REVIEW OF WASTE ROCK SAMPLING TECHNIQUES

MEND Project 4.5.1-1

This work was done on behalf of MEND and sponsored by
SENES Consultants Limited in association with
Golder Associé Ltée and Laval University Département de Géologie Faculté des Sciences et de Génie

June 1994

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SAMPLING TECHNIQUES

Prepared for:

Energy Mines and Resources
CANMET- MSL Division
(MEND Project 4.5.1)

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June 1994

ABSTRACT

This report is a review of waste rock sampling techniques. Part A presents a literature review and discussions of the various waste rock sampling techniques. Part B provides guidance to a broad spectrum of concerned parties as to the available sampling techniques and suggested methodologies to apply during the various stages of a mine development. The objective is to ensure that adequate data are collected during all stages of the mine development to ensure the database exists to evaluate the acid generating potential of the waste. The evaluation would normally include Acid Rock modelling using both empirical and computer based models. For demonstration of how these techniques have been applied, Part C of this report also provides an actual example of how data were collected and utilized to assess ARD potential at a site in Canada.

Version française - MEND

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1.0 INTRODUCTION

1.1 OVERVIEW

Over the past decade, one of the most serious environmental concerns facing the mining industry has been the control of acid rock drainage (ARD). While mining companies have made significant progress in managing tailings and mine effluents, considerably less care has historically been directed at the management of waste rock. Waste rock was often considered to be an inert pile of overburden whose management represented a major cost only during the development phase of a mine. As a result, the key driving force to management of the waste was economics, and waste was placed for convenience, with little regard to the chemical characteristics and pollution potential of the waste.

It is now apparent that waste rock can represent a serious long-term environmental concern, and a liability. Often times these liabilities are far greater than those associated with tailings disposal. Recent experience has shown these liabilities have been as high as tens of millions of dollars at selected locations. This order of expenditure can play a major role in the feasibility of mine development.

Understanding the scope of the waste management problem and good upfront planning can lead to rational engineered solutions which can mitigate potential environmental concerns and reduce financial liabilities.

Environmental monitoring has become an integral component in the development and operation of all mines. Monitoring is required to establish baseline information, to evaluate the performance of control measures, to assess the need to revise management plans, and to demonstrate compliance with regulations. Monitoring requirements can generally be divided into three phases for a mine development: the Predevelopment or Exploration phase, the Operation phase and the Decommissioning or Closure phase.

This review of waste rock sampling techniques is intended to provide guidance to the mining industry, consultants and regulatory personnel as to: the type of data required to identify whether a problem exists; the types of testing and analytical procedures available to obtain this data; and the procedures that should be followed to ensure appropriate solutions can be identified.

This document has been prepared for the Mine Environment Neutral Drainage (MEND) Program, of the Canadian Centre for Mineral and Energy Technology (CANMET), Energy, Mines and Resources (EMR) Canada.

The British Columbia Acid Mine Drainage Task Force has also issued a documented entitled "Field QA/QC Protocols for Monitoring and Predicting Impacts of Acid Rock Drainage" (Norecol 1992) which reviews sampling program design and field procedures for sampling the mining wastes and environmental components.

Saskatchewan Environment and Public Safety, Mines Pollution Control Branch have also issued a document entitled "Mine Rock Guidelines: Design and Control of Drainage Water Quality" (SRK 1992) which is intended to be a working draft document for regulatory agencies, industry and researchers and scientists in the uranium mining industry, to provide guidance and recommendations for state-of-the-art in prediction, control and monitoring of ARD.

1.2 TERMS OF REFERENCE

The original terms of reference for preparation of a Waste Rock Sampling Manual were tabled in a request for proposal from the MEND Monitoring Committee. The requirement was subsequently modified into a phased development:

- Phase I - Review of Waste Rock Sampling Techniques; and
- Phase II - Handbook for Waste Rock Sampling.

The Review is intended to form the basis for representative and cost effective sampling of physical and chemical properties and the sampling of bacteria. Physical attributes include such parameters as gas diffusion, dump porosity, thermal conductivity and size distribution, while total sulphur, buffering capacity and effluent chemistry would be included in chemical sampling. The parameters measured should encompass those required for current predictive techniques. Future liability associated with ARD is being predicted through simple sample testing and increasingly through more complex modelling.

For the Review, all applicable, state-of-the-art techniques for sample collection are described. Sampling is considered for the mining stages of exploration, operation and post-operation. The objectives of each of the various procedures is outlined. The limitations and advantages of each procedure (qualitative/quantitative), relative to the others are stated. An international survey of industry, researchers and regulators was used to identify currently used techniques and which techniques are and are not recommended and why. This survey is described below in Section 1.4.

Phase II Handbook is intended to highlight the recommended approach and key sampling techniques identified through:

- Phase I review of sampling techniques;
- a survey of industry, researchers and regulators; and
- an experts workshop (proceedings available as a separate MEND document).

The Phase II Handbook is also intended to address the following issues: the notion of a representative sample; quality assurance and control; sampling program design; data management; effect of data on management/operational decisions; and, the potential generation and use of waste rock standard reference materials.

1.3 REPORT FORMAT

The Phase I Review of Waste Rock Sampling Techniques is divided into three parts:

- Part A (Chapter 2) provides a state-of-the-art review of all waste rock sampling techniques that have been identified through the course of this study. These techniques are all potential test procedures that could be applied to obtain data that are required to characterize and model ARD in either the exploration, operational or decommissioning phases of a project. References are provided.

- Part B (Chapters 3, 4 and 5) addresses the specific data requirements and strategies to be employed for each of the mine development phases:

    (i) Predevelopment or Exploration;
    (ii) Operation; and
    (iii) Decommissioning or Closure.

- Part C (Chapter 6) provides an overview of a case study for a current state-of-the-art waste rock monitoring program, at La Mine Doyon, Quebec, Canada.

1.4 WASTE ROCK SAMPLING SURVEY

An international survey of industry, researchers and regulators was carried out to identify currently used sampling techniques for waste rock and develop a list of recommended approaches and key sampling techniques. An attempt was made to ensure balanced representation from:

(i) industry, researchers and regulators;
(ii) international/geographical areas;
(iii) types of mines (e.g. base metal, precious metal, etc.)
(iv) stage of mine (e.g. exploration, operation, closure); and
(v) nature and magnitude of acid mine drainage.

The actual representation was determined from the responses to the survey and is described below.

The waste rock sampling techniques (described in Chapter 2) were listed by category and the participants were asked to indicate which technique(s) were or were not used and which techniques should be added (deleted) and why. A summary of the number of responses for each category is provided below.

In addition, for each category of techniques, participants were asked to provide written response to the following typical questions:

- How often, and/or how many samples do you use to determine a particular parameter?
- Which techniques do you recommend and why?
- Which techniques have you used, and is use of these techniques current, regular, experimental or planned?
- What is the cost associated with implementation of these techniques and what is the basis for the cost estimate (e.g. sample collection, labour, analysis, instruments, etc.)?

The results of the survey were entered into a database and were used in the preparation of both this Review and the Handbook of Waste Rock Sampling Techniques.

<u>Representation</u>

The respondents to the survey were identified as belonging to one of the following three categories:

19	Industry (mining company, consultants)
6	Researchers (universities, organizations)
8	Government
33	total

The type of mines represented by the respondents to the survey included:

28	Base Metal (open pit/underground)
18	Precious Metal (open pit/underground)
8	Coal (surface/underground)

6	Non-mining ARD uranium (open pit/underground)

The international/geographic areas represented by the survey respondents were:

6	Canada wide	
4	Atlantic Canada	
8	British Columbia	
1	Western Canada	
2	Manitoba	
3	Ontario	
4	Saskatchewan	
2	Quebec	Total Canada30
3	United States	
1	Eastern U.S.	
3	Western U.S.	
1	Northern U.S.	
1	Southern U.S.	Total U.S.9
2	Australia	
4	Sweden/Norway	
2	Indonesia	
2	Papua New Guinea	
1	Peru	
1	Mexico	
2	Miscellaneous Countries	Total International 14

The stages of mining represented were:

2	predevelopment/exploration
3	development
12	production/operation
8	closure
14	all stages

The location and/or configuration of the waste rock included:

8	surface
13	surface-lifts
2	surface-end dumping
1	surface - alternating layers acid generating/acid consuming
1	surface - tailings dam
1	surface - tailings
2	underground - backfill
2	submerged in water
1	open pit and underground mine wall rock
1	various

In total, 93 surveys were sent out; 23 persons declined to participate, and 33 completed surveys were returned. In our experience, a survey response rate of 15 to 20% can be considered to be a good response. Since the waste rock sampling survey was mailed to a carefully selected list of individuals that are known to be active or interested in this area, we expected and obtained, a higher response rate. Based on the total number of surveys sent out, the response rate was 35%, however it should also be noted that a number of persons who were sent a survey actually returned a collaborative response with others.

Although most respondents did not complete every page of the survey (i.e. category of techniques), the responses provided were generally adequate.

The following summary shows the number of respondents that provided information for the various categories:

28	1.	Statistical Sampling Methodologies for Obtaining a Sufficient Number of Representative Samples of Waste Rock
27	2.	Chemical Characterization of Waste Rock
28	3.	ARD Assessment Test Procedures for Waste Rock
24	4.	Physical Stability of Waste Rock
29	5.	Water Monitoring Associated with Waste Rock
15	6.	Gas Sampling in Waste Rock
22	7.	Temperature Measurements in Waste Rock
20	8.	Permeability Measurements in Waste Rock
24	9.	Waste Rock Particle Size Characterization
13	10.	Porosity of Waste Rock
18	11.	Water Content of Waste Rock
26	12.	Flow Monitoring Associated with Waste Rock
20	13.	Infiltration Associated with Waste Rock
12	14.	Biological (Bacteria) Monitoring Associated with Waste Rock
24	15.	Meteorology Measurements Associated with Waste Rock
6	16.	Thermal Analysis of Waste Rock
17	17.	Drilling Techniques for Waste Rock

The nature of the ARD described by the various respondents was:

- weakly to strongly acidic;

- contained trace to high levels of heavy metal contamination (and in some cases radionuclides);
- often contained high sulphate;
- often varied considerably within or between waste rock dumps;
- often ARD at site not fully understood or characterized; and
- in some cases ARD and contamination not yet detected.

The results of the survey are incorporated into Chapter 2.0 - Sampling Techniques.

PART A

2.0 SAMPLING TECHNIQUES

2.1 SAMPLE PROGRAM DESIGN

It has been stated, that perhaps the most important step in the collection of geologic data is the sampling procedure (Freeman et al. 1987). For a meaningful sampling strategy, the objectives of the sampling need to be clearly defined. Once these are defined, the design of the sampling program is relatively straight forward. Whitfield (1988) has recommended a five-step process for developing a sampling strategy for water quality monitoring. This process application differs from the present case, and the five-steps have been reworded accordingly: establish the objectives, select a sampling strategy to meet the objectives, periodically review the sampling strategy, optimize the sampling, and review the adequacy of the objectives.

