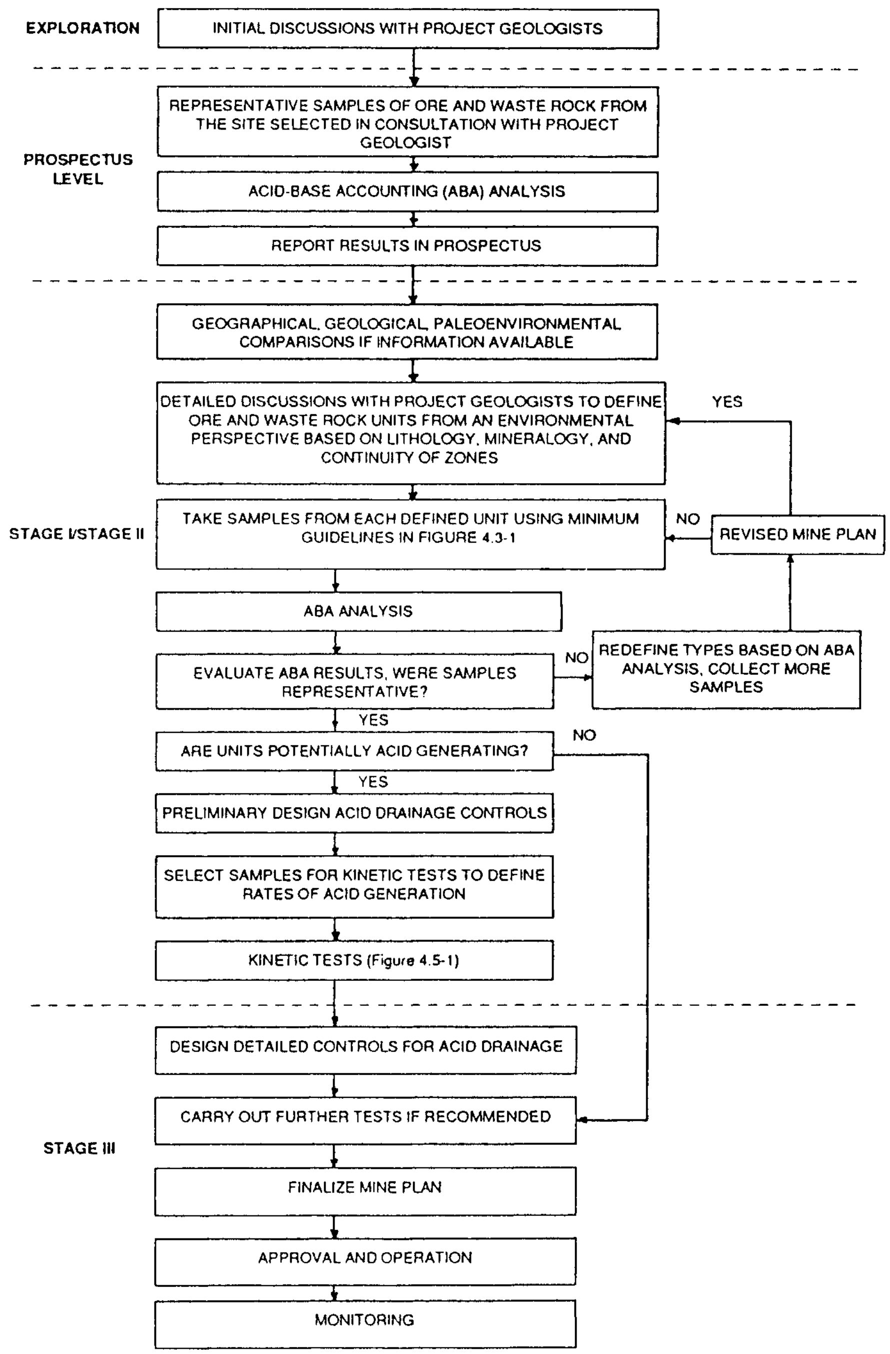


FIGURE 4.1-1
PROCEDURE FOR EVALUATING THE POTENTIAL FOR ACID GENERATION IN BRITISH COLUMBIA

A detailed sampling program should then be implemented to collect representative samples from each geological unit for static geochemical testing. The primary objective of the sampling program is to obtain high quality representative samples of all geologic units related to the mine development plan. The units must be defined on the basis of physical and chemical homogeneity. A proposed schedule to indicate the minimum number of samples that should be collected in order te be representative of the different rock units is presented in Figure 4.3-1. This relationship between the minimum number of samples and the mass of the geological unit being sampled is based on experience from a limited number ef mining projects in B.C. The empirical and limited nature of the function shown in Figure 4.3-1 dictates that it should only be used as a guideline. The actual number of samples tested in Stage I will depend on the homogeneity of the units at the mine.

The potential sources of samples for acid generation prediction testwork are outlined in Table 4.1. The main souroe is drill core from exploratory drilling. Pilot plant bench scale test or rock cycle test samples should be retained to test tailings and/or spent ore. For existing mines, samples may be obtained on-site from each component.

TABLE 4.1

POTENTIAL SOURCES OF SAMPLES FOR ACID GENERATION PREDICTION

Mine Component	Existing Mines	Proposed Mines
Pit walls	Drill core Pit walls	Drill core Underground exploration passages Trenches
Underground workings	Drill core Walls Excavated rock	Drill core Underground exploration passages
Waste rock/overburden Piles	Waste rock piles Drill core	Drill core Underground exploration passages
Tailings	Tailings impoundments	Laboratory bench scale tests Pilot plant for mill process
Ore stockpiles	Ore stockpiles	Drill core Underground exploration passages
Spent ore	Heap leach	Laboratory bench scale tests Pilot plant for heap leach

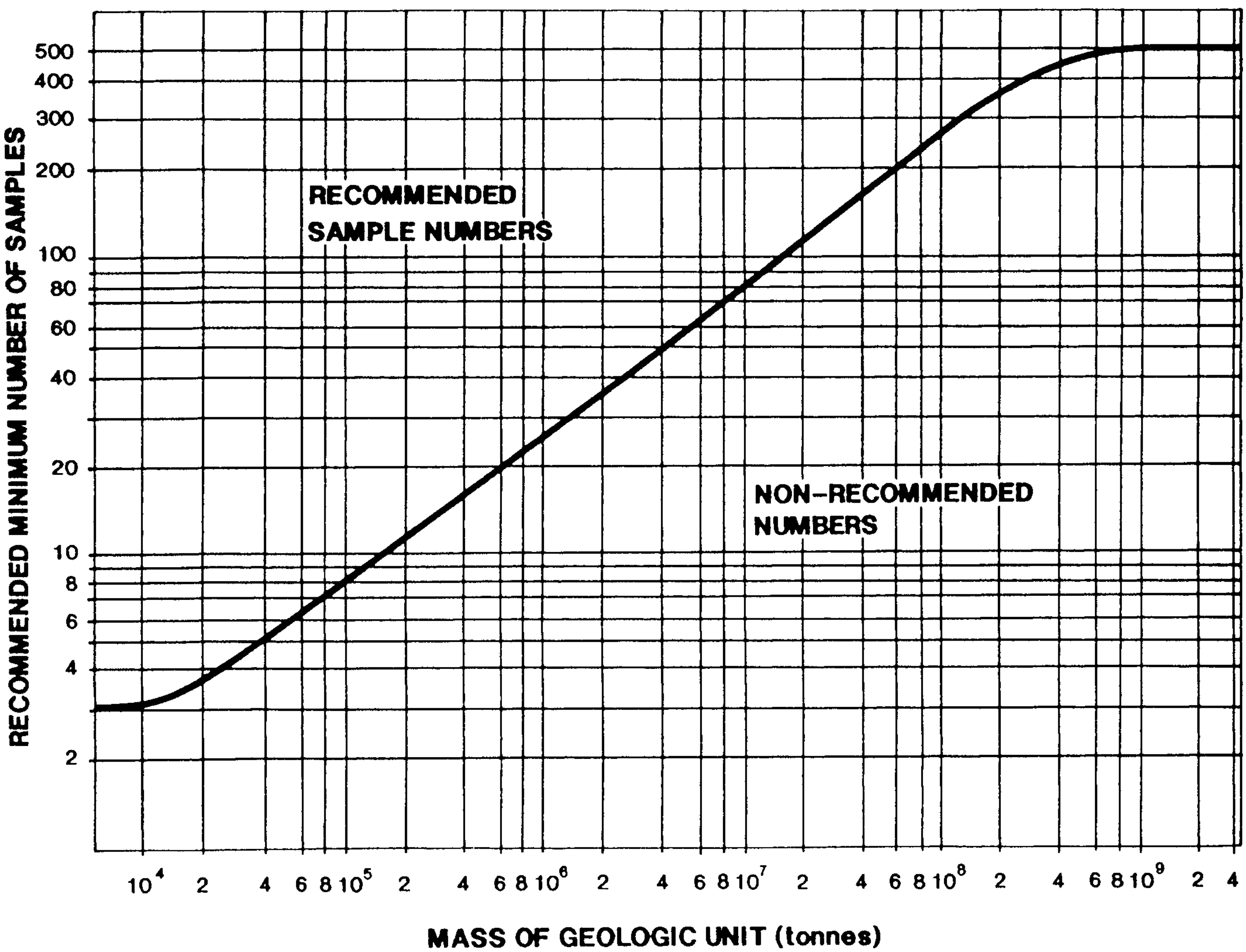
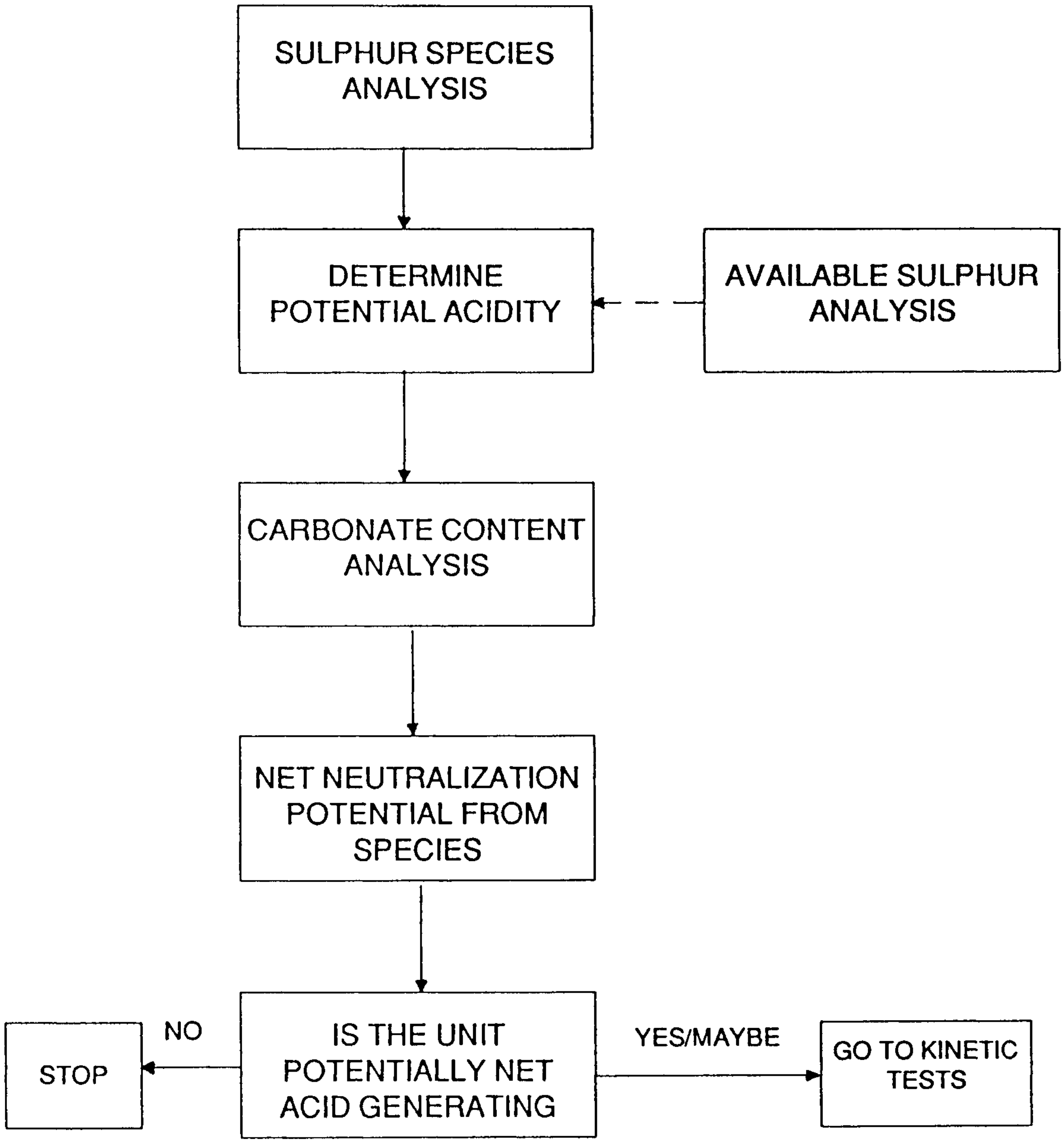