2.1.1 Statistical Sampling Methodology

The primary objective in ARD sampling is the collection of a sufficient number of representative samples to obtain the required precision. ARD sampling is preferably performed on *in situ* rock during the exploration, development and operation stages of mining, usually in conjunction with sampling to assess the economic potential of the ore body. If records and samples from exploration and operation of a mine do not exist, then the waste rock piles themselves will have to be sampled. Part B of this report discusses waste rock sampling requirements for the exploration, operation and decommissioning phases.

For ARD sampling of *in situ* rock, a statistically sufficient sampling of each physical and chemical geological unit is required to ensure that the units are adequately characterized. The accepted methods of geostatistical ore reserve estimation should be followed to characterize *in situ* waste rock. The method used at a mine for ore reserve estimates should be suitable and cost-effective to use for waste rock. Advice and assistance should be sought from the geologist/engineer involved in assessing the ore deposit. David (1977) provides an excellent and thorough discussion of geostatistical ore reserve estimation. Peters (1979) summarizes the sampling of orebodies and estimating of reserves. For ARD assessment, a record of where and when each unit of waste rock is placed in waste rock piles is also required.

For ARD sampling of existing waste rock piles, each pile may be sampled as a single unit, or divided into regions depending on variation within the pile. A record of the placement of waste rock in the pile is useful for determining how to sample the pile. For example, if dumps are built in small lifts, various rocks sizes will be relatively well distributed throughout the dump. However if waste dumps are constructed by end dumping from a high face, substantial segregation of the rock sizes will occur with the larger rocks located in the lower horizons. This will affect rock porosity, permeability etc. throughout the dump. Both horizontal and vertical characterization need to be assured. Waste rock piles are, by nature of construction, heterogeneous; sampling should be sufficient to ensure that the waste pile can be adequately characterized by homogenous regions.

Statistical sampling methodology and statistical analysis, as applied to earth science, have been thoroughly documented by Marsal (1987). Till (1974) offers an introductory overview, while Williams (1986) presents a more detailed treatise of statistical methodology. Data analysis is usually parametric (mean, variance) and based on the normal distribution. Sample population homogeneity is tested by either the student-t test or by the analysis of variance (ANOVA). Non-parametric (i.e. distribution-free) statistical tests such as the Wilcoxon's rank sum, for example, are applied less frequently since they require a larger number of samples for the same degree of certainty (i.e. probability level).

The minimum sample number for ARD characterization is currently under review. The British Columbia Acid Mine Drainage Task Force (1989) recommends a tentative minimum sample number based on the size of a geological unit (refers to *in situ* rock during exploration or operational phase). The curve generated has been based on unpublished field data. An approximate mathematical expression for the recommended minimum number of samples is as follows:

$$N \quad 0.026\ M^{0.5}$$ **Error! Switch argument not specified.** (2.1.1)

where:

N = number of samples

M = mass of geologic unit in tons ($M > 6 \times 10^3$ ton)

For a mass of 6×10^3 ton, the minimum number of samples is two. For a 10^6 ton waste deposit, for example, the minimum predicted sample size is 26. This value is in good agreement with the estimate based on field data.

In the state of Pennsylvania, the suggested rule for calculating the minimum number of boreholes per seam (coal mine) based solely on acreage (Brady and Hornberger 1989) is as follows:

$$\frac{acres}{100\ acres} + 2 \quad number\ of\ overburden\ holes$$ **Error! Switch argument not specified.** (2.1.2)

where overburden refers to geologic strata located above the reserve.

Freeman et al. (1987) have recommended that the areal extent of a coal mine be used as the basis for determining the sample number. The number of overburden column samples are to be collected at intervals of 1 km or less at critical regions. A large mine site may require one to three sample columns for each 1,000 acres of consistent stratigraphy. This approach to ARD methodology is not applicable for base metal mines.

Robertson (1990) warns against a sampling strategy based on fixed sample numbers, and recommends a preliminary sampling program for determining the optimum sampling strategy. Recommended improved sampling strategies include combinations of the following techniques; replicate sampling, sequential sampling, exceedence driven sampling, and stratified sampling (Robertson 1990).

Replicate sampling involves taking several samples at the same location. These are useful, when the objective is the determination of the mean (rather than extreme value) and the sample variance is predictable. Replicate sampling is said to be ideal for parametric statistical methods.
Sequential sampling is a good strategy when the variance (i.e. the variation) between sample is unknown. Unnecessary, redundant sampling is avoided, since the sampling is performed until a desired precision (i.e. variance reduction) is obtained.

Exceedence driven sampling strategy is designed to identify maximum (extreme) values. In this case, the sampling number is increased at locations where a given constituent tends to peak or reach a minimum (for example pyrite concentration or acid neutralization capacity). This is a non-parametric sampling method and the estimation of a "true" average value is of secondary importance. In fact, the estimate of the mean is likely to be biased.

Markovian sampling strategy also reflects the rise above a threshold level determined by previous (preliminary) sampling. The sample size is adjustable and based on "alert" levels. In a highly variable sample space, Markovian sampling is more responsive than the exceedence driven strategy. However, Markovian sampling cannot be used to obtain an unbiased estimate of either the mean or the extreme value.

Stratified sampling strategy divides the waste rock pile into homogeneous units. After a preliminary sampling, further sampling within that unit would be based on the variance within that strata. Stratified sampling allows cross correlation of data, and hence, provides some statistical predictability. The data may be used in parametric statistical tests of unequal sample size. Some parametric statistical tests are sensitive to departure from equal sample size (e.g. ANOVA).

2.1.2 Data Management

The sampling program will generate a considerable amount of data that will need to be properly managed to facilitate periodic review and revision of the sampling strategy. A database format is recommended.

The British Columbia Acid Mine Drainage Task Force authorized the construction of an acid drainage database. This database, DBARD, the Data Base for Acid Rock Drainage, is designed to accept, store, and retrieve relevant data from acid-drainage test work, including data from one-time or repetitive laboratory experiments and static and kinetic tests. Table 2.1.1 lists the input data for DBARD. The database is currently being filled with data available from proposed and operating mines in British Columbia. The database structure may be made available to individual mines to store and organize their own data from ARD testwork conducted specifically for their facility.

Smith and Brady (1990) describe the use of spreadsheet programs for personal computers to carry out the numerous repetitive calculations necessary for integrating large quantities of data (in this case, for acid-base accounting analysis of overburden). The spreadsheet approach allows for more complex and detailed analysis and facilitates the comparison of calculation methods.

The relatively recent development of expanded database management software and geographic information systems (GIS) are also of great assistance for managing and interpreting data.

2.2 SAMPLING TECHNIQUES

2.2.1 Chemical Characterization

There are three types of data required to chemically characterize waste rock: elemental content, mineralogy, and mineral forms.

i) Elemental Content

The recommended procedures would be total acid digestion of the sample with multi-element determination by ICP/mass spectrometry or an equivalent method. Most laboratories offer packages for elemental analyses. An elemental scan of about 40 elements would normally encompass the minerals for which data are required. Analyses for uranium and radionuclides (radium-226, polonium-210, lead-210, thorium-230) would also be required for waste rock from uranium mining properties, for example. Low cost, low quality labs should be avoided. For arsenic, mercury etc. alternative analysis methods should be selected. A quality assurance program is required and limits of detection should be specified.

The waste rock samples should be analyzed for the various forms of sulphur (sulphide, sulphate, organic sulphur). The sulphide form is generally considered to be the primary source of acid. Methods for determining sulphide content are described under ARD prediction methods in the next section. ICP sulphur analysis may not be reliable unless a quality assurance program is included (i.e. correlation with LECO sulphur). Also, other elements such as arsenic and mercury have to be assessed by alternate methods such as wet chemistry or atomic absorption.

Samples are usually taken when boreholes are logged. Sample preparation (e.g. crushing) and analysis is usually done by a commercial lab.

Sample preparation and analysis is about $200/sample on average. ICP laboratory analysis costs $5-$75/sample, depending on number of elements requested, lab, etc. X-ray diffraction laboratory analysis costs ~$25/sample. Sulphur speciation is $25/sample.

ii) **Mineralogy**

Data on elemental content are routinely collected at mining properties. However, the distribution of various sulphide minerals is often not established. Considering ARD, the most significant sulphide minerals are pyrite ($Fe\ S_2$), pyrrhotite ($Fe_{1-x}S$), chalcopyrite ($Cu\ Fe\ S_2$), sphalerite ($Zn\ S$), and arsenopyrite ($Fe\ As\ S$). These minerals differ in their inherent chemical and biochemical oxidation rates. Therefore, the determination of the mineralogical content (as % pyrite, pyrrhotite etc.) is essential.

Both chemical and biological oxidations are pH dependent. The presence of buffering minerals, particularly calcite ($Ca\ CO_3$) dolomite ($Ca\ Mg\ (CO_3)_2$) siderite ($Fe\ CO_3$), aluminum ($Al\ (OH)_3$) and iron hydroxides ($Fe\ (OH)_3$) and silicates are important. The sulphide mineral content together with the buffering mineral content are necessary to characterize the waste and permit geochemical modelling.

The most common technique for mineralogical analysis is x-ray diffraction. X-ray scans with clay speciation may be required.

An analytical procedure still under development called SIMS (Secondary Ion Mass Spectrometry) may have good application. This procedure provides both mineralogical data as well as information on the spacial distribution of the minerals at the near surface. It has been used experimentally to probe sulphide crystals to determine amorphous layer characteristics.

Petrographic microscopic examination of thin sections (for non-opaque minerals) and polished sections (for opaque minerals such as sulphides) is also common and provides valuable information on: mineral types, mineral forms, mineral percentages, secondary mineralization and weathering.

Another test procedure which may have application is QEM*SEM or automated scanning electron microscopy. Pignolel-Brandom and Lapakko (1990), describe an automated scanning electron microscope system that was designed by the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia to provide quantified data on mineral liberation. The system determines mineral volumetric percentages, grain sizes, and associations, particle surface mineralogy and the liberation or distribution of a mineral in particles.

Trace minerals can effect ARD production and may be of substantial environmental concern. Percival et al. (1990) describe the development of a sequential (liquid) extraction procedure which provides a means of identifying the chemical forms and mineral associations of the heavy metals. Sequential extraction procedures are commonly used in exploration programs to investigate geochemical anomalies, and have also been used in sediment studies. Percival et al. (1990) have applied this procedures to wall-rock samples from open-pit mines to evaluate the feasibility of flooding the pits for decommissioning; application to acid mine drainage studies may be useful. The extractant liquids can be non-selective (i.e. extract total metals) or selective. Partial extraction methods can be used to identify materials that act as sinks for trace metals and how they are incorporated (e.g. co-precipitation, adsorption, surface complex, ion exchange and penetration of crystal lattices). Selection of the most suitable method (i.e. reagents, sequence of reagents) to leach a particular mineral is not straightforward; sequential extraction procedures are more time consuming than bulk chemical analyses but can provide additional information about the potential behaviour of specific contaminants (Percival et al. 1990).

LaCount et al. (1993) describe a technique for determining mineral sulphides/sulphates and carbonates in ores and the overlying/underlying strata. This technique, called CAPTO (controlled-atmosphere programmed-temperature oxidation) is applicable to particles of -60 mesh, or smaller. Samples are heated in an oxygen atmosphere from room temperature to 1050 C. The profiles of the evolved gases are monitored and compared to identify the types of metal sulphide/sulphates/carbonates. The authors consider that the CAPTO technique may also be of general utility for predicting acid/neutralization potential, provided the sulphides/ sulphates/carbonates are allowed to react selectively and the oxidative reactivity (temperature) can be related to weathering tests.