FIGURE 4.3-1
RECOMMENDED MINIMUM NUMBER OF
SAMPLES AS A FUNCTION OF MASS OF EACH GEOLOGIC UNIT
(Based on unpublished field data obtained
by Norecol Environmental Consultants)



- - -Method development required

FIGURE 4.4-2
OPTIONAL STATIC TEST PROCEDURE FOR EACH GEOLOGIC UNIT

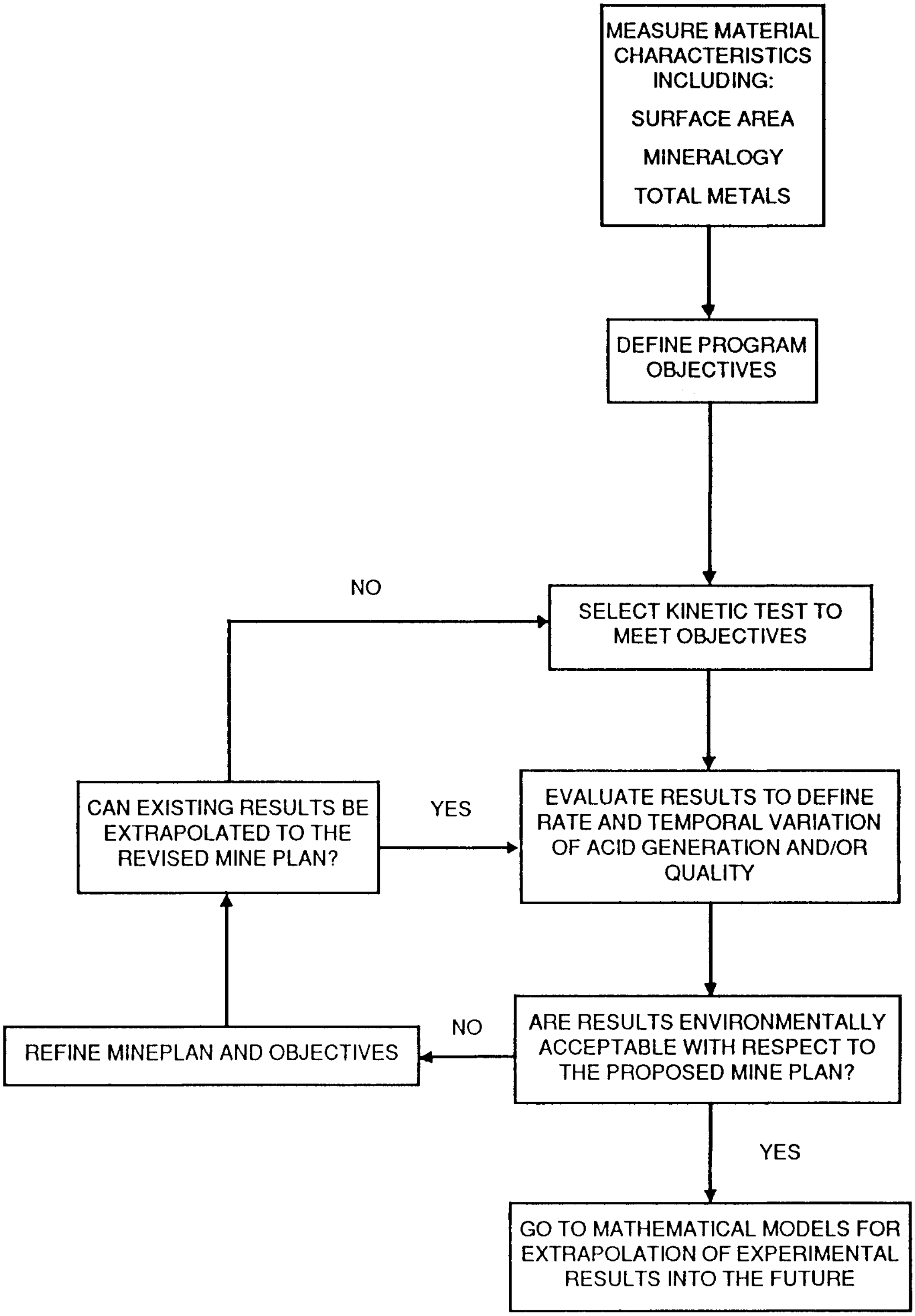


FIGURE 4.5-1
RECOMMENDED KINETIC TEST PROCEDURE

TEST	B.C. Confirmatory Test	Shake Flasks	Humidity Cells	Soxhlet Reactor	Columns/lysimeter	Test Plots/Piles
OBJECTIVES						
Selection or Confirmation of Disposal Options			●		●	●
Determination of Overall Quality Impacts		●	●	●	●	●
Determination of Effect of Flushing Rates			●		●	●
Determination of Influence of Bacteria		●	●		●	●
Confirm Potential to Generate Acid under Test Conditions	●	●	●	●	●	●
Determination of Rate and Variability in Rate of Acid Generation		●	●		●	●
ADVANTAGES						
Simple to Use	●	●	●	●		
Test Widely Accepted in Canada			●		●	●
Data May be Used for Mathematical Models		●	●		●	●
Large Numbers of Samples Can be Tested in a Relatively Short Time	●			●		
DISADVANTAGES						
Complex Interpretation		●	●	●	●	●
Long Time to Complete Test		●	●		●	●

FIGURE 4.5-2
COMPARISON OF AVAILABLE KINETIC TEST METHODS

Finally, acid generation under site conditions can be investigated with rock piles constructed on impervious bases at the mine site. Field test piles subject the material to actual site weathering conditions. Natural precipitation which leaches through the rock pile is collected and analyzed. Humidity cells, columns and test rock piles allow trials of control methods such as blending of different kinds of waste rock and addition of limestone.

Kinetic tests provide results of acid generation rates for the time period over which the tests were run, generally periods of the order of a number of months. In practice, confident prediction of the acid generation potential is required for periods extending beyond operation and closure of the mine. The extrapolation of rates of acid generation and pH neutralization in the long term, beyond the time frame of the tests, may be attemptod using mathematical models. Care should be exercised in using mathematical models. Models should be used that suit the requirements for prediction and the level of input data. While a complex and sophisticated model may be available, the quality of the output is largely a function of the quality of the input data. More simple models can be used to determine best-fit functions. These rolationships may be used to expropriate trends in short-term laboratory and field tests results to obtain estimates of the long-term water quality. All models suffer from a lack of sufficient field data for complete validation. True model improvement can only be realized when a more extensive database becomes available.

4.4 References and Bibliography

BRUYNESTEYN, A. and HACKL, R.P., 1984 Evaluation of acid production potential of mining waste material. pp 5-8. Minerals and the Environment, Volume 4.

DI PRETORO, R.S. and RAUCH, H.W., 1988. Use of acid-base accounting in premining prediction of acid drainage potential: A new approach from northern West Virginia., Mine Drainage and Surface Mine Reclamation, Vol. I.: Mine Water and Mine Waste, U.S. Bureau of Mines Information Circular 9183, p2-10.

FERGUSON, K. and ERICKSON, P., 1987. Will it Generate Acid? An Overview of Methods to Predict Acid Mine Drainage. Proc. Acid Mine Drainage Seminar/Workshop, Halifax, Nova Scotia. March 23-26. Environment Canada Catalogue En 40-11-7/1987.

PROVINCE OF BRITISH COLUMBIA, ACID MINE DRAINAGE TASK FORCE, 1989. Acid Mine Drainage Draft Technical Guide - Volume I, Chapters 4.0 & 5.0 Prepared by Steffen Robertson and Kirsten, in association with Norecol Environmental Consultants and Gormely Process Engineering.

5.0 CONTROL OF ACID ROCK DRAINAGE

5.1 Introduction

The control of ARD includes both prevention and abatement techniques. Prevention refers to measures designed before mining starts and with the knowledge of the acid generation potential of the waste. Abatement refers to measures implemented either at facilities where ARD is occurring and was not anticipated, or at facilities where control measures are not sufficiently effective.

The objective of ARD control is to achieve the necessary control to satisfy environmental criteria using the most cost effective technique. There are at present three generally accepted stages in ARD control, as follows (Barton-Bridges and Robertson, 1989):

1) Control of the acid generation process (Volume I, Chapter 6.0)

2) Control of acid rock drainage migration (Volume I, Chapter 7.0)

3) Collection and treatment of acid rock drainage (Volume I, Chapter 8.0)

The above three control categories are listed in order of preference. If acid generation is prevented there is no risk of the products, or contaminants, entering the environment. Where acid generation is not prevented, control of contaminant migration should be implemented. If neither of these control measures are in effect, it is necessary to collect and treat the ARD.

A combination of control measures from one or more of these categories may provide the most secure control.

5.2 Control of Acid Generation

The objective of acid generation control is to limit the formation of acid at the source by inhibiting sulphide oxidation. This may be done by excluding one or more of the principal ingredients to the reactions, or by controlling the environment around the sulphides. The process of acid generation is described in Volume I, Chapter 2.0, and the objectives, approach, and available measures for acid generation control are discussed in Volume I, Chapter 6.0. The available control measures are summarized in Table 5.1.

The conclusions that can be drawn from the currently available technology for acid generation control may be summarized as follows:

1. Prevention of the acid generation reactions is the most preferable form of control and should, if at all possible, be the primary long-term approach. The design of ARD

prevention at proposed facilities should aim to exclude one or more of the principal ingredients in the acid generation reactions.

TABLE 5.1

SUMMARY OF AVAILABLE ACID GENERATION CONTROL MEASURES

Objective of Control	Control Measure	References
Sulphide removal or isolation	• Conditioning of waste	Broman, 1988 Hester & Associates, 1984 Knight & Haile, 1983 Steffen Robertson & Kirsten, 1987(b)
Exclusion of water	• Covers and seals	
Exclusion of oxygen	• Subaqueous deposition	Nolan, Davis & Associates, 1987 Steffen Robertson & Kirsten, 1988(c) Ladwig et al, 1984 Pedersen, 1983 Errington & Ferguson, 1987 Hallam et al, 1974 Daly et al, 1981
	• Covers and seals	Bell, 1987 Steffen Robertson & Kirsten, 1988(c) NTDME, 1986 Magnusson & Rasmuson, 1983
pH control	• Waste segregation & blending	Sturm, 1987 Milner, 1987
	• Base additives	Morin and Cherry, 1986 Dubrovsky, 1986 Helz et al, 1987 City Resources, 1988
Control of bacterial action	• Bactericides	Kleinmann & Erickson, 1983 Sobek, 1987

2. The exclusion of oxygen from reactive wastes by means of a water cover is currently the most effective acid generation control measure. Water cover (underwater disposal or a saturated soil/bog cover) for preventing acid generation should be evaluated first. Care should be exerciaed when considering flooding existing waste deposits due to potential high loads of oxidation products within the waste. Proposals to dispose mine wastes, such as tailings, into natural water bodies is often opposed by regulatory agencies and the public for environmental and political reasons. The cost of on-land disposal under water cover, relative to lake or marine disposal, and the environmental implications associated with all methods need to be investigated in full.

3. Control of the acid generation process for abatement of ARD at existing facilities is often not practical or is extremely costly. In these cases, acid generation control techniques may be used to reduce the rate of acid generation in conjunction with control of ARD migration and, if necessary, collection and treatment of ARD.

4. A combination of various measures may produce the most efficient control of ARD for both existing and proposed facilities and in the short or long term. Measures for the control of acid generation should be evaluated in conjunction with control of ARD migration and collection and treatment.

5. Construction methods and extraction processes that result in conditions favourable for preventing acid generation, such as bulk sulphide flotation of tailings, separating high sulphide rock waste, etc. should be considered for proposed facilities. However, additional control measures are likely to be required.

6. Covers and seals show promise as inhibiters of acid generation provided these are maintained in good order as designed. Certain types of covers and seals are very effective in reducing infiltration of precipitation and soil covers, in particular, are suitable for rehabilitation and re-vegetation purposes.

7. The use of bactericides might be a suitable short-term acid generation control measure. It should be remembered that bactencides have a limited life, are difficult to apply effectively, and, at best, control only the biological oxidation processes and not chemical oxidation of sulphides. Additional controls are necessary if the waste has insufficient natural potential to neutralize acid that is generated through chemical oxidation of sulphide minerals.

8. Base additives are generally a suitable short-term control measure. In some cases, base additives may be suitable in the long-term, depending on the quantity, type and reactivity of the sulphide minerals. Blending of mine wastes is a form of base addition in areas where limestone or other alkaline strata occur in the overburden. This method has been successfully used in the coal mining industry.

5.3 Control of ARD Migration

Where acid generation is not prevented, the next level of control is to prevent or reduce the migration of ARD to the environment. Since water is the transport medium for contaminants, the control technology relies on the prevention of water entry to the ARD source. Control of water exit is of little value since in the long term all water entering the ARD source must exit, long term storage being negligible. Water entry may be controlled by:

- Diversion of all surface water flowing towards the ARD source.
- Prevention of groundwater flow into the ARD source.
- Prevention of infiltration of precipitation into the ARD source.
- Controlled placement of acid generating waste.

The available measures to control ARD migration include:

- Covers and seais to minimize infiltration of precipitation.
- Controlled placement of waste to minimize infiltration of precipitation.
- Diversion of surface water.
- Interception of ground water.

The conclusions that can be drawn from current technology for control of ARD migration may be summarized as follows:

1. Diversion of surface water is best achieved during operation (short term) by means of diversion ditches or berms. In the long term, site selection to minimize contact with surface water runoff should be considered if possible. If necessary, ditches, berms and other structures may be used in the long term, however, a certain level of inspection and maintenance will be required.

2. Interception of groundwater by means of wells and pumps may be suitable in the short term only. Impermeable cut-off walls and gravity drains may be suitable in the long term but will require on-going monitoring and maintenance.

3. Infiltration control is essential for controlling ARD migration. This is best achieved by means of soil and/or synthetic materials or a combination of these. Synthetic membrane liners are most suitable in the short term to cover, for example, ore stockpiles. The design of soil covers must consider cost, the degree of infiltration

control required, the requirements for revegetation, long-term disruptive forces and maintenance requirements. All types of covers require some form of long-term monitoring and maintenance. Covers and seals to exclude infiltration are discussed in detail in Volume I, Chapter 7.0, Section 7.4.

4. Methods of placing waste rock, spoil or tailings to minimize infiltration should be considered in conjunction with other control methods.

5. The methods to control ARD migration are sensitive to both the nature of the site and the duration for which control is required. Consideration of all site parameters is critical to selecting the optimum combination of methods.

5.4 Collection and Treatment of ARD

5.4.1 Introduction

Collection and treatment of ARD is to date the most widely applied ARD control measure. This is probably due to the fact that at many existing operations, where ARD was not anticipated or adequately controlled, collection and treatment is the only practical option available.

Collection systems may be required to recover both surface waters and groundwater contaminated by ARD. Collection of surface flows is usually fairly readily achieved by means of surface ditches. The collection of subsurface flows requires the installation of collection trenches, wells, or cut-off walls to force groundwater flow to the surface where it can be collected. Most collection systems require long-term maintenance.

Treatment measures may be classified as either active systems that require continuous operation, such as a chemical treatment plant, or passive systems that are intended to function with only occasional intervention by man, such as wetlands, alkaline trenches, etc.

The objective of acid rock drainage treatment is to eliminate acidity, precipitate heavy metals and remove deleterious substances such as suspended solids, arsenate and antimonate.

5.4.2 Chemical Treatment

Chemical treatment involves technology which is well established and is working effectively at a number of mines. A recommended approach to the development of a chemical treatment plan, from the time of the decision to pursue this route through to commissioning and start-up, is presented in Figure 5.1 and discussed in Section 5.5 (Stage 7).

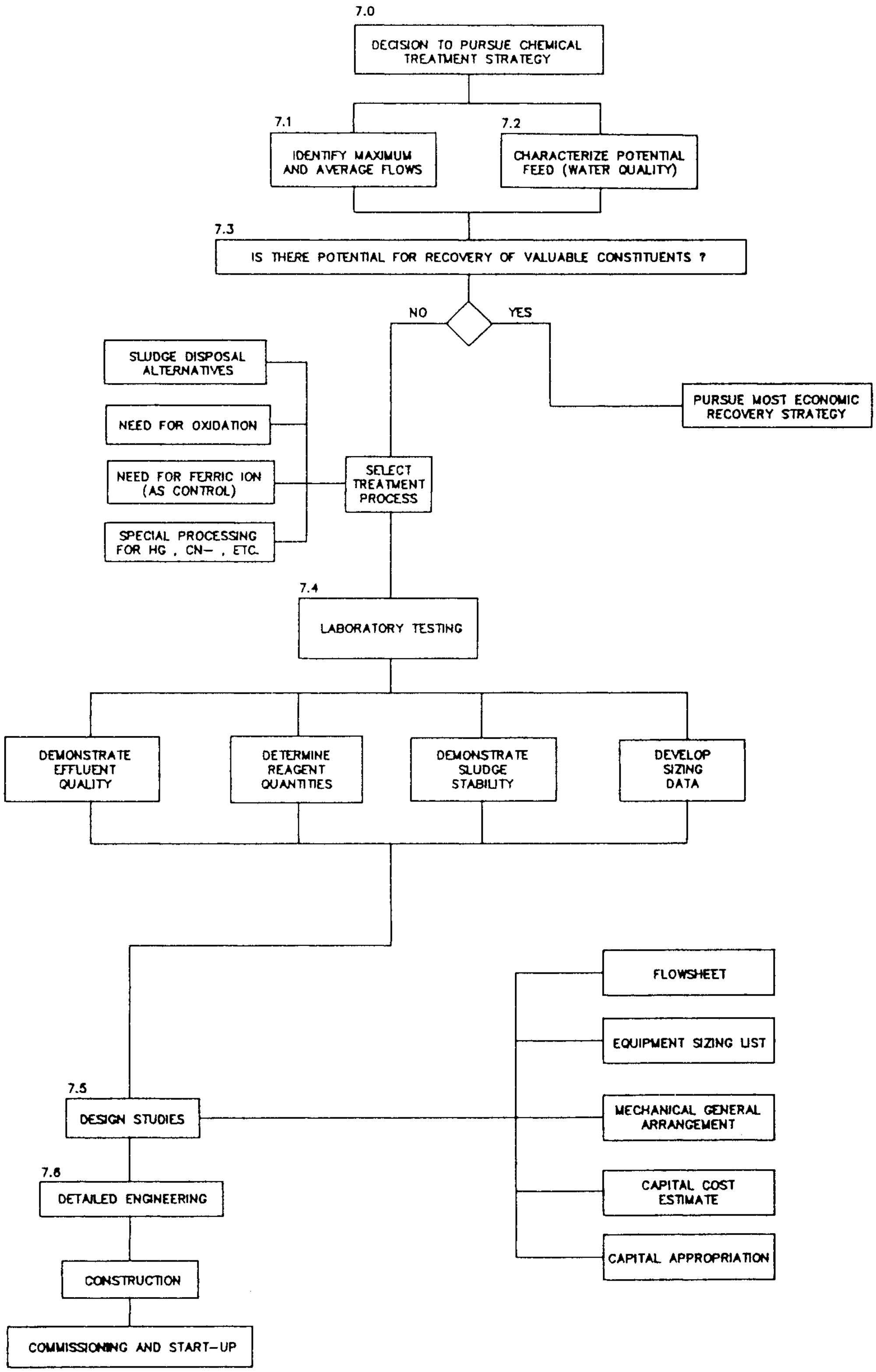


FIGURE 5.1
FLOWCHART SHOWING DEVELOPMENT OF CHEMICAL TREATMENT PLAN

Treatment Process Description

Acidity, present as sulphuric acid In acidic rock drainage, is eliminated by neutralization with an alkali, primarily ground limestone (calcium carbonate, $CaCO_3$) and/or hydrated lime ($Ca(OH)_2$). Limestone is a cheaper reagent but has a number of limitations, mainly its inability to raise the pH to the level required for effective precipitation of metals. It may be used in conjunction with hydrated lime in some cases. Lime can be supplied in two different forms, quicklime and hydrated lime. Quicklime is the product of the calcination of limestone, and consists primarily of the oxides of calcium and magnesium, while hydrated lime is a dry powder obtained by combining quicklime with a stoichiometric quantity of water to form hydroxide. Quicklime is generally hydrated prior to use.