The conventional methods for differentiation of the various carbonate minerals (e.g. calcite, dolomite, siderite) are quantitative x-ray diffraction, evolved gas analysis and automated pressure cells (Morrison et al. 1990). Additional methods are described in Norecol 1991. An alternate method, routinely used to determine total carbon and carbonate, called CO_2 coulometry, can also be used to differentiate and quantify carbonate minerals. This technique is reported to improve the accuracy of the determination of the neutralization potential (NP) as the conventional NP analyses (digestion in hydrochloric acid, described in the next section) typically results in partial digestion of the siderite, which does not have the same neutralization capabilities as other carbonates (Morrison et al. 1990).

Analysis is normally done commercially. Petrographic analysis, if done in house, would require geologist, microscope and preparation of thin sections from rock sample.

Petrographic microscope examination costs approximately $100-$200/sample. X-ray diffraction costs $10-

$150/sample, depending on parameters analyzed.

iii) Mineral Forms

Data on the form of mineral is often not present. It is essential to establish whether minerals are massive, nodular, disseminated, occurring on fracture planes, etc. In addition, the degree of crystallinity, weathering and secondary mineralization need to be assessed. This data is normally collected through observation by the geologist in the field and through microscopic examination of thin sections (for non-opaque minerals) or polished sections (for opaque minerals such as sulphides) or as a component of the mineralogical analysis. Microscope examination may be required, especially for small grain sizes. The form of the mineral can have a major impact on the potential of a waste to generate ARD.

The stratigraphy and lithology of a site are also of interest and can be derived from drill hole data. Paleoenvironmental and lithologic factors, such as the depositional environment for sedimentary rocks, influence the type, amount and stratigraphic variations of sulphide and carbonate minerals (Brady and Hornberger 1989).

Cost for assessing mineral form is the geologist's time and expenses. This would vary widely, depending on the size of the mine, geological complexity and nature of mineralization, etc. Geological descriptions, however, would normally be prepared as part of the exploration and development programs, and therefore may be available for the purpose of ARD assessment at little or no additional cost. Petrographic microscope examination costs approximately $100-$200/sample.

2.2.2 ARD Assessment Test Procedures

The objective of the ARD assessment task is to evaluate the results of tests and the translation of the results of these studies to field conditions, to predict the rate, the extent, and the time course of acid generation. The "laboratory-to-field" translation is often difficult. Acid generation in the field depends on the interplay of kinetic (i.e. inherent oxidation rate) and mass transport phenomena (oxygen diffusion, pore water convection). The reproduction of the field conditions in the laboratory is nearly impossible. For this reason, it may be more appropriate to establish the kinetic and transport parameters separately and to combine these in appropriate mathematical models for assessing ARD under field conditions.

It is convenient to distinguish between static and dynamic tests. The main purpose of the static tests is the determination of the net potential acidity (e.g. acid-base accounting), while dynamic tests address both the rate and the extent of acid generation. Dynamic tests may also give some indication of the kinetics of neutralization reactions and the evolution of the acid conditions. Perhaps, the major drawback of many or all of the laboratory test procedures is the lack of validation in the field. Consequently, the results of the tests should be employed with caution. Recognizing their limitations, they serve as important tools in the ARD assessment.

Static tests are based on geochemical analysis of the rock samples. The capacity to generate acid is calculated on the basis of sulphide sulphur analysis and this value is offset against the total neutralization capacity, usually calculated on the basis of the alkaline earth metal (calcium, magnesium) carbonate content. This procedure is referred to as Acid-Base Accounting (ABA). The convention in Canada and the United States is to report the results as kg of $CaCO_3$ equivalent of net neutralization potential per ton of rock.

$$NNP \quad NP - AP$$

Error! Switch argument not specified. (2.2.1)

$$AP \quad S\%\ x\ 31.25\ kg\ CaCO_3\ equivalent\ /\ t$$

where:

NNP = net neutralization potential (kg $CaCO_3$/t)
NP = neutralization potential (kg $CaCO_3$/t)
AP = acid producing potential (kg $CaCO_3$/t)
S = sulphide sulphur content

The conversion factor of 31.25 is derived from the standard stoichiometric equation for complete oxidation of pyrite to sulphate and iron hydroxide by oxygen. Morin (1990) provides a discussion of the assumptions of geochemistry and environmental conditions required to support the use of this conversion factor, and proposes alternate conversion factors to account for oxidation of sulphide minerals other than pyrite (e.g. chalcopyrite) and oxidation by oxidants other than oxygen (e.g. ferric iron).

A negative value of the calculated neutralization potential (i.e. equation (2.2.1)) may be indicative of acid conditions. The procedure is subject to several constraints. Since the rock sample is pulverized for analysis, both the sulphide sulphur availability for oxidation and carbonate availability for neutralization are likely to be overestimated. In actual waste rock, the oxidation and the neutralization reactions are likely to be physically hindered. The assumption, that the degree of hindrance on oxidation and neutralization are equivalent is conjectural. Furthermore, the net neutralization capacity does not take into account the inherent differences in the stoichiometry and the oxidation rates of the various sulphide minerals. The effect of chemolithotrophic bacterial activity on accelerated oxidation is also neglected. Since bacterial colonization tends to be localized initially, the mismatch of acid production and neutralization in space and time may give rise to unexpected acid conditions in the field.

Furthermore, the presence of excess buffering or positive net neutralization potential does not guarantee that acid production will not occur. Many metal sulphates cannot be precipitated at the buffering pH levels present in waste rock leachates. Constituents such as arsenic, copper, zinc, iron (II), etc. can be present at tens of mg/L in leachates from waste dumps with positive net neutralization potential.

To interpret NP, AP and NNP results, four classification criteria have been developed and are commonly used:

1. ABA accounting - Sobek manual, 1978
   NNP $\leq$ 5 - problem
   NNP > 5 - no problem
2. B.C. AMD Task Force Techn Guide, 1989
   NNP >+20 - non-acid generating
   NNP <-20 - acid generating
   between - uncertain
3. Neutralization Ratio of NP:AP, used by many practitioners
   NP:AP >3 - non-acid generating
   NP:AP <1 - acid generating
   between - uncertain
4. Neutralization Ratio, B.C. Interim Policy for ARD at mine sites, July 1993
   NR > 4 - non-acid generating
   NR $\leq$ 1 - acid generating
   between - uncertain

The first category is generally regarded as not conservative enough for hard rock mining. The fourth category is very conservative, as it is intended as a preliminary screening method. The second and third categories are most commonly used. M.G. Li (1994 in preparation) proposes a single function that uses NR 3:1 ratio (Method 3) when AP $\leq$ 10, and uses NNP > 20 (Method 2) when AP > 10. The function is proposed so that data can be used in a statistical analysis using a single parameter.

The Static Test Procedure is summarized in Figure 2.2.1. The experimental protocol has been developed by B.C. Research (Duncan & Bruynesteyn 1979) as the initial (presumptive) test for acid generation. Various static prediction methods and their advantages and disadvantages are listed in Table 2.2.1. The analytical procedures, calculations and interpretation of the results for the conventional static prediction methods are presented in MEND's "Acid Rock Drainage Prediction Manual" (Coastech 1991), and new methods for ABA are described in Norecol 1991.

Determination of AP

Total sulphur is determined using a LECO sulphur analyzer. In this assay, the rock sample is pulverized and heated to 1,600 C in a stream of oxygen to oxidize the sulphur. The resultant sulphur dioxide is collected and analyzed for total sulphur by titration. The total sulphur content is reported as percentage of sulphur in the original sample. The differentiation between oxidized (i.e. sulphate) leachable, and nonleachable sulphur involves splitting the sample and the determination of the oxidized sulphur content by using a hydrochloric acid wash and precipitating the sulphate with barium chloride as barium sulphate. The sample is then exposed to hot nitric acid solution to oxidize the leachable sulphur fraction, presumably the sulphides, to sulphate. The remainder, unreacted sulphur is regarded as unleachable sulphur.

The Alkaline Production Potential/Sulphur Ratio (APP/S Ratio) test is intended to provide a rapid indication of ARD potential during the exploration/development and operating phases of a mine. The APP values obtained for samples from geologic units are plotted against total sulphur to provide an APP/S plot. The results of simulated weathering (kinetic) tests (e.g. humidity cells, described later) performed on the same samples are compared to the APP/S plot to give an indication of the validity of using the APP/S plot to make predictions regarding potential ARD behaviour. If good agreement is obtained, then fewer samples will need to be submitted for kinetic testing (Coastech 1991).

A procedure using hydrogen peroxide to determine the reactive sulphur content has been developed by Finkelman and Giffin (1986). The test involves the addition of hydrogen peroxide solution (15% - 40% H_2O_2) to the sample to oxidize the reactive sulphides to sulphate. The sulphide content of the sample may be estimated from the rate of change of the solution pH or by determining the sulphate content of the sample either by precipitation with a barium salt or by ion exchange chromatography. The test is reported to be of rather short duration (15 minutes) and can be employed under field conditions. Good reproducibility of the hydrogen peroxide method has been observed. The sulphur content is evaluated as a percentage of the sample (%S) based on total sulphur (LECO analyzer), leachable sulphur (HNO_3 oxidation), or reactive sulphur (H_2O_2 oxidation). The choice of the "correct" sulphur content remains debatable (Miller et al. 1991).

The Net Acid Production (NAP) test described in Coastech (1989) can be used to determine the balance between acid producing and acid consuming components without determining the sulphide content. This feature, plus simple analytical procedures, make this test attractive for field use. In the standard NAP test, hydrogen peroxide is added to a pulverized rock sample to react with the sulphides; the acid produced is consumed by the natural carbonate or other neutralizing minerals in the rock and the excess acid remaining in the suspension after reaction is titrated to pH 7 with standardized base. This method was reported to overestimate NP, due to incomplete reaction; therefore, Lapakko and Lawrence (1993) have proposed a modification where: stronger hydrogen peroxide solution is used; the suspension is heated to near boiling for 1 hour; and, the solids are removed prior to titration to pH 7. The modified NAP test was evaluated by comparison to mineralogical analysis and predictions made on the same rock samples using three standard static tests. The method still overestimates NP but shows promise as a qualitative field test (Lapakko and Lawrence 1993).

Miller et al. (1990) describe a similar procedure, NAG (Net Acid Generation), which is used to confirm if acid generation is possible in potentially acid-forming material identified by ABA. Hydrogen peroxide solution is added to the rock sample, and after reaction, the pH, temperature and acidity of the suspension are determined. They have observed a correlation between NAG and the NAPP (net acid producing potential, i.e. AP-NP) at most sites they have investigated in Australia and Southeast Asia. These results indicate that a constant fraction of the total sulphur is either unavailable/unreactive or not present as pyrite (Miller et al. 1990). The NAG test provides a quick assessment of acid-forming potential and can be carried out routinely on-site (i.e. can be used in-pit to test blast hole cuttings prior to mining). However, development of the procedure is site-specific and requires laboratory calibration to determine:

- most suitable sample preparation procedure;
- sample to solution ratio;
- hydrogen peroxide strength; and
- reaction time (1 to 10 hours).