The primary product of ARD neutralization using either limestone or limo is gypsum ($CaSO_4.2H_22O$), produced largely as a precipitate. Gypsum commonly forms scale on tanks and in piping which can require acid treatment and mechanical removal. Proper design can reduce the severity of some scaling problems. Heavy metal ions hydrolyse and precipitate as their respective hydroxides during neutralization while anions such as arsenate and antimonate form insoluble compounds at neutral pH with many of the heavy metals (notably iron) present. Each species has an optimum pH (level of neutralization) for its removal. During neutralization, the slurry is commonly aerated to oxidize any ferrous present to ferric iron and to precipitate ferric hydroxide.

Sludge Characteristics

Sludges resulting from neutralization of ARD can contain gypsum, heavy metal hydroxides, heavy metal arsenates, calcium arsenate, and heavy metal sulphides. Stability is gauged by the potential for various components of the sludge to re-enter the environment. ARD treatment sludges may be unstable if exposed to air or excessive water movement over an extended time period. Protective alkalinity in the form of excess lime and careful selection of the disposal site can enhance long term stability.

Sludges containing calcium arsenate in contact with carbon dioxide, bicarbonate, or carbonate can break down releasing arsenate ion. Alternatives resulting in precipitation of arsenic as ferric arsenates are preferred for long term stability. Sludges containing sulphide precipitates must be given careful consideration due to the possibility of acid generation occurring in the sludge with time.

Process Alternatives

The treatment process is straightforward; nevertheless, there are alternative methods and unit operations to carry out the neutralization and clarification steps.

Neutralization can be conducted using a number of different reactors types including;

- stirred tank reactors which can be operated reliably at steady feed flow with predictable product quality, using minimal instrumentation and operator intervention, and,

- pipeline reactors which can be used when the reaction is rapid or extended distance pumping is involved. With this reactor type reactants are injected at the start of the pipeline while the sludge and treated effluent are separated at the discharge end.

Clarification is a relatively inexpensive process for solids separation when large volumes are treated and can be accomplished using several alternatives:

- Conventional gravity clarifiers are analogous to gravity thickeners, common in the mining industry. The tank in this case provides sufficient residence time and settling area to permit solids separation and sludge densification.

- Reactor clarifiers provide for flocculation, clarification, sludge recycle and potentially sludge thickening in one vessel. With this design flocculation efficiency is improved by adding polyelectrolytes to high solids concentration feed in a "flash mix" chamber followed by a flocculation chamber. Recycle of solids from the clarifisr underflow to the feed, upstream of polyelectrolyte addition, is essential to build high density sludge.

- Hopper clarifiers, a variant of the sludge blanket clarifier, accomplishes the same objectives as a reactor-clarifier without recourse to mechanical drives.

- Lamella clarifiers are based on the idea of multiplication of settling area through stacking of plates. This reduces floor area requirements. The lamella clarifier can provide both clarification and sludge thickening in one vessel but sludge recycle to a separate reactor is essential to build density.

Process Development

Process development for ARD treatment can involve the following items:

Feed Characterization
Batch precipitation Tests
Settling Tests
Sludge Characterization
Batch Oxidation Tests
Process Testing for Mercury and Arsenic

Design

Design of an ARD treatment plant will be based on a combination of design criteria and standard engineering practice.

Design Criteria

Design criteria include a large number of items such as pH, feed rate and clarifier loading. The criteria selected for design purposes consider both bench tests results and industrial experience. Items include:

- Feed Rate and Hydraulic Loading. Based on site hydrology.

- pH. Probably in the range of 7.5 to 9.5.

- Residence Time. Typically in the range 30 to 60 minutes.

- Reagent Dosages. Lime dosage varies according to acidity loading, there may be seasonal factors. Flocculant dosages based on tests.

- Clarifier Loading. Selection of a design hydraulic loading is based on a combination of settling test data, practices and experience at existing operations, and recommendations provided by equipment vendors. Design criteria for clarification equipment are generally conservative.

- Aeration and Agitation. Complex design, involving estimation of required dissolved oxygen level, oxidation rates, and mass transfer coefficients.

- Recirculation Rates. Typical sludge recycle would be 5-20% of the feed flowrate.

Design Procedures

The design sequence consists of the following steps;

- review testwork,
- outline process concept, reactor type, select reagent type,
- layout process flowsheet,
- balance flows, solid loadings, calculate reagent addition rates and review process chemistry,
- size equipment and compile equipment list,
- complete general arrangement drawings, define structural and mechanical requirements,
- complete detailed engineering, specify and procure equipment, select contractor and build plant.

Equipment Sizing and Design

The bulk of detailed design and engineering work involves equipment sizing, design and selection as follows;

- Reactor Design. Reactors are sized to provide the required residence time. Internal feed and/or exit baffles can be added to help eliminate short circuiting but can cause problems for descaling. Best practice will keep the reactor internals as simple as possible. The solids are typically very fine and suspend easily. Agitator vendors will provide recommendations on selection of agitators and the best arrangement for sparging air under the impeller if aeration is required.

- Clarifier Design. Selection of the type of clarifier will be the result of the experience and preference of the designer, the recent experience of others with similar plants, and an economic evaluation basad on solicitation of quotes from vendors. In the high density sludge process, flocculation is critical to successful performance, and thus, separate reactors may be provided for "flash" mixing of flocculant with the feed followed by gentle agitation while the flocs form and consolidate.

- Sludge Thickening, Recycle and Disposal. In terms of design, equipment handling sludge such as rakes and sludge pumps should be selected with expected density ranges in mind. Industrial experience with similar equipment should be referred to for recycle systems. An adequate flow range for the sludge pumps is essential, since the sludge density can vary widely. Sludge thickening is normally conducted in conjunction with clarification. Clarifiers can be provided with a separate thickener zone if a reduction in sludge volume is necessary. Conventional clarifiers normally provide sufficient thickening for the HDS process.

Control and Monitoring

Lime dosage can be controlled manually or automatically by manipulating the lime slurry feed rate using either a pH or a flowrate control signal. Flocculant is generally added at a pre-set fixed rate that can be changed periodically if required. In addition if oxidation is involved it can be controlled either manually or automatically using a redox potential or dissolved oxygen control signal.

Process monitoring can involve either manual or on-line turbidity measurements since upsets are commonly associated with an increase in the level of effluent suspended solids. pH monitoring would normally be included as part of lime dosage control.

Process Reliability and Plant Integrity

Process reliability will be closely related to the level of maintenance. Equipment service lives will be directly related to this factor, as well as site specific factors such as consistency of electrical power, abrasive solids entering the process system, care and frequency of descaling equipment. The process is relatively reliable although seasonal trends in feed rate and characteristics may affect performance. Proper maintenance should ensure long term plant integrity.

Capital and Operating Costs for Typical Installations

Capital and operating costs for typical AMD treatment plants are outlined in Volume I, Chapter 8.0, Section 8.3.7. Estimated capital and operating costs for ARD treatment, based on published data and case histories, are provided in Figures 5.2 and 5.3 respectively. This data has been extracted from cost information published in a report by Environment Canada titled " Mine and Mill Waste Treatment" and from cost information issued for treatment systems at Brunswick Mining and Smelting Corp Ltd, Les Mines Gallen, Equity Silver and Sullivan. An analysis of cost data from the case histories examined indicates that operating costs are primarily a function of lime consumption which in turn is directly linked to acid loading. Capital costs vary considerably depending on plant design and mechanical complexity, as well as on flow rate.

5.4.3 Wetland and Other Treatments

Wetlands such as bogs, marshes, and swamps show promise in being able to treat acid rock drainage and other wastewaters. Research to date has shown that the ability of wetland systems to treat wastewaters is dependent on water flow distribution, above and below ground, and residence time. These factors are more easily controlled in constructed rather than natural wetlands. The principal advantage of wetland systems is that they are generally self-sustaining with low operational and maintenance costs. The main disadvantage of wetland systems is that their effectiveness has yet to be demonstrated in the field, particularly in the long term.

5.5 Recommended Approach to ARD Control

The recommended approach to ARD control is presentad as a flow-chart in Figure 5.4 and the procedure is described below. The development of a plan to control ARD should begin by investigating means of controlling acid generation. If these methods are not practical or feasible, measures to control the migration of contaminants should be investigated. If neither acid generation or contaminant migration control are suitable, a plan to collect and treat the ARD should be developed. The staged description below should be read in conjunction with Figures 5.1 and 5.4.