The pH and temperature profiles from the NAG test illustrate the range of kinetic mechanisms that can occur. Miller et al. (1990) are correlating results from column tests and field monitoring and expect the NAG test could eventually be used for predicting lag times for material to become acid generating.

Determination of NP

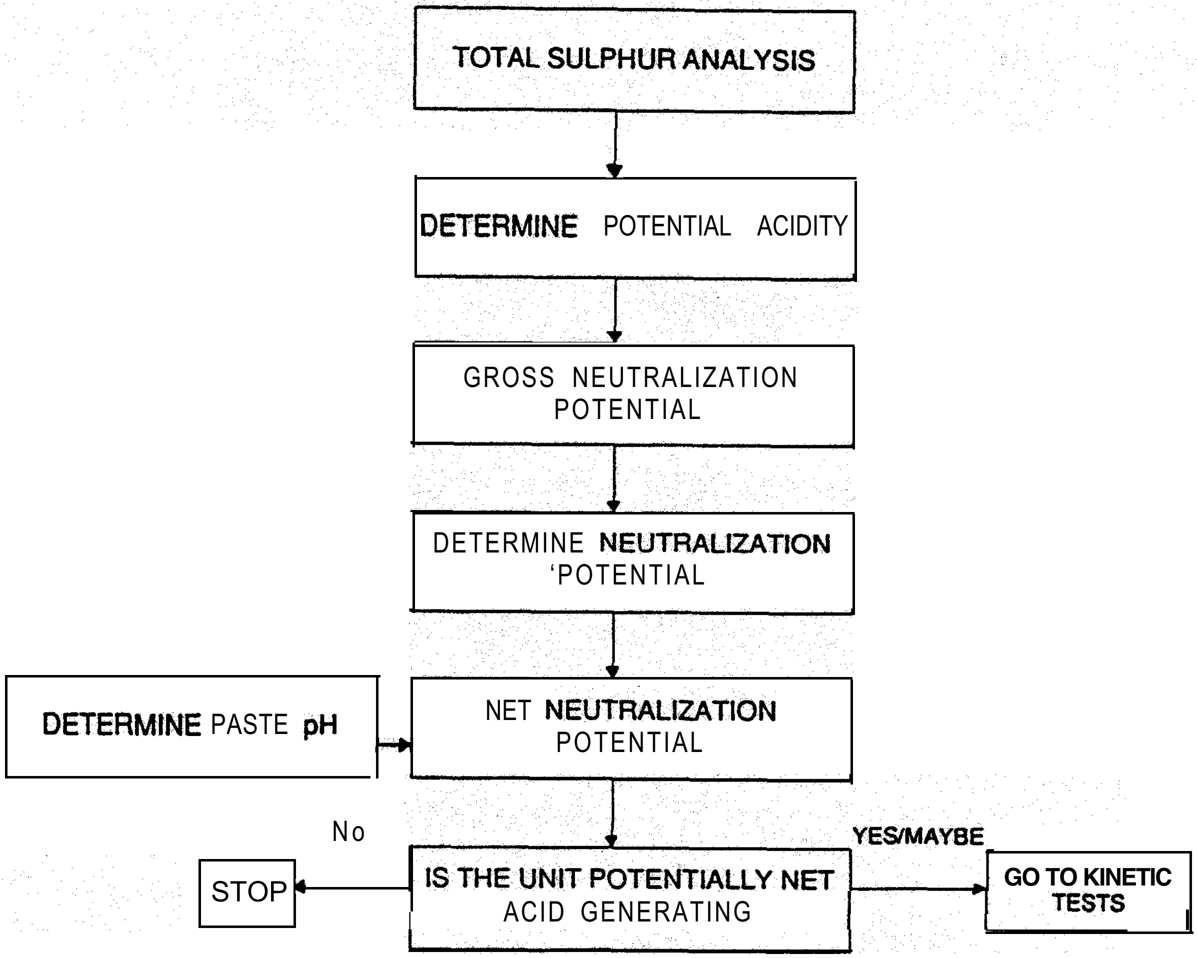
The determination of the neutralization potential for the standard ABA test involves the addition of excess quantity of hydrochloric acid solution to the sample and boiling gently to bring the acid-base reactions to completion (Sobek et al. 1978). The unreacted hydrochloric acid is determined by titration with sodium hydroxide to pH = 7.0. The method is well known and highly reliable provided that no significant HCl is lost to the atmosphere during the heating process.

Lawrence (1990) describes a modified ABA method in which the acid digestion is carried out under milder conditions than boiling to prevent an overestimation of the neutralizing capacity, and the amount of excess acid added is selected to result in a final pH between 1.0 and 1.6 to provide consistency and minimize over- and under-reaction.

In the modified ABA test, the NP is determined by treating a sample with a predetermined (e.g. fizz test) excess hydrochloric acid at ambient (25 to 30 C) for 24 hours. The unconsumed acid is titrated to pH = 8.3 to allow the calculation of the calcium carbonate equivalent of the acid consumed (Coastech 1991).

FIGURE 2.21

RECOMMENDED STATIC TEST PROCEDURE
FOR EACH GEOLOGIC UNIT



SOURCE: SRK INC.. NORECOL AND GORMELY (1990). BC AMD TASK FORCE. DRAFT ARD TECH. GUIDE, VOL II

Table 2.2.1

CHARACTERISTICS OF THE STATIC ARD TESTS

Test Type	Advantages	Disadvantages
Fizz Test Coastech 1991 Horberger 1989	- easy to apply - can be used in the field - indicator of carbonate buffering	- qualitative only - cannot be applied for prediction
Paste pH Renton et al. 1989	- easy to apply - can be used in the field - indicates net free acidity/alkalinity	- does not measure total acidity - false positive/negative response - cannot be applied for prediction
Neutralization Potential (NP) Sobek 1978 Coastech 1991 *U.S. EPA and Modified U.S. EPA Methods* Norecol 1991 *B.C. Research Initial and Modified (NP) Tests* Coastech 1991 SRK, Norecol and Gormely 1990 Duncan and Bruynesteyn 1979	- well known, popular laboratory procedure - quantitative measure of total buffering capacity - low cost - reproducible if performed properly - recommended by government agencies	- gives little indication of ARD potential - no mineralogy (source of neutralization potential)
Alkaline Production Potential Sulphur Ratio (APP/S) Coastech 1989	- simple calculations - rapid indicator of potential ARD - useful preliminary analysis	- theoretical analysis - results need to be confirmed by experimentation
Net Acid Production (NAP) Coastech 1989 *Standard and Modified Acid Base Accounting (ABA)* Coastech 1991	- combination of acid production and acid neutralization test procedures - can differentiate between sulphide minerals (pyrrhotite/pyrite) - allows determination of carbonate and non-carbonate buffering capacity	- long, often complex procedures - interpretation may be difficult - no indication of reaction rate
Net Acid Generation (NAG) Miller et al. 1990 *Hydrogen Peroxide* Finkelman and Giffen 1990	- simple, straight forward test procedure - good reproducibility	- overestimates net acid production - requires pulverized (unrepresentative) samples - seldom used in Canada
B.C. Research Confirmation Test	- used to confirm results of static prediction tests	- usually grouped with dynamic test methods

Table 2.2.2

CHARACTERISTICS OF THE DYNAMIC ARD TEST

Test Type	Advantage	Disadvantage
Soxhlet Extraction Extraction with reactive, hot liquid Renton et al., 1988 Sobek et al., 1978	- simple to operate - rapid test procedure - options may be tested - easy to interpret (model) results	- geochemistry may be altered - oxidations tend to be aggressive - unnatural conditions - bacterial, temperature, pH effects cannot be determined
Stirred Reactor Studies Reactions in fluidized solid suspensions B.C. AMD Task Force, 1989 Duncan and Bruynsteyn, 1979 Filipek et al., 1991 Halbert et al., 1983 Lawrence et al., 1989 Scharer et al., 1991 Scharer & Nicholson, 1991	- amenable to fundamental studies (surficial reaction rate) - environmental factors are easily assessed: i) oxygen concentration ii) temperature iii) pH iv) specific surface area v) bacterial activity - allows multilevel factorial statistical design - control actions (submersion, oxygen exclusion, bacterial inhibition) may be evaluated	- tend to overestimate reaction rates (ideal rate) - cannot be used to evaluate effect of moisture content on oxidation - may be oxygen limited - secondary mineralization may be affected - complex data interpretation and modelling
Stationary Bed Test Studies Reactions in stationary solid columns Bradham and Caruccio, 1991 B.C. AMD Task Force, 1989 Caruccio, 1968 Caruccio et al., 1981 Hood and Oerter, 1984 Ritcey, 1989 Ritcey and Silver, 1982 Sobek et al., 1978	- simulates natural conditions (including submerged conditions) - simple to operate - environmental factors can be assessed - gives overall acid generation per unit mass of waste rock - easy to monitor - widely used in US and Canada - control actions may be evaluated	- confounds kinetics with transport phenomena - may be diffusion limited - bacterial acclimatization may be difficult - surfaces are undefined - complex data interpretation and modelling - may not represent field conditions

Table 2.2.3
SAMPLE CONTAINERS, PRESERVATION METHODS AND STORAGE TIMES

	Sample Container					
Parameter	**Field Analysis**	**Glass(1)**		**Polyethylene**	**Preservation With**	**Maximum Storage Time**
pH	X				unpreserved	6 hours
Electrical conductance	X				unpreserved	24 hours
Temperature	X				-	-
Dissolved Oxygen	X				-	-
TDS		X	or	X	unpreserved	7 days
TSS		X	or	X	unpreserved	7 days
Acidity		X	or	X	unpreserved	24 hours
Alkalinity		X	or	X	unpreserved	24 hours
Calcium				X	HNO_3	6 months
Magnesium				X	HNO_3	6 months
Sodium				X	HNO_3	6 months
Potassium				X	HNO_3	6 months
Chloride		X	or	X	unpreserved	7 days
Sulphate		X	or	X	unpreserved	7 days
Nitrate		X	or	X	unpreserved	24 hours
Total Iron				X	HNO_3	6 months
Ferrous Iron				X	HNO_3	24 hours
Aluminum				X	HNO_3	6 months
Arsenic				X	HNO_3	6 months
Cadmium				X	HNO_3	6 months
Copper				X	HNO_3	6 months
Lead				X	HNO_3	6 months
Nickel				X	HNO_3	6 months
Zinc				X	HNO_3	6 months
Mercury		X			$H_2SO_4+K_2Cr_2O_7$	1 month
Uranium		X		X	HNO_3	6 months
Radionuclides(2)		X		X	HCl or HNO_3	5 days

Notes:
(1) Glass containers are not commonly employed except when analyzing for organic constituents.
(2) Radium-226, Polonium-210, Lead-210, Thorium-230.