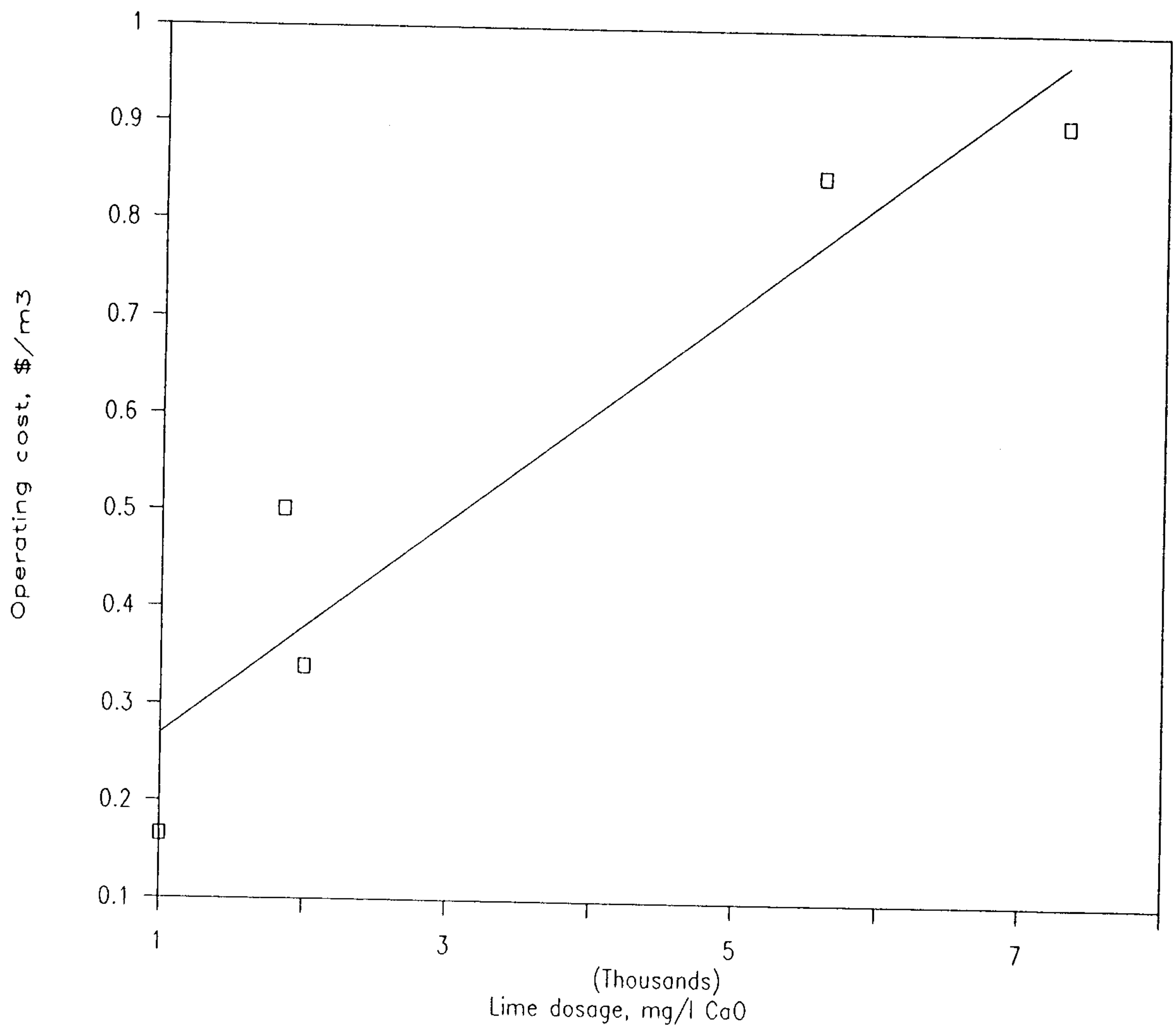


FIGURE 5.2
OPERATING COSTS FOR ARD TREATMENT

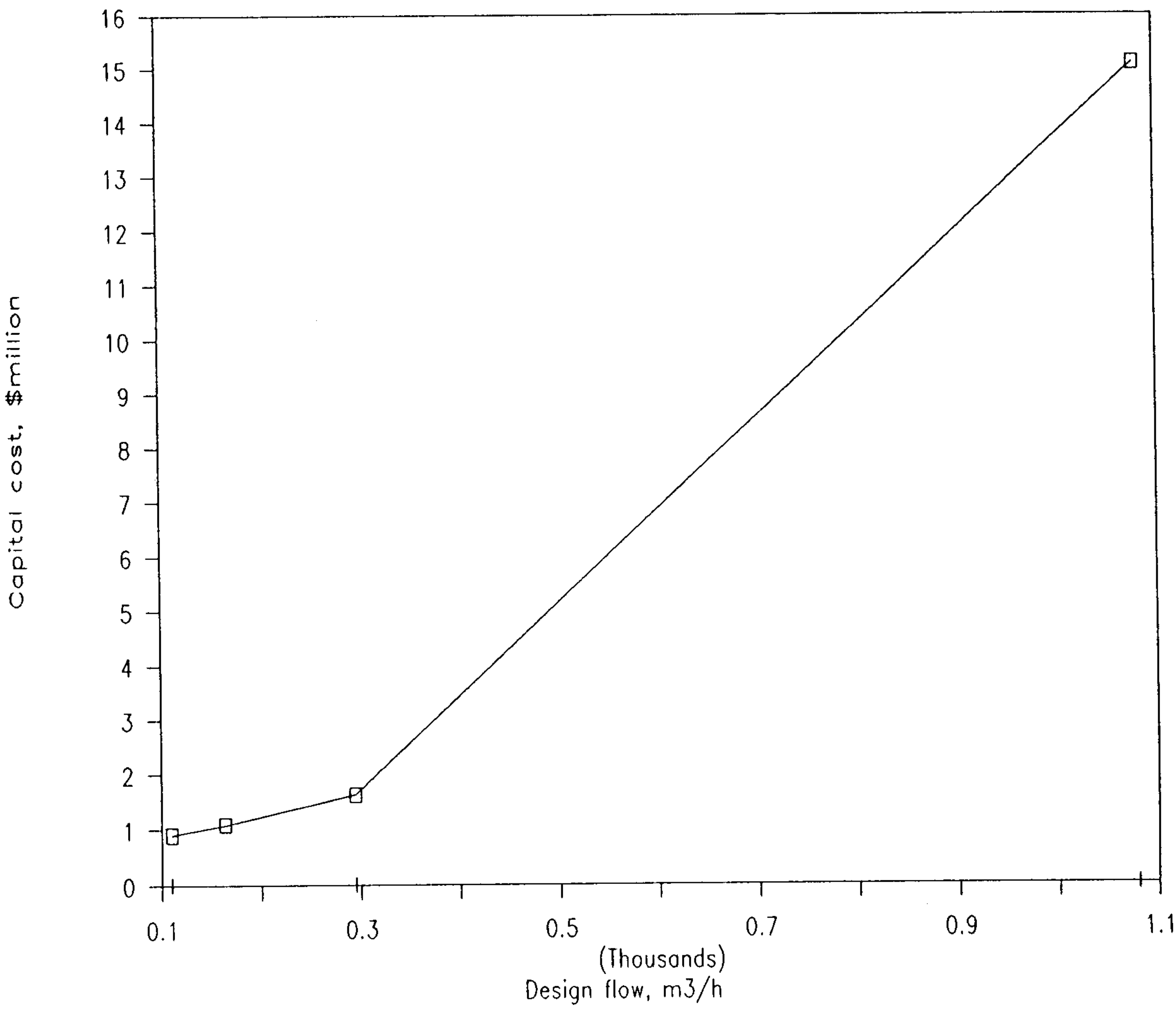


FIGURE 5.3
CAPITAL COSTS FOR ARD TREATMENT

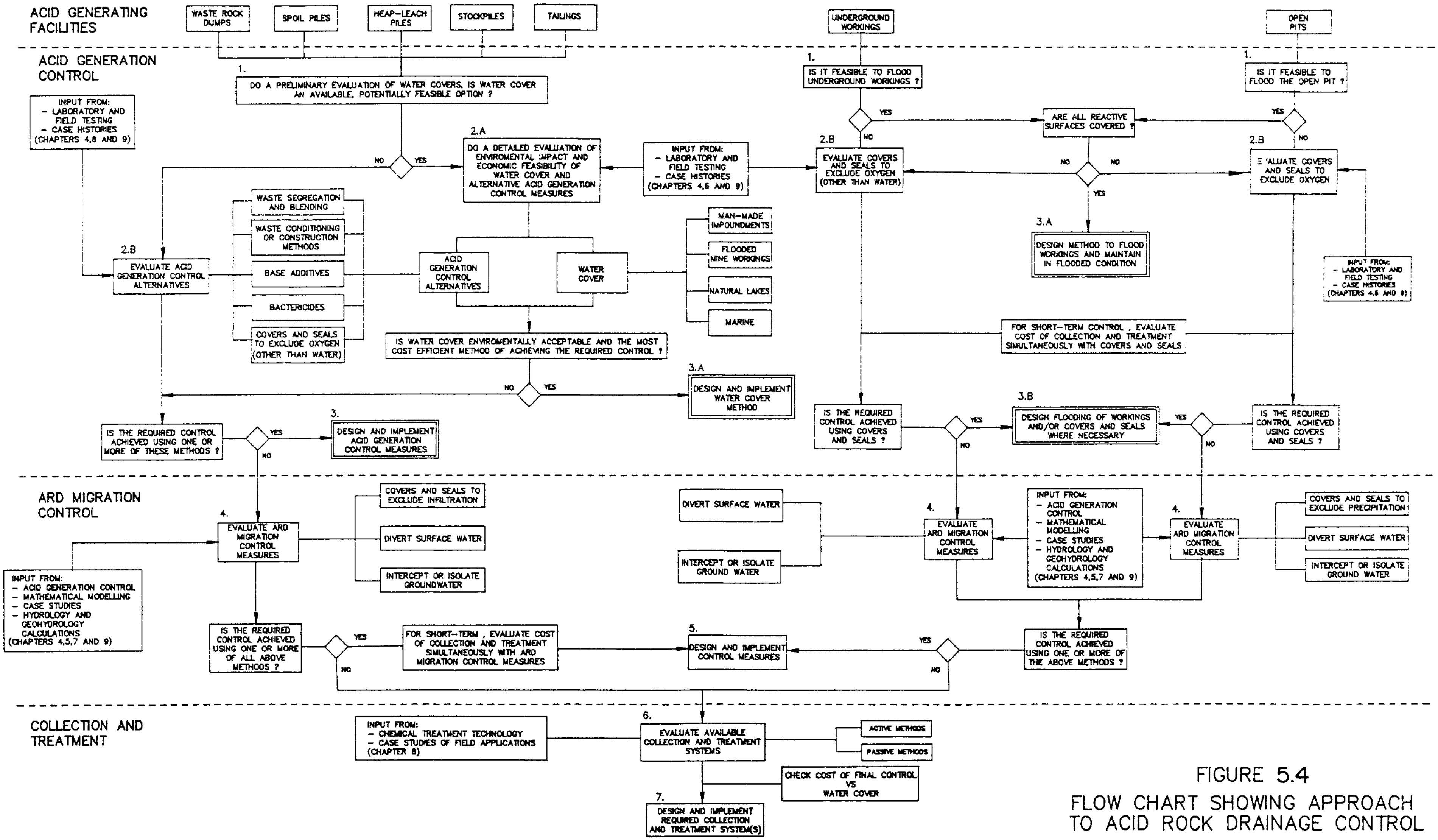


FIGURE 5.4

FLOW CHART SHOWING APPROACH TO ACID ROCK DRAINAGE CONTROL

Stage 1

Do a preliminary assessment of the availability of sites for water cover and the feasibility of this method. The purpose of the preliminary evaluation is to determine whether water cover is at all possible, given that this is currently the most promising control measure. Water cover can be provided by means of any of four general methods as follows:

1) Man-made impoundments that maintain the waste under saturated conditions. This includes man-made lakes and saturated soil/water covers (e.g. constructed swamp/ wetland conditions).

2) Flooded mine workings including underground and open pit mines.

3) Waste disposal into natural lakes.

4) Waste disposal into marine waters

The different types of water cover are discussed in detail in Volume I, Chapter 6.0. Current legislation (e.g. Federal Metal Mining Liquid Effluent Regulations) and the politically controversial nature of lake and marine disposal of mine tailings (acid generating or otherwise) suggests that gaining approval for an application for this method of disposal for tailings will be difficult to achieve (Knapp, 1989). For this reason it is probably beneficial to fully investigate "on-land" means of achieving water cover first i.e. items 1) and 2) above. Lake and marine disposal of tailings should generally only be considered when all on-land options have been exhausted.

The preliminary evaluation should take into account the existing environmental conditions at the site (base-line), the level of control required, availability of suitable sites, and approximate cost estimates. If the initial evaluation indicates that water cover may be feasible, proceed to Stage 2A, if not proceed to Stage 2B.

Stage 2A

Do a detailed environmental appraisal and economic feasibility study of water cover options and the available acid generation control alternatives. The evaluation should first determine whether the required control can in fact be achieved using only acid generation control measures (other than water cover). In some cases, it may be necessary to include one or more measures from the categories of acid generation control, ARD migration control, and/or collection and treatment of ARD to achieve the required control. The cost of water cover should be compared to the cost of the alternatives, or combinations of alternatives, that provide the required level of control. Input at this stage will be derived from the results of laboratory and field prediction tests (see Volume I, Chapter 4.0), some level of baseline environmental measurements (see Volume I, Chapter 11.0) or conclusions drawn from field observations, and records of material and construction costs. Evaluations should consider long-term performance and stability of alternatives (see Volume I, Chapter 9.0). If this study shows that water cover is environmentally acceptable and the most cost efficient method of achieving the requirod control, proceed to Stage 3A. If a combination of alternative meaeures achieves the required control at lower cost, proceed to Stage 3B. If water cover is not feasible, and alternative acid generation control measures do not achieve the required control, proceed to Stage 4.

Stage 2B

If the initial, preliminary evaluation of water cover indicates that this method is out of the question, the acid generation control alternatives should be evaluated in detail to determine the most efficient combination of measures to achieve the required control. If the required control can be achieved using a combination of these measures, proceed to Stage 3B, if not, proceed to Stage 4.

Stage 3A

If water cover is environmentally acceptable and provides the most cost efficient method of achieving the required control, the design and implementation of this method should proceed.

Stage 3B

If one or a combination of acid generation control measures achieve the required control at a lower cost than water cover, design and implement the method(s).

Stage 4

Evaluate available measures to prevent the flow of water into or onto the waste. These include means of excluding infiltration of precipitation, diversion of surface runoff, and interception of ground water. This evaluation may be assisted by input from:

i) The results of Steps 1 to 3B above i.e., what further control is required to meet environmental acceptance criteria.

ii) The results of mathematical modelling of, for example, infiltration through soil covers (see Volume I, Chapter 7).

iii) Data from case histories, e.g., Rum Jungle, Mt. Washington, etc. (see Volume I, Chapter 7).

iv) The results of hydrology and geohydrology calculations to determine design flows, etc.

v) Geotechnical studies (e.g., availability and cost of construction materials for covers).

vi) The results of geochemical testing to evaluate the effectiveness of specific control measures (see Volume I, Chapter 4).

If this evaluation indicates that these measures, together with acid generation control, are adequate, proceed to Stage 5. In the cases where only short-term control is being evaluated, and the cases of control for existing facilities, collection and treatment should be evaluated simultaneously with migration control measures. The reason for this is that collection and treatment may be a feasible short-term measure or, for existing facilities, may represent the only practical option. If the results of the evaluation indicate that further control is required, proceed to Stage 6.

Stage 5

Proceed with the design and implementation of the control measures. A sound design will include a contingency or back-up measure in the event that the predicted level of control is not achieved on site. The design and decision making procedure should be integrated with the monitoring program (see Volume I, Chapter 11.0).

Stage 6

Evaluate available treatment systems including both active and passive chemical treatment methods (e.g., chemical treatment plant, alkaline trenches), and natural treatment methods (e.g., wetlands).

Stage 7

Design and implement collection and treatment. A recommended approach to the development of a chemical treatment plan is shown separately as a flow-chart in Figure 5.1 and described below:

7.1 Identify maximum and average flows. For proposed projects, assign a probability of contamination to each potential source, and list them all. Then, evaluate the potential for equalization ponds before and after treatment, as these are desirable for minimizing plant size and permitting steady, reliable operation.

7.2 Characterize feed (water quality) as well as possible. For proposed operations, make projections based on mineralogy, as well as testwork effluent quality (see Volume I, Chapter 4.0). For an existing problem, conduct a sampling program over at least one year (see Volume I, Chapter 11.0). Estimate the future seasonal quality, and try to determine the requirement for treating new sources that are not currently a problem.

Estimate the probable sludge quality and quantity based on the expected ARD chemistry.

7.3 Evaluate any potential for recovery of valuable constituents. Select the simplest process route. Evaluate the sludge disposal options. The high density sludge process should only be required if sludge disposal is a problem, and there is insufficient pond capacity for clarification. Pressure filtration of sludge should be considered if the sludge has to be trucked off the site. Aeration may be necessary in the treatment process if significant ferrous iron is anticipated. Addition of ferric iron for arsenic control may be necessary if there is insufficient in the feed. Consider special processing options if it is necessary to remove problem contaminants; e.g., Hg, CN, etc. Investigate cheap local sources of alkalinity versus purchased reagents, e.g., tailings, fly ash, limestone, etc.; do a preliminary economic comparison. Generally, try to limit the use of mechanical equipment in favour of long term reliability and reduced operating cost.

7.4 Test the proposed concept in the laboratory. Demonstrate the technical feasibility of meeting the required level of control, determine the required quantities of reagents, demonstrate sludge composition and stability, and develop information for sizing equipment.

7.5 Develop conceptual design. Design the flowsheet, and develop an equipment list. As part of this activity, study the economics of process alternates. Determine the reagent supply arrangements, and design storage and makeup facilities. Decide on the lime slaking method, and determine the need for aeration, clarifier, sludge recycle, and filtration. Determine the type of clarifier. Remember that staged neutralization is preferred over a single vessel. Lay out the general mechanical arrangement. Estimate the capital cost, for budgeting and cost control.

7.6 Complete the detailed engineering, build the plant. This step should be delayed as late as possible so design is based on best available information, however, time must be allowed for commissioning. Emphasize a simple, reliable, minimum maintenance design.

5.6 References and Bibliography

BARTON-BRIDGES, J.P. and ROBERTSON, A.MacG, 1989. Design and Reclamation of Mine Waste Facilities to Control Acid Mine Drainage. Proc. joint conf. CLRA and ASSMR, Calgary, August.

BELL, A.V., 1987. Prevention of Acid Generation in Base Metal Tailings and Waste Rock. Proc. Acid Mine Drainage Seminar/Workshop, Halifax, March.

BROMAN, P.G., 1988. Sulphidic Mine Tailings Deposits in Sweden-Past, Present and Future. Proc of International Conference on Control of Environmental Problems from Metal Mines. Roros, Norway, June.

CITY RESOURCES (CANADA) INC., 1988. Cinola Gold Project, Stage II Addendum Report, Chapter 6.

DALEY, R.J., CARMACK, E.C., GRAY, C.B.J., PHARO, C.H., JASPER, S. and WIEGAND, R.C., 1981. The effects of upstream impoundments on the limnology of Kootenay Lake, B.C. Scientific Series No. 117. West Vancouver, B.C.: National Water Research Institute, Environment Canada.

DUBRORSKY, N.M., 1986. Geochemical Evaluation of Inactive Pyrite Tailings in the Elliot Lake Uranium District. Ph.D. thesis, Department of Earth Sciences, University of Waterloo, Ontario.

ERICKSON, P.M., KLEINMANN, R.L.P. and ONYSKO, S.J., 1985. Control of Acid Mine Drainage by application of bactericidal materials. Control of Acid Mine Drainage, U.S. Bureau of Mines Information Circular 9027, p. 35-40.

ERRINGTON, J.C. and FERGUSON, K.D., 1987. Acid mine drainage in British Columbia: today and tomorrow. Proceedings of the Acid Mine Drainage Seminar/Workshop, Halifax, Nova Scotia, March 23-26, p.67-87. Environment Canada Catalogue En 40-11-7/1987.

HALLAM, R., KUSSAT, R. and JONES, M., 1974. A biological assessment of Benson Lake following cessation of deep lake tailings disposal. Surveillance Report EPS-5-PR-74-2. West Vancouver: Environmental Protection.

HAMILTON, R. and FRASER, W.W., 1978. A case history of underwater revegetation: Mandy Mine high sulphide tailings. Reclamation Review 1:61-65.

HELZ, G.R., DAI, J.H., KIPAK, R.J., FRENDINGER, N.J. and RADWAY, J.C., 1987. Processes controlling the composition of acid sulphate solutions evolved from coal. Applied Geochemistry, 2, 427-436 pp.

HESTER, K.D. & ASSOCIATES, 1984. Practical Considerations of Pyrite Oxidation Control in Uranium Tailings. Research Report prepared for National Uranium Tailings Program. CANMET, EMR, Ottawa.

KLEINMANN, R.L.P., and ERICKSON, P.M. 1983. Control of acid drainage from coal refuse using anionic surfactants. U.S. Bureau of Mines Report of Investigations 8847.

KNAPP, W.D., 1989, Letter and detailed comments on Technical Guide draft, addressed to B.C. AMD Task Force, dated May 30, 1989, Fisheries and Oceans Canada Reference 8366-1.

KNIGHT, R.B. and HAILE, J.P., 1983. Sub-Aerial Tailings Deposition. Proc. 7th PANAM Conference, Soil Mechanics and Foundation Engineering, Vancouver. Vol. II.

LADWIG, K.J., ERICKSON, P.M., KLEINMANN, R.L.P. and POSLUS, E.T., 1984. Stratification in Water Quality in Inundulated Anthracite Mines, Eastern Pennsylvania. U.S. Dept. of the Interior, Bureau of Mines Report RI 8837.

MAGNUSSON, M. and RASMUSON, A., 1983, Transportberakningar pd vittringsforloppet i gruvavfall. The National Swedish Environmental Protection Board, Report SNV PM 1689 (in Swedish).

MILNER, T.E., 1987. Management Plan for Acid Mine Drainage for the Quinsam Coal Mine. Proc. 11th Annual B.C. Mine Reclamation Symposium, Campbell River , April.

MORIN, K.A. and CHERRY, J.A., 1986. Trace amounts of siderite near a uranium-tailings impoundment, Elliot Lake, Ontario, and its implication in controlling contaminant migration in a sand aquifer. Chemical Geology, 56, p. 117-134.

NOLAN, DAVIS and ASSOCIATES, 1987. Study of Acid Waste Rock Management at Canadian Base Metal Mines. June.