Table 2.2.4

GROUNDWATER SAMPLE COLLECTION METHODS (Golder and SENES, 1985)

Type	Application	Limitations
Saturated Zone		
1) Bailers	- Simple, inexpensive method for collection of samples.	- Samples are highly disturbed and must be extensively handled during filtration. - Can be time consuming in small diameter wells.
2) Depth-specific bailer	- Simple, inexpensive method less disruptive than bailer.	- Requires relatively large diameter wells.
3) Syringe sampler	- Allows collection of samples without exposure to the atmosphere and allows filtration down-the-hole. - Can collect samples from any depth.	- Only small volumes of pore water are collected in each syringe. - Requires piezometers greater than 3 cm diameter.
4) Suction-lift pumping	- For collection of relatively large volumes of water from shallow depth. - Permits use of in-line filters to reduce sample handling.	- Sampling limited to water depths less than 8 m.
5) Submersible pumps	- For collection of large volume samples from depths greater than 8 m.	- Requires relatively large diameter wells. - Costly.
6) Air-lift	- For collection of water samples from conventional wells or special air-lift samplers. - No limitation on depth of water.	- Samples can be highly disturbed.
7) Inertia pumping system (Waterra)	- Low cost, unlimited depth, no power requirements, dedicated instalment (no cross-contamination), direct filtering capabilities.	
Unsaturated Zone		
8) Suction lysimeters	- For collection of pore water samples from unsaturated tailings solids samples.	- Reliable only in relatively coarse sandy materials.
9) Core squeezing	- For collection of pore water from tailings solids samples by squeezing or displacement.	- Destructive sampling, monitoring at precisely the same location is not possible.

Table 2.1.1

DATA INPUTS FOR DBARD[*]

Mineralogy	Metal Leaching	Static Test	Kinetic Test[**]
Mineral name	Sample weight	Paste pH	Type of cycle
Concentration	Grain size distribution	Total % sulphur	Cycle number
Particle size	Volume of leach water	Sulphide (% sulphur)	Sample weight
Appearance	Initial pH of leach water	Sulphate (% sulphur)	Volume of water collected
Crystallinity	Comments	Organic (% sulphur)	pH
Comments	Final pH	Other (% sulphur)	Temperature
	Temperature	Acid potential	Redox potential
Metal Content	Redox potential	Sulphate acid potential	Sulphate
Type of test	Total alkalinity	Neutralization potential	Other sulphate
Elements/species	Bicarbonate & carbonate alkalinity	Carbonate neutralization potential	Total alkalinity
Concentration	Acidity to pH 4.5	Net neutralization potential	Alkalinity
	Acidity to pH 8.3	Neutralization potential/acid potential	Acidity to pH 4.5
	Elements/species	Refined net neutralization potential	Acidity to pH 8.3
	Concentration	Carbonate neutralization potential/sulphide acid potential	Elements/species
			Concentration

Notes:

[*] Database for Acid Rock Drainage, Morwijk (1992).

[**] Because on-site monitoring data for water quality is repetitive, this data can be entered into DBARD as a "Kinetic Test".

In the BC Research Initial Test the NP is determined by titrating a pulverized rock slurry with standardized sulphuric acid to a stable pH of 3.5 which is the pH limit above which iron and sulphide oxidizing bacteria are not active (Coastech 1991).

The NP can also be assessed by controlled addition of hydrochloric acid solution to a suspension of a pulverized rock sample to prepare a titration curve of suspension pH versus acid consumption. This curve can provide insight into the pH levels where buffering reactions occur, and therefore, data on the minerals species which determine the buffering capacity.

A comparison of methods for pyritic sulphur and carbonate determination in acid-base accounting (ABA) has been performed as a MEND project (Norecol 1991). In this study, two methods have been employed for determination of the pyritic sulphur (Norecol 1991). The first method involves the selective dissolution of the pyrrhotite fraction in hot hydrochloric acid (2:1; water:acid) and an assay for sulphur on the basis of iron (atomic adsorption spectrometry) in both the dissolved (pyrrhotite) and solid (pyrite) fractions. The iron from pyrite is released oxidatively with nitric acid. The second method uses hydrogen peroxide (15% H_2O_2) as the oxidizing agent. The first method is reported to be superior, although more complicated to perform.

Similarly, two methods have been compared to assess the neutralization capacity. The first method involves a modified version of the conventional U.S. EPA (United States Environmental Protection Agency) method of excess hydrochloric acid treatment and titration of the unreacted acid. The modification involves the removal of siderite ($FeCO_3$) before titration (Norecol 1991). The second procedure involves direct determination of the dissolved alkali earth metals (Ca, Mg) and iron (Fe) by atomic adsorption spectrometry and calculation of the equivalent $CaCO_3$ content, rather than by titration. Although neither technique is completely satisfactory, the titration (first method) is preferred, since the acid leach releases non-carbonaceous calcium and magnesium.

Numerous studies have commented on the difficulties associated with application and interpretation of ABA (e.g. Morin 1990; Brady and Hornberger 1989; Norecol 1991; Lawrence 1990). All tests have limitations and the data alone provides little insight into whether ARD problems will occur. Interpretation of tests results is difficult and many times, the benefit of the procedure is overstated. For samples with a large positive NNP, significant acidity will not occur. For conditions with small positive NNP, acidity is possible and for either large or small NNP results, contaminated leachates are possible. Regarding procedures, BC research initial test (1979), modified BC research initial test (1990) and Sobek et al. (1978) are all in common use, and are recommended by government and industry. For simplicity and speed, Sobek is preferred.

Tests normally performed by commercial laboratory. Samples normally obtained during drilling and logging of boreholes. Average cost is $75/sample.

It is recommended that any waste rock samples with sulphide mineralization be subjected to dynamic testing to substantiate the absence of ARD or contaminated leachates.

Dynamic tests entail the time-dependent study of acid generation. These tests are designed so that the variables indicating sulphide oxidation (dissolved iron concentration, sulphate concentration, pH) can be routinely monitored. Generally, the dynamic experiments are short-term laboratory procedures lasting no more than a few months. It is convenient to classify the dynamic test procedures into three distinct categories, namely i) Soxhlet extraction tests, ii) stirred reactor studies, and iii) stationary bed reactor studies. The characteristics of these three categories of procedures are summarized in Table 2.2.2. Soxhlet extraction involves the diminution of the rock sample and extraction with a hot reactive (oxidative) liquid. Stirred tank reactor studies are performed with pulverized rock powder suspensions, which are fluidized by continuous stirring. Stationary bed reactor studies involve the application of leachate solution and/or air to stationary rock sample columns or lysimeters. Of special interest are humidity cells that are intermittently aerated and flooded with water (Caruccio 1991). The BC Research Confirmation Test has commonly been grouped with these dynamic tests but it is not considered to be a true kinetic or dynamic test; rather, this test was designed to confirm the results of static prediction methods, and is not widely used as it suffers from inherent reluctance by researchers to use bacteria.

Soxhlet Extraction Studies

These studies have been developed originally to examine the kinetics of pyrite oxidation in coal samples (Sobek et al. 1978). A pulverized, weighed rock sample is placed in an extraction thimble and positioned in the Soxhlet extraction chamber. The solids are extracted by cooled condensates produced by continuous boiling of the leachate solution. The leachate solution may be water, weak organic acid (acetic acid), or inorganic acid (hydrochloric acid) solutions. The solids may be periodically withdrawn and dried at 105 C to simulate oxidative conditions in nature (Renton et al. 1988). The extraction test is claimed to simulate natural weathering of coal refuse and the results conform with a simple mathematical model, which is claimed to reflect the dynamics of the oxidative processes (Hart et al., 1991). The disadvantages of the test procedure are the inherent difficulties of investigating factors such as bacterial activity on the reaction rate. The corrosive environment is believed to result in unnaturally high oxidation rates. Time scaling from the laboratory to the field is a difficult and unresolved task.

Stirred Reactor Configurations

To date, several stirred reactor configurations have been used. A simple procedure involves flasks (Erlenmeyer flasks) which are stirred continuously on a rotary shaker (Halbert et al. 1983). Pulverized rock samples (200 g) are suspended in 600 mL solution containing extractant and/or bacterial culture. The flasks are placed on a shaker apparatus and incubated at a pre-assigned temperature. Using -200 mesh screened samples, a rotary shaking speed of 60 rpm is adequate to maintain the powder in uniform suspension. Alternatively, internal split flow, pneumatically mixed reactors may be used (Scharer and Nicholson 1991). Typically, a 1.0 L reactor has an internal diameter of 5.6 cm and a height to diameter aspect ratio of seven. Each reactor is jacketed to maintain a pre-assigned water temperature between 4 C and 40 C. A liquid reactor volume of 600 mL may contain 3 g/L to 10 g/L pulverized rock sample. Simultaneous oxygen transfer and mixing are provided by sparging either air or oxygen/nitrogen mixture through a 110 micron sintered glass sparger located at the bottom of the vessel at a flow rate of 0.3 vvm (volume of air/volume/min of liquid). The reactors are operated in a continuous flow through manner. Fresh extraction fluid (nutrient solution) is supplied at a rate of 0.5 mL/min and removed from the headspace by overflow.

Stirred reactor configurations are particularly well suited to fundamental studies for determining the effect of variables such as oxygen concentration, temperature, pH, specific surface area, and bacterial activity. Routine, frequent analysis of the leachate is performed for dissolved iron, sulphate, bacterial density, pH etc. Since a number of experiments can be run simultaneously, sophisticated, multi-level factorial experimental design is possible. The experimental equipment and procedure are designed to minimize mass transfer effects, consequently, the stirred reactor tests with their well-defined conditions provide a unique opportunity for kinetic parameter estimation. The major disadvantage of the system is that the reaction conditions tend to be ideal, hence, the reaction rates are overestimated. Furthermore, the effect of moisture on the reaction rate cannot be evaluated directly from these studies, which may be important in the unsaturated zone. The high water content may prevent secondary mineral formation which may have profound influence on the overall acid formation rate.

Stationary Bed Reactor Configurations

These studies include column and lysimeter tests, as well as humidity cells. The solid rock sample constitutes a stationary phase, while liquid and/or air is transferred either continuously or periodically through the pore space of the rock sample.

Columns are constructed of various materials such as glass, PVC plastic, etc. Generally, a known amount of crushed rock sample is placed in the column and distilled water or extract solution is allowed to percolate through the column (Ritcey 1989). The liquid flow may be continuous or periodic. Continuous flow conditions are maintained by an overflow arrangement. There are no standard conditions for column operation. Variations include periodic wet and dry cycles, fluctuating water levels by manipulation of the overflow arrangements, variations in flushing rate, and bacterial inoculation. Rainfall may be simulated by intermittent water spray over the top of lysimeters (Ritcey and Silver 1982).

Lysimeters are usually rectangular vessels constructed from acrylic plastic sheets (plexiglass) or similar material. They need to be sufficiently robust and leak-proof as experimentation may last several years. The lysimeters used at CANMET (Silver and Ritcey 1985; Silver 1985) ranged in size to contain up to one ton of solids. For a one ton waste sample, a 120 cm deep, 120 cm long and 60 cm wide container was constructed from 1.25 cm thick (") plastic sheets. The mortice and tenon joints are reinforced with screws and the sides are braced externally for additional support. A U-shaped siphon at the bottom controls the water level. An infra-red heater and fan arrangement is utilized to simulate surface drying. Liquid (distilled water or nutrient solution) is sprayed on the top to simulate rainfall. Oxygen is transferred by passive diffusion. Lysimeters were operated for up to two years to examine the dynamics of acid generation in uranium tailings (Silver and Ritcey 1985; Silver 1985). Lysimeters can also be useful for collection of field data.