NTDME (Northern Territory Department of Mines and Energy), 1986. The Rum Jungle Rehabilitation Project - Final Project Report. Darwin. June.

PEDERSON, T.F., 1983. Dissolved heavy metals in a lacustrine mine tailings deposit-Buttle Lake, British Columbia. Mar. Pollut. Bull. 14(7):249-254.

POLING, G.W., 1979. Environmental considerations in tailings disposal. CIM Bulletin.

PROVINCE OF BRITISH COLUMBIA, ACID MINE DRAINAGE TASK FORCE, 1989. Acid Mine Drainage Draft Technical Guide - Volume I, Chapters 6.0, 7.0, 8.0, & 9.0. Prepared by Steffen Robertson and Kirsten, in association with Norecol Environmental Consultants and Gormely Process Engineering.

RASTOGI, V. and SOBEK, A.A., 1986. Reclaiming abandoned mine lands using controlled release bactericides: a case study. Proceedings of the 8th Annual Abandoned Lands Conference, Billings, Montana, August 10-15.

ROBERTSON, A. MacG., 1987. Alternative Acid Mine Drainage Abatement Measures. Proc. of the 11th annual B.C. Mine Reclamation Symposium. Campbell River, B.C. April.

SENES CONSULTANTS LIMITED, 1984. Report on the Assessment of the Mechanism of Bacterially-Assisted Oxidation of Pyritic Uranium Tailings. Reseacch Report Prepared for the National Uranium Tailings Program, CANMET, EMR, Ottawa.

SKOUSEN, J.G., SENCINDIVER, J.C. and SMITH, R.M., 1987. A Review of Procedures for Surface Mining and Reclamatien in Areas with Acid-Producing Materials. W. Virginia Surface Mine Drainage Task Force, W. Virginia Energy and Water Research Center, W. Virginia and Reclamation Assoc. Morgantown, W.V.

SOBEK, A.A., 1987. The use of surfactants to prevent AMD in coal refuse and base metal tailings. Proceedings of the Acid Mine Drainage Seminar/Workshop, Halifax, Nova Scotia, 23-26 March. Environment Canada Catalogue No. EN 40-11-7/1987.

STEFFEN, ROBERTSON AND KIRSTEN, 1987(a). Acid Mine Drainage Abatement Study, Mount Washington, Vancouver Island, British, Columbia. Report No. 62701/1 for Province of British Columbia Ministry of Environment and Parks.

STEFFEN, ROBERTSON AND KIRSTEN, 1987(b), Alternative Measures for Acid Mine Drainage Abatement at Norwegian Mines. Report 64701/1. November.

STEFFEN ROBERTSON AND KIRSTEN, 1988(a). Report on the Technology of Acid Generation and Metal Leaching from Solid Mine Waste. Report 63701/1, Prepared for the American Mining Congress, January.

STEFFEN, ROBERTSON AND KIRSTEN, 1988(b). Acld Mine Drainage in British Columbia. Analysis of Results of Questionnaire for the B.C. Acid Mine Drainage Task Force. Report 66001/1.

STEFFEN, ROBERTSON AND KIRSTEN, 1988(c). Cover Technology for Acid Mine Drainage Abatement: Literature Survey for Norwegian State Pollution Control Authority, Report No. 64701/1.

STURM, J., 1987. Materials for Mine Spoils and Coal Refuse. Proc. of Acid Mine Drainage Seminar/Workshop, Halifax, Nova Scotia. March.

6.0 MONITORING

6.1 Introduction and Objectives of Monitoring

In general terms, environmental monitoring in and around a minesite is intended to define baseline conditions and to identify changes in conditions during and after mining. This information is generally used for decision making regarding mitigation and reclamation strategies.

The environmental conditions monitored typically include physical processes such as water flow and geotechnical stability, chemical characteristics such as water quality, along with biological response and impacts such as productivity. The major objective of a monitoring program in the acid rock drainage context is to monitor the effectiveness of the prevention/control/treatment techniques and to detect at the earliest point in time if the techniques are unsuccessful.

6.2 Recommended Approach to Monitoring

A flowchart outlining a proposed environmental monitoring approach is presented in Figure 6-1 addressing Pre-operational, Operational, and Closure Phases of a mining project.

6.2.1 Pre-operation Monitoring

In the pre-operational phase (Figure 6-1), baseline monitoring defines existing environmental conditions of the physical, chemical and biological aspects of the area. This information leads to the identification of areas that are particularly sensitive to changes in environmental conditions and provides essential data to allow the assessment of changes or impacts caused by each component of the mine and mining activities.

In terms of acid generation, testwork is conducted in the pre-operational phase to determine the potential of each waste material from the various mine components to generate net acidity and acid drainage. Each of the potentially acid generating materials may be further tested to determine the rate and duration of acid generation and its associated water quality. The design and testing of the required control and treatment techniques may also be conducted in this phase. The mine plan is adjusted in order to reliably implement the control/treatment techniques, to reliably eliminate acid drainage, and to minimize combined costs of environmental protection, mine construction, and operation.

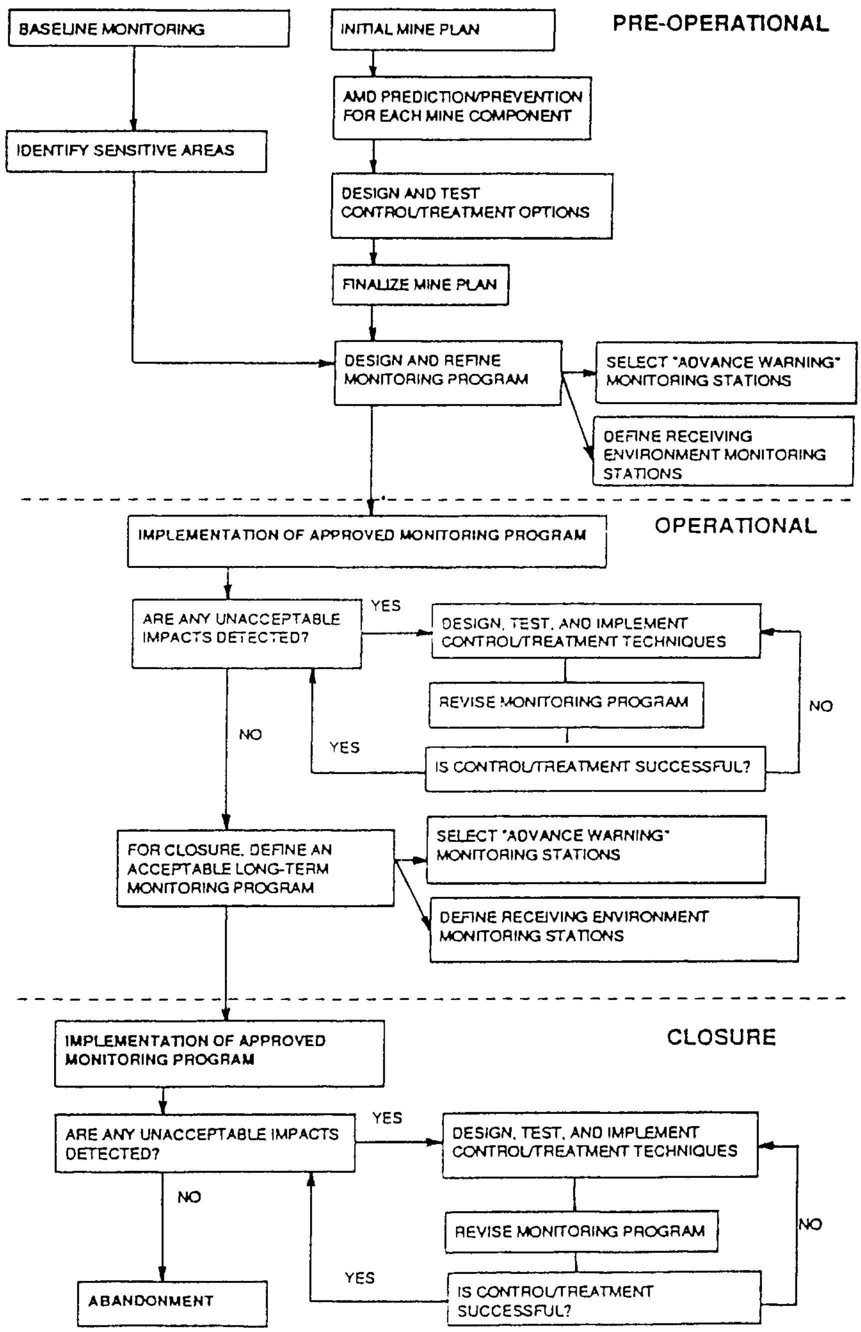


FIGURE 6.1
RECOMMENDED APPROACH TO ENVIRONMENTAL MONITORING

6.2.2 Monitoring During Operation

Using the baseline information and the final mine plan, a monitoring program is established for mine operation. A detailed flowchart of a proposed integrated on-site/off-site monitoring program for operation and closure is presented in Figure 6-2. Two types of monitoring stations have been defined for this approach: an effluent discharge point and the receiving environment. An effluent discharge point is generally, but not necessarily, located on the mine property (on-site) while the receiving environment stations will generally, but not necessarily, be off-site.

In the proposed program, monitoring stations are established in or near all environmentally sensitive areas potentially affected by the development including both surfacs water and groundwater stations.

A minimum of one surface water and/or groundwater monitoring station should be selected at a defined disoharge point from each component to be an "advance warning" station in order to provide early warning of potential failure of acid prevention/control/treatment techniques. The advance warning stations should be located downstream and as close to the potential source as possible. Each mine component usually has at least one discharge point that can be selected as an advance warning station. These stations should be monitored at least monthly for; pH, sulphate, alkalinity, acidity, electrical conductance and selected metals depending on site specific conditions. Zinc is usually monitored because elevated zinc concentrations at neutral pH in drainage from wastes can be an indication that acid generation is occurring within the waste material but is being neutralized before it emerges and is intercepted. A significant decrease in pH or alkalinity and an increase in sulphate, acidity, iron, or conductance will indicate the onset of acid drainage. However, extreme care must be used in separating site-specific trends in water quality, such as seasonal variations in pH, from the onset of acid drainage.

Monitoring stations in the receiving environment in the vicinity of each mine component can be established within, upgradient of, and downgradient of the component for surface and groundwater flows. Downgradient stations, as defined by the movement of surface water or groundwater from the component, should be placed at various distances from the mine component in the receiving surface water and groundwater. Upgradient stations provide data for comparison with downgradient stations to determine the degree and spatial extent of impacts due to each component.

All stations should be monitored at least semi-annually for a full set of water quality analyses: pH, sulphate, alkalinity, acidity, electrical conductance, major cations and anions, nutrients and a suite of metals. Stations monitoring may also be used for monitoring water flow rates. Biological monitoring is not considered to be as reliable, as rapid, or as consistent as water-quality measurements and visual observations for the detection of acid drainage. Consequently, biological monitoring is not emphasized here for detecting acid drainage,

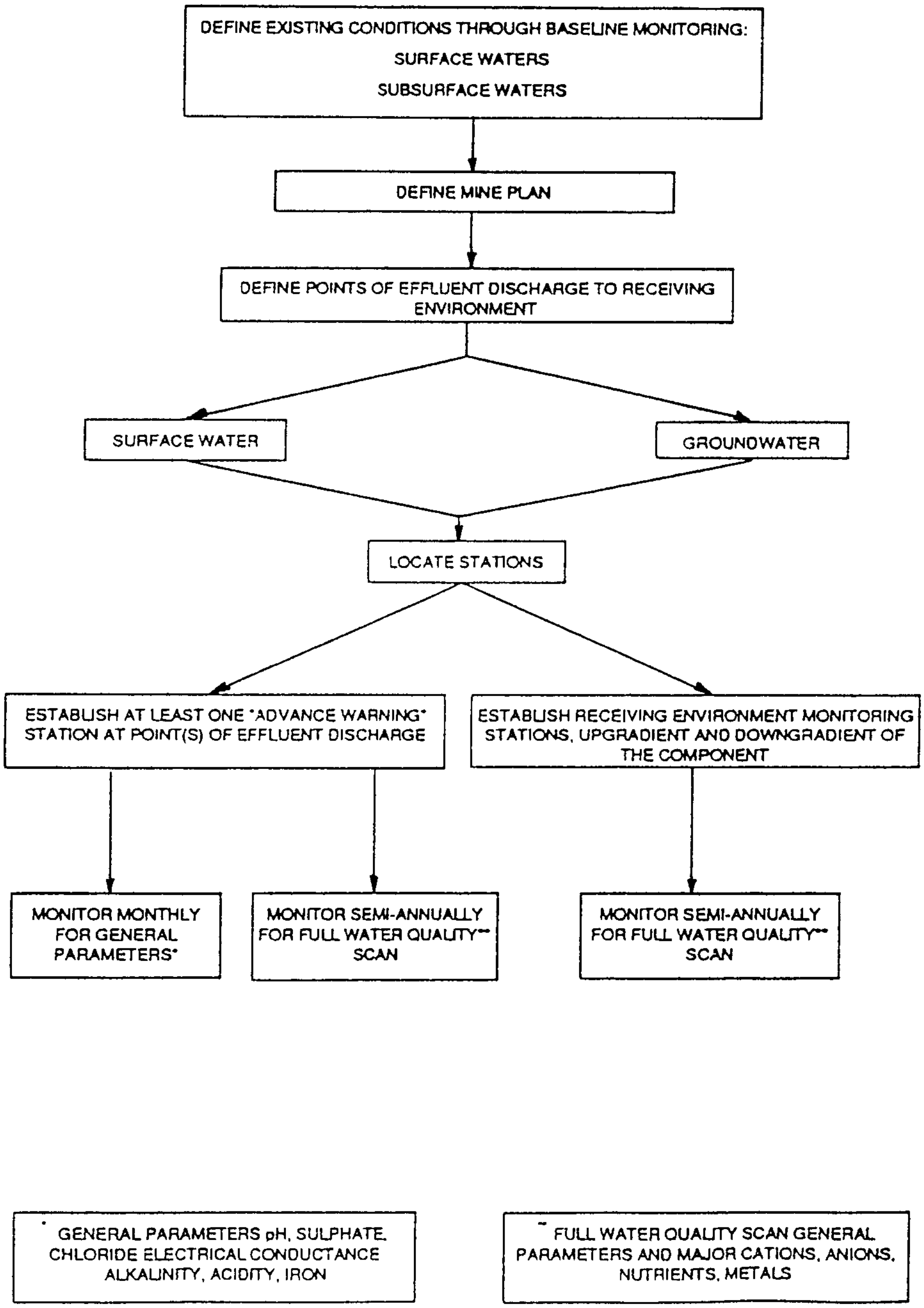


FIGURE 6.2
DESIGN AND REFINEMENT OF INTEGRATED ON-SITE/OFF-SITE MONITORING PROGRAM (FOR OPERATIONS AND CLOSURE)

although certain mines such as those located near important fisheries may be required to monitor productivity, species diversification, or metal levels in fish tissue. Nevertheless, an annual biological survey of the minesite and surrounding off-site region is recommended as contingency monitoring to check for changes in vegetation or fisheries which may indicate the migration of acid drainage not detected by an established monitoring network. This situation, for example, could arise during a first flush event where acid products are released between sampling periods of the monitoring stations. Visual inspections of seeps and streams is recommended so that metal salts and other noticeable precipitates can be identified as early as possible.

The monitoring program implemented during the operational phase of the mine (Figure 6-1) should detect changes in environmental conditions at any station. If these changes are significant, more frequent monitoring should be performed at that station and at other stations to confirm the presence and spatial extent of the change. If an adverse impact is determined, alternative control or treatment techniques should be designed, tested, and implemented. The monitoring program should be revised to moniter the success of the new techniques.

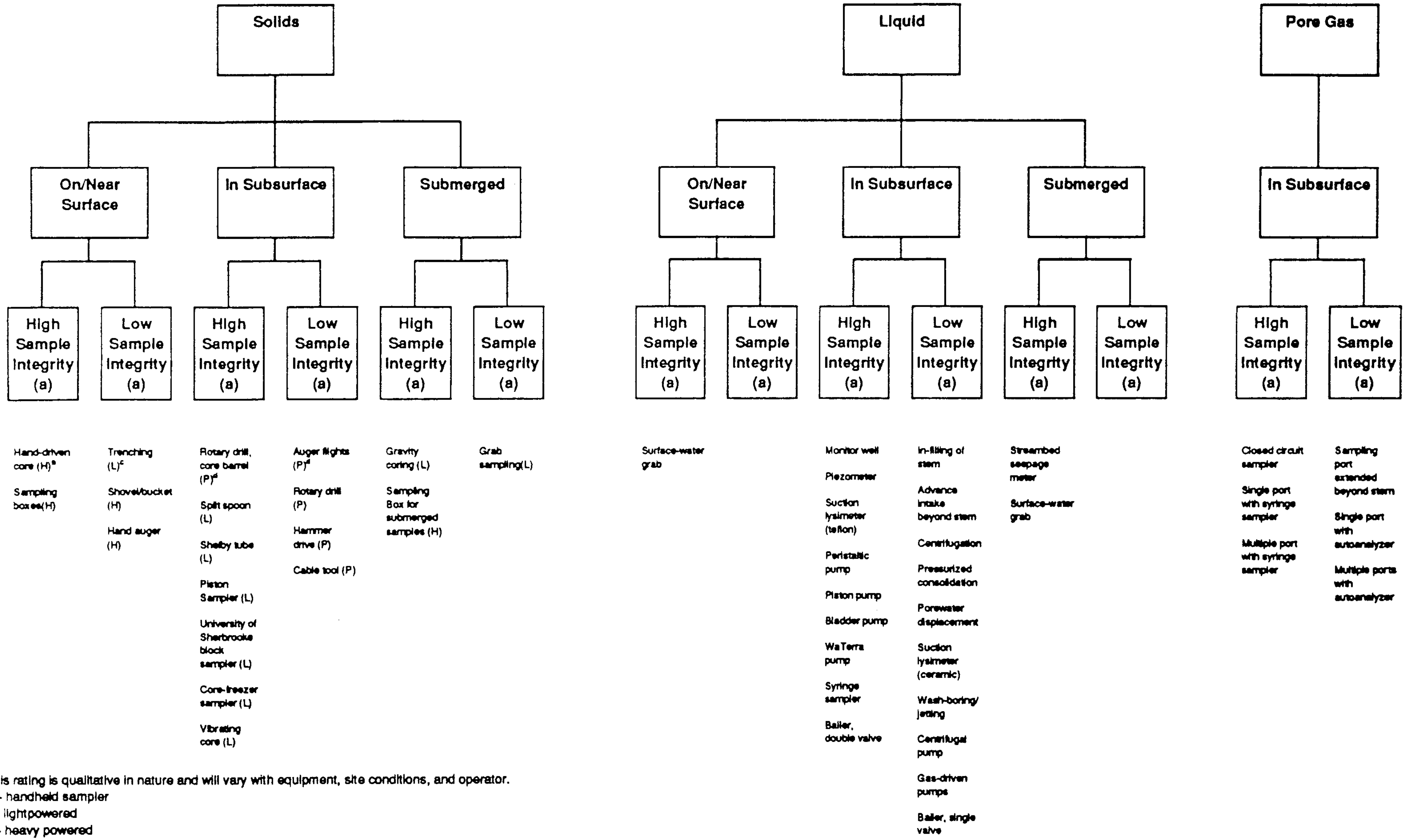
If no unacceptable impacts exist towards the end of the mine life, a long-term monitoring program for closure would be defined (Figure 6-2). Each of the steps in Figure 6-2 should be performed because operational conditions at a mine ("baseline" for closure) will be different than pre-operational conditions.

6.2.3 Monitoring After Closure

The long-term monitoring program implemented during and after closure would decrease in frequency of sampling as time-from-closure increases. If significant changes in environmental conditions are detected at any station, additional monitoring should be performed at that station and at other stations to confirm the presence and spatial extent of the change. If the adverse impact is confirmed, alternative control or treatment techniques must be designed, tested, and implemented. The monitoring program must then be revised to monitor the success of the new techniques. If no unacceptable impacts are detected over an acceptably long period of time the site can proceed with abandonment.

6.3 Sampling Methods

There are numerous methods available for on-site and receiving environment monitoring for acid rock drainage impacts. Figure 6-3 provides a flowchart to select the sampling method required for various types of samples, either on or near surface, in the subsurface or submerged. The methods are further separated to high and low sample integrity. The methods are described along with its advantages and disadvantages in Field Sampling Manual for Reactive Sulphide Tailings (Canect Environmental Control Technology, 1989).



This rating is qualitative in nature and will vary with equipment, site conditions, and operator.
H - handheld sampler
L - lightpowered
P - heavy powered

FIGURE 6.3
FLOWCHART FOR SELECTION OF SAMPLING METHODS

6.4 References and Bibliography

CANECT ENVIRONMENTAL CONTROL TECHNOLOGY, 1989 Field Sampling Manual for Reactive Sulphide Tailings. Prapared for CANMET.

PROVINCE OF BRITISH COLUMBIA, ACID MINE DRAINAGE TASK FORCE, 1989. Acid Mine Drainage Draft Technical Guide - Volume I, Chapters 6.0, 7.0, 8.0, & 9.0. Prepared by Steffen Robertson and Kirsten, in association with Norecol Environmental Consultants and Gormely Process Engineering.

STEFFEN, ROBERTSON AND KIRSTEN, 1988. Acid Mine Drainage in British Columbia. Analysis of Results of Questionnaire from Acid Mine Drainage Task Force. Report 66001/1.