There are numerous protocols for flow through columns that have been developed and are used to assess the dynamics of ARD production. A typical experimental protocol for long-term leaching studies in waste rock (SENES 1987) involves crushing the rock sample to a nominal size of 1 to 2 mm. Exactly 1 kg of rock sample is placed in a column. Oxygen-rich water is allowed to pass at a controlled rate through the waste rock. Once the column is filled, the water is allowed to stand for a one-day time period and then allowed to drain for four days. The entire procedure is repeated in every 15 days (10 days fill, one day idle, four days drain).

Column studies may also be conducted using: whole rock samples; continuous flow through; up flow orientation; aerated water; freeze/thaw cycles; wet/dry cycles, etc. All procedures have merit but again the primary problem is that data interpretation is difficult and there are no established or accepted procedures. Too often claims have been made that a single procedure is better. Such claims are simply not defensible based upon the body of knowledge at this time.

The humidity cell configuration has been pioneered by Caruccio (Caruccio 1968; Caruccio and Geidel 1981) and Sobek (Sobek et al. 1978). The suggested design consists of an acrylic pipe segment of 20 cm height and 10 cm diameter. The vessel is designed to hold a 1 kg rock sample. The sample is held in place by a perforated plate. The plate can be covered by stainless steel screening to prevent the loss of fine material. The vessel has a fixed base and drainage hole. Air is introduced through an inlet located on the wall of the vessel between the base plate and the perforated plate holding the sample. The humidity cell is covered with a removable top plate. Air is exiting through a nipple at the centre of the cover. The operation consists of seven-day cycles. Dry air is passed through the rock sample for three days. After the initial three-day period, pre-humidified air of 100% humidity is passed through the sample for three days. On the last day of the cycle, the air flow is stopped; the rock sample is flooded with 500 mL distilled water and left to stand for one hour. The cell is then drained and left to stand until the next day for the restart of the cycle. The leachate is analyzed for dissolved iron species (Fe(II), Fe(III)), dissolved aluminum, sulphate and pH. The method is an accepted procedure in the U.S. and Canada. Although it has not been fully validated in the field, the results compare favourably with other tests. It is relatively simple to perform. The test procedure can be modified to reflect submerged conditions. One of the options is the inoculation of the cell with chemolithotrophic bacteria. Although the conditions in the cell are suboptimal for bacterial activity (low water content, drying periods), it does provide a means of assessing bacterial activity.

The principal drawback of the humidity cell and other stationary beds is the interpretation of the results. The experimental design confounds kinetic effects with mass transport. For this reason, the acid generation flux is an undefined average value, which is difficult to relate to either surficial reaction rates or diffusive oxygen transport. There is no means of independently estimating either the kinetic or the transport parameters. Therefore, the results depend strongly on the choice of the operating cycle. In fact appropriate air/water cycling may depend on local climatic conditions. The determination of the appropriate cycle for a particular locality may be a very difficult and risky task.

As stated previously, the primary objective of the dynamic tests is the prediction of both the rate and the extent of acid generation. It is doubtful that accurate prediction can be currently achieved. The value of the dynamic tests is in comparative assessment of waste management strategy and control alternatives. Dynamic tests should be used to provide a range of parameter estimates that could be utilized more fully in a probabilistic prediction framework (i.e. a model).

Stationary bed reactor configurations are most common and of these column and humidity cell tests are most frequently used.

Column tests are preferred especially for samples with large particle sizes. For existing sites, on-site monitoring takes the place of dynamic tests. Samples that are not crushed and that include larger, more representative particle sizes are preferred. Quality control (duplicates, triplicates) are important to assess the variability and reproducibility of the dynamic test program. The major issue with most dynamic tests is that the test duration is too short. Nominal test programs are conducted for 10 weeks while practice has shown it can take much longer periods (e.g. 1 year) for sample to become acidic and/or produce contaminated leachates.

Costs for stationary bed reactor tests commonly range from $1,000-$5,000/test, including sample analysis. Costs for lysimeter tests are: $50,000 plus for design and set-up; and $30,000 to $50,000/year for operating.

2.2.3 Physical Stability

Hardness and durability of rocks may be key factors in addressing long-term ARD. Physical characterization of the rock samples include density, hardness, porosity, permeability. Little data are available to assess test procedures however several procedures have been and continue to be investigated. These are addressed below.

2.2.3.1 Hardness

Given that physical stability of waste rock may have a significant impact on the rate of acid generation, physical stability can be assessed using a test technique usually used to evaluate concrete aggregate. The procedures basically consist of measuring an abrasion coefficient or percentage (percentage of fine particles generated during the test). Fine particles result from friction between the aggregate material particles when churned in a cylindrical drum containing steel balls (dry conditions) (ASTM C131-89 and C535-89 Los Angeles Abrasion test).

The rock quality designation (RQD) can also be used as an estimate of hardness. This is a simple method for assessment of the hardness of rock samples taken from drill core, which involves counting the number of pieces of drill core that are 10 cm or longer in 1 m of core length.

Costs for abrasion, hardness and slake testing are usually about $200 to $300/sample. The tests provide an indication of rock stability rather than a quantitative estimate regarding rock weathering rates. Hardness testing is experimental when applied to ARD assessment, and there is no preferred method yet.

2.2.3.2 Weathering Tests

Weathering of rocks is a natural process where rocks are chemically, biologically and/or physically broken down through exposure to natural environmental factors, and may result in the following:

- loss of carbonate minerals which will influence drainage quality;
- coating (or armouring) of rock surfaces with metal precipitates which can restrict the availability of buffering minerals and/or the reactive surface area of sulphide minerals; and
- fracturing or crumbling of rocks which can create fresh reactive surfaces.

The test procedures for assessing weathering are much more common, however these tests are qualitative, not quantitative. Weathering tests are important to determine the manner and potential rates of deterioration of the rock matrix in the field. The natural weathering process will increase the total surface area of the sulphidic minerals that will become subject to oxidation and leaching through the creation of fresh surfaces, opening of fractures and production of more fine particles.

Weathering can be easily observed on the surface of waste rock samples as worn surfaces, staining, open or broken fractures where the original mineral veins have been altered or dissolved, and by waste rock samples that crumble easily. Climatic factors (freeze/thaw cycles), oxygen, the infiltration of precipitation, the percolation of acidic leachate, and internal temperatures within the waste rock pile actively promote the weathering process. Consequently, obtaining samples of weathered waste rock is not difficult. It is more difficult to obtain samples of unweathered waste rock from existing waste rock dumps.

It is important to be able to predict the weathering rate of the waste rock since this will influence not only the physical stability of the dump, but the long-term generation of acidic drainage as well. Therefore fresh or unweathered samples of waste rock should be subjected to weathering tests prior to design and construction of the dump.

Weathering tests are normally combined with acid generation tests where the initial and final weathered state of the waste rock samples are documented and compared using scanning electronic microscope and microprobe analyses. The dynamic ARD tests empirically determine leachate quality by subjecting the waste rock sample to simulated weathering; however, this simulated weathering may or may not accurately represent true field conditions. The air/water cycle selected for the testwork should be appropriate for the local climatic conditions.

Research underway at the National Hydrology Research Institute in Saskatoon involves the use of an innovative humidity cell test designed to assess the relative weatherability of various sulphide and gangue minerals. This research is in the early development stages and the potential for this test to become a standard analyses is difficult to determine at this time. In addition to the investigation of relative weathering of common sulphide minerals, this research project aims to clarify the susceptibility of difficult types of ore deposits to ARD problems and to examine the role of the field geologist in ARD assessment. Seven common types of metallic mineral deposits in western Canada have been ranked according to ARD potential, and a formula for assessing ARD potential based on field estimates of mineral abundance has been suggested (Kwong 1993).

Klohn Leonoff and the University of Western Ontario are conducting a study to demonstrate the potential for Secondary Ion Mass Spectrometry (SIMS) in the prediction of acidic mine drainage. Part of this project will investigate the nature of weathering reactions and the mechanisms by which the primary minerals are altered.

A standard test used to determine resistance of aggregates to weathering is the magnesium sulphate test. In this test a sieved sample is immersed in a magnesium sulphate solution for about seventeen hours and then dried. This cycle is repeated several times. The dried sample is then sieved and the percentage of finer particles resulting from disintegration of the initial aggregate particles is calculated (ASTM C88-90).

Another criteria related to the weathering resistance of rock is known as the *Weathering Potential Indicator* (WPI). It is based on chemical composition of the rock sample and is formulated as follows:

$$WPI \quad \frac{100\left(K_2O + Na_2O + CaO + MgO\right)}{\left(K_2O + Na_2O + CaO + MgO + Al_2O_3 + SiO_2\right)}$$

Error! Switch argument not specified.(2.2.2)

Weathering is commonly assessed through: visual observation, humidity cell tests, and as part of acid generation tests. There is no current recommended technique. This is a major area of deficiency in current state-of-the-art waste sampling programs which seem to focus on static and dynamic test work. Weathering tests cost $200-$300/sample, excluding sample collection. Costs for humidity cells range from $1,000-$5,000/test, including sample analysis.

2.2.4 Water Quality

This section covers sampling techniques and chemical analyses of surface water, groundwater and pore water. Table 2.2.3 presents a summary of the appropriate container and preservation method for various analyses. Flow monitoring should always be carried out in conjunction with water quality sampling, so that contaminant loadings can be calculated.

The water within the waste rock dump originates as precipitation, part of which infiltrates the cover, if a cover is present, and percolates through the pile. A fraction of the precipitation will be diverted as surface run-off which may or may not enter the dump further down gradient. Samples of surface water (run-off) can be obtained during precipitation events. Chemical analyses of the surface run-off will allow for better design of laboratory tests, since some tests performed using distilled water should be conducted with simulated precipitation. Grab sampling of run-off is the standard procedure, and samples should be collected during winter melt or spring run-off, and the month(s) with the highest precipitation. Samples may also be taken with an automatic sampler, which is less labour intensive but can fail. Analyses should include field pH, conductivity, major metals (iron), sulphate, acidity, total dissolved solids. Measurement of the surface run-off quality prior to placement of a cover will given an indication of the contamination originating from surface run-off. Comparison of pre-cover and post-cover data on chemical loadings can demonstrate the level of improvement achieved by the use of a cover.

Cost for run-off and seepage sampling is labour, which is site-specific. An automatic programmable sampling system could cost $5,000 - $10,000/station.

Waste rock dumps contain much larger particles than tailings, therefore the interstitial spaces are larger and cannot hold very much water except ice. Rather, in the unsaturated zone of waste rock dumps the retained pore water is either present as a surface film on the rock or in cracks or voids in the rock particle, which are the locations where oxidative (biological and chemical) reactions occur. Moisture content in a waste rock dump is dynamic, in that it is always changing in response to precipitation events, seasonable conditions, etc. Some of this water may evaporate due to the high temperatures created by these exothermic reactions. Sampling of the pore water is difficult as samples of the wetted waste rock will be required. A weighed sample of the wetted waste rock can be washed into a measured volume of distilled water, while a separate sample is dried and weighed; chemical analyses for pH, major metals, sulphate, acidity, total dissolved solids, etc., can be corrected to the original volume of pore water. This is the most common technique.

Other pore water sampling techniques include suction lysimeters and core squeezing (see Table 2.2.4). Choice of method is site-specific, although suction lysimeter technique is preferred as pore water is collected *in-situ*. Field measurements on pore waters include pH, dissolved oxygen concentration and conductivity.

If the water table extends into the waste rock dump, sampling the pore water will be much easier as samples can be collected from sample wells at various depths using mechanical pumps. During precipitation events, the pore water will be diluted by infiltrating precipitation. Similarly seepage flows from the bottom of the dump may represent the steady-state seepage flow or the induced seepage flow from a wash-out effect. Therefore the time of sampling or sampling period is important.

Seepage flows may be collected from a drainage trench constructed at the bottom of the waste dump, or from other representative collection points. As seepage may be acidic the sampling vessel should be polyethylene, glass, or stainless steel. The pH should be measured in the field prior to preservation. The samples should be analyzed for pH, major ions, sulphate, acidity (alkalinity), total dissolved solids, as a minimum set.

Seepage from the waste rock dump will infiltrate through the base of the dump, if a liner or collection system is not present, and pass into the groundwater regime. Groundwater flows will enter the surface water regime at a discharge location. Piezometers or standpipes installed downgradient can be used to obtain groundwater samples for chemical analyses. EM surveys are excellent screening tools for defining high conductivity plumes and provide guidance for designing borehole installation program. Similarly the surface water quality monitoring program for the mining facility should include samples, both upstream and downstream of locations known or suspected to be discharge locations for the contaminated seepage.

Piezometers and standpipes are normally constructed of plastic which is compatible with acidic leachate. To drill hole and install piezometer, the cost is typically $100/metre for 20 metre well. Sampling techniques include mechanical pumps, bailers and displacement methods. Each of these methods has advantages and drawbacks (see Table 2.2.4). Prior to sampling, the piezometer wells should be flushed with a minimum of two to three volumes, if possible, and allowed to recover between flushing and prior to final sampling. Groundwater samples should always be filtered before preservation with acid. If samples are not filtered, metals leached from silt will give incorrect dissolved metal concentrations. The standard filter size used is 0.45 micron; however, U.S. EPA suggests 0.1 micron filters. Filter size must be taken into account when data are compared. Sample containers should be polyethylene or glass, as shown in Table 2.2.3

2.2.5 Gas Sampling

Oxygen, Carbon Dioxide

Gas sampling is an essential operation to evaluate the oxygen availability as a function of depth in rock waste dumps. Oxygen (O_2) is critical in controlling oxidation rates and carbon dioxide (CO_2) is a common byproduct of acid neutralization by carbonate rocks; these are the two gases commonly assessed. Since the bulk permeability of most waste rock dumps is orders of magnitude larger than the permeability of tailing ponds, barometric pumping, wind induced currents and thermal convection cells are significant factors that control rapid air movement in dumps.

Temperature, gas density, and phase changes of water are also important factors controlling gas distribution in dumps and have impact on sampling procedures. Temperature gradients may prevent full oxygenation of deeper or central parts of a dump by maintaining strong upward movement of gases in the first five to 15 metres near surface. The vapour density of CO_2 (molecular weight of 44) is more than twice that of water vapour (molecular weight of 18) and it may partly explain the higher concentration of CO_2 near the base of waste dumps. Where waste dumps have been built on grounds containing organic material or when they are covered with organic containing wastes, methane (CH_4) may be present.

Other atmospheric gases, especially nitrogen (N_2) should also be monitored occasionally to check for total gas composition and give an estimate of air density variations with depth inside the waste rock dumps.

Sampling Techniques

Gas sampling is commonly done through plastic tubes installed at different depths in the dump along with thermistors for temperature measurement and piezometers in the same borehole. It is essential that temperature be measured near the gas sampling port to correct for water vapour content.

Samples are recovered through a portable peristaltic pump or a hand bulb pump. In typical installations, tubes have a small diameter (5-10 mm) so that the volume of gas contained in a 10 m length of tube varies from 0.2 to 0.8 litres (see Figure 2.2.2). Purging (exhausting) must be done prior to sample collection; three to five volumes of air column are usually recommended for purging.

According to the goals of a monitoring program, gas samples may actually be recovered for further analysis or else oxygen and carbon dioxide are monitored directly by using appropriate gas meters while pumping gas. Most routine work can be done with an oxygen meter after calibration. Sample recovery may be obtained in the following ways:

- A gas sampler made of glass or plastic consisting of an oval chamber with two valves is placed on line between the well and the pump with both valves open. After adequate purging, valves are closed, the sampler is disconnected and stored at low temperatures until analysis by chromatography. Some samplers have fittings that adapt directly to gas chromatographs; others are built with a septum through which a sample can be recovered

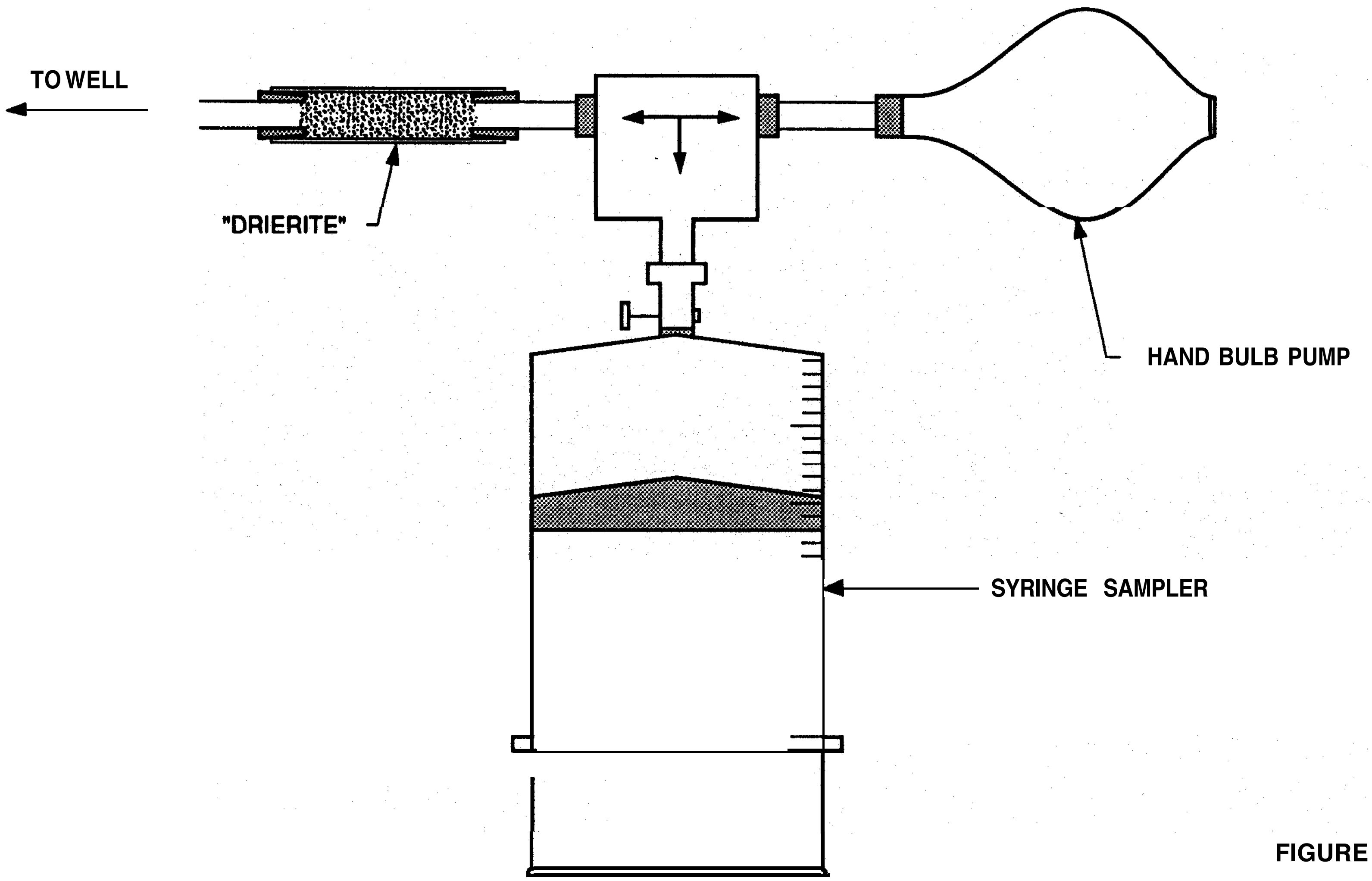


FIGURE 2.2.2

APPARATUS FOR GAS SAMPLING

for analysis.

- Samples can be recovered using a three-way valve between the well and the pump. Plastic syringes containing 50 to 100 mL are used for sampling after appropriate purge of the system. To prevent leakage from the syringe, a special cap is used on the tip and vacuum grease is placed around the plunger in extended position. This way of recovering samples is much more economic than the use of sampling tubes with valves.

If the sample is to be analyzed using a gas chromatograph, water vapour may interfere with analytical techniques. Deep sampling points at high temperatures (45 C and more) may have partial pressures of vapour in excess of 100 mm of Hg and represent up to 30% of the total gas volume. To prevent water accumulation in the sampler, a small tube filled with "drierite" (crushed granules of $CaSO_4$) is mounted on line between the well and the sampler. Drierite changes colour from blue to pink when saturated with water. In both cases, samples are kept at low temperatures until analysis.

Monitoring with O_2 and CO_2 probes is usually done on a routine basis. Meters can also be mounted on line, the way samplers are, to prevent ambient air contamination. Low cost meters (several hundred to a few thousand dollars) are available. Operating temperatures may be a problem for some models that cannot be used below 0 C as sample lines freeze up. Automatic pumping, sampling or monitoring can be designed for specific purposes but is seldom needed.

Analytical Requirements

As required for modelling purposes, the results of gas analyses are reported either as a percentage by volume or as partial pressures. On routine surveys, oxygen measurements using O_2-meters are accurate from atmospheric O_2 content (21%) to low values of 0.1%. Gas temperature and partial pressure at the point of sampling are both factors that control oxygen solubility in water. Iron bacteria can utilize dissolved oxygen only. Under normal atmospheric pressure and at temperatures between 0 and 10 C, the dissolved oxygen is currently between 8 and 10 mg/L at saturation with respect to air.

Carbon dioxide concentrations in the atmosphere are low (350 ppm or $10^{-3.5}$ atm). In waste dumps undergoing strong bacterial activity and in the presence of carbonates, carbon dioxide may reach several percent by volume; values between 5% and 10% are not uncommon near the base of unsaturated zones of waste rock dumps. Most low-cost CO_2 meters cannot measure values higher than 2% to 3% CO_2 by volume. Analyses using gas chromatograph or infrared spectrometers are then required.

Routine analyses on gas chromatographs usually determine composition of atmospheric gases as total volume fractions. N_2, O_2, CO_2, and traces of H_2O are first analyzed and if the sum is close to 100%, the analysis is considered complete since water concentration is variable with temperature and sampling procedure. For special purposes other gases can be also be monitored such as hydrogen sulphide (H_2S), sulphur dioxide (SO_2), or methane (CH_4). Gas containing sulphur species is analyzed separately.

A major concern in the use of gas analyses in modelling is to assess the water vapour content. Total gas density at different temperatures and depth in waste rock dumps is a key parameter for any modelling of air convection under thermal gradients. Water vapour is removed in the sampling process and as a result of condensation in the tubes when difference in temperatures are large between sampling ports and surface, particularly during winter.

Sampling at depth is possible in larger boreholes (more than 5 cm diameter). But costs involved in installing a bundle of large sampling tubes are not usually justified on that basis. An alternative solution is to measure relative humidity at depth using psychrometers; models for small diameter tubes and deep sounding are not readily available. In most practical applications for modelling, water vapour is calculated with the assumption that air is at 100% relative humidity at the point of sampling. Knowing the temperature, the water vapour pressure is determined from gas tables.

A document by Nolan Davis and Associates (N.B.) Limited, to be published in Spring 1994, addresses specifically gas permeability, gas diffusion, and thermal conductivity measurements in waste rock piles.

Drilling and installation of gas ports costs approximately $1,000 to $2,000/hole (depending on depth and number of ports). Drilling costs approximately $70-$100/metre, and may also be used for temperature measurements, waste rock sampling, installation of piezometers, etc. Instrumentation cost $15-$20/metre. Costs for an on-line gas analyzer range from $1,000 to $3,500. Labour time estimates to sample a hole range from 10 to 30 minutes (depending on depth and number of ports). Re-usable syringes ($30 to $50 each) are used to collect samples for gas chromatography ($50 to $80/sample).

2.2.6 Temperature Monitoring

Procedures and Apparatus

Temperature recordings inside waste rock dumps are important to evaluate several processes: reaction rates, gas movements in the porous medium, effects of diffusion and convection, control of bacterial growth and oxygen solubility in water, water movement in the vapour phase and general monitoring of dump evolution.

The recommended procedure is to install strings of thermistors within boreholes, located at short intervals near surface (0.3 m, 0.5 m, 1 m, 1.5 m, 2 m, 3 m, 5 m) and at 5 m intervals in deeper parts of the dump. If boreholes reach the original soil surface and are drilled to bedrock, it is recommended to install thermistors in each geological unit of the saturated zone. At least two thermistors should be present in this zone for two reasons: temperature readings at two different depths make possible the estimate of a thermal gradient used as a boundary condition in thermal models; temperature gradients are also used to calculate leakage of groundwater through the dump foundation.

Thermistors are mounted on a single cable with colour-coded wires that terminate by pairs at different depths. Thermistors should have temperature ranges from -30 to 100 C to cover a wide spectrum of temperature conditions. Calibration curves of temperature against electric resistance are established for each type of thermistors (see Figure 2.2.3).

Sampling Techniques and Requirements

According to the thickness and extent of the dumps, different strategies can be designed for temperature sampling. For dumps less that 5 m thick, air temperature has a major influence in cooling reactions and some thermal models may have limited applications. Temperature monitoring every month for a year is recommended; thereafter readings can be taken quarterly unless anomalous behaviour is noted.

For dumps thicker than 5 m, nearly isothermal conditions may establish with time in deeper parts. By fitting analytical solutions to temperature profiles, it is possible to derive important thermal properties such as thermal conductivity and thermal diffusivity. With an estimate of heat capacity based on rock types and water content, a full range of analytical thermal models can be used for calculations of heat production and heat transfer through the dumps. For such models, monthly temperature recordings are essential, at least to cover a full year of monitoring. Later on, quarterly measurements are sufficient as a monitoring tool. Continuous monitoring using a data logger is sometimes used over short periods of time for research purposes.

Field data should be recorded with minimal information on weather conditions (air temperature, wind velocity, rainfall, snow cover thickness). On major monitoring programs, a weather station registering temperature, rainfall, atmospheric pressure and relative humidity should be installed on site. For sensitive models, accuracy to 0.1 C is an asset.

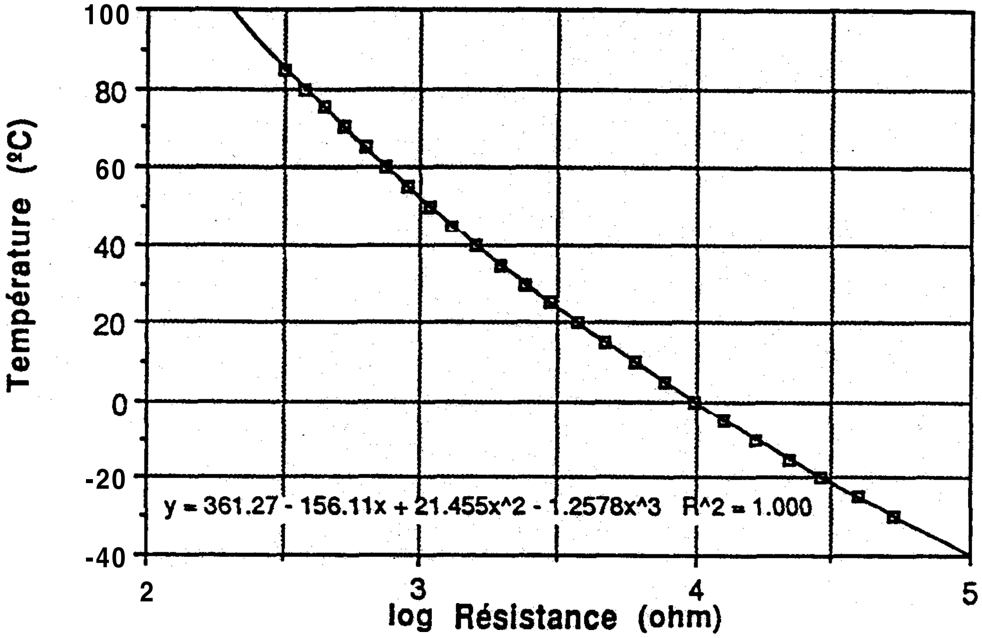
Temperatures to 1 m depth are affected by diurnal changes in surface temperatures. To a depth of 3 to 5 m monthly variations from normal may be recorded. Deeper than 10 m, thermistors respond to an annual cycle or remain isothermal. Internal heat generation is usually an order of magnitude more important than heating or cooling due to infiltration of rainfall or snowmelt. The annual cycle of air temperatures has a more profound effect than occasional extreme warm or cold episodes. Detailed analysis of data may show the effects of air convection in the first 5 m near surface. Otherwise, temperature profiles are dominated by heat convection from and to surface and heat generation by chemical and biochemical reactions.

Thermistors are usually installed in boreholes drilled for a combination of purposes such as rock sampling, installation of piezometers, gas ports, etc. The cost of installing instrumentation is typically \$500-\$2,000/hole. Thermistors are read at a rate of 7-15 per hour, and each hole may have 10-20 thermistors. Cost for measurements may be reduced by combining with gas monitoring costs. Automatic data logger capital cost is \$2,000 to \$3,000 plus per borehole and is more expensive than manual readings unless readings are required frequently (this is site-specific and also depends on sampling frequency).

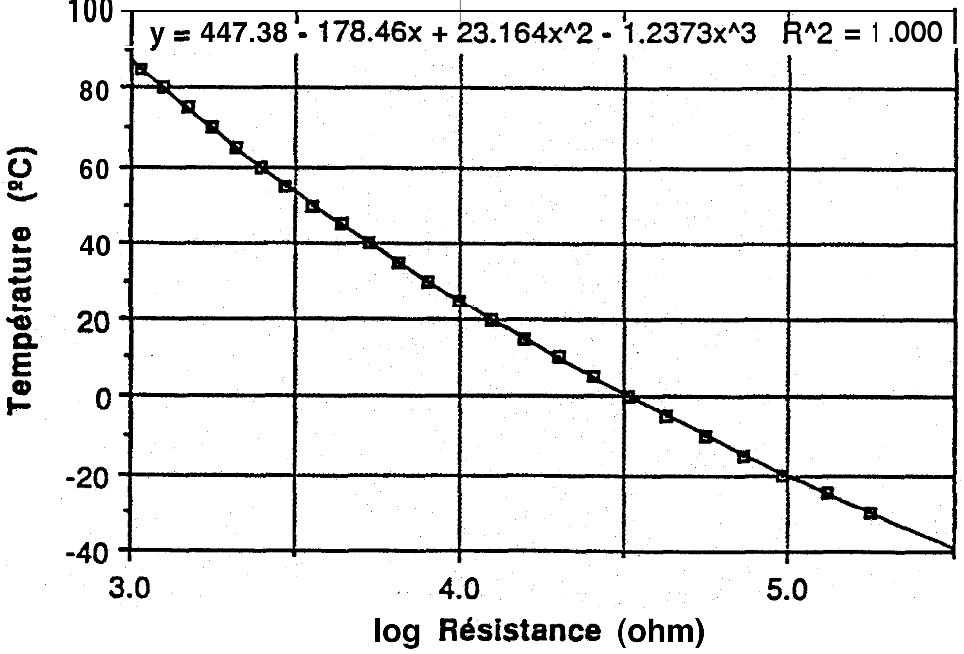
FIGURE 2.2.3

CALIBRATION CURVES FOR THERMISTORS

TEMPERATURE versus RESISTANCE
GEOKON THERMISTORS FOR BOREHOLES IN THE SOUTH PILE


Temperature vs Résistance
Thermistances Geokon des puits de la halde sud

TEMPERATURE versus RESISTANCE
ROCTEST THERMISTORS FOR BOREHOLE No. 1


Temperature vs Résistance
Thermistances Roctest du puits #1 (25 et 30 m)

2.2.7 Permeability Testing

Soil Permeability (Hydraulic Conductivity)

Different testing techniques can be used to estimate the permeability (hydraulic conductivity) of saturated soils to water. Hydraulic conductivity of soils can be estimated by *in situ* testing, laboratory testing of samples, and from grain size distribution (Freeze and Cherry 1979).

(i) ***In Situ* Techniques**

There are two *in situ* testing techniques which are commonly used, slug tests and pump tests. Slug tests can be performed on both very permeable and formations with low permeability. Slug testing may consist of removing a volume of water (using a bailer or pressurized nitrogen) from either a piezometer riser pipe or an open casing penetrating the tested formation (rising head test). Slug tests can also be performed by adding a certain volume of water (falling head tests) into a piezometer riser pipe or an open casing. In both cases, water levels through time are recorded until the water level has recovered at least 63% of the water level difference between static water level (level before adding or removing water) and the first water level recorded after removal or addition of water (Hvorslev 1951) (see Figure 2.2.4).

The equipment required to carry out a falling head test consists of: a bucket, a funnel, a water level finder and a stop-watch. Equipment required to do a rising head test consists of: small diameter (1/8" I.D.) gas tube, pressure regulator and nitrogen tank or large bailer.

Cost for slug test is approximately $100/hour, or on average $200/borehole, although this will vary widely with the permeability of the material being tested. Drilling and installation of monitoring well costs approximately $100/metre.

Standard procedures for testing in soils through open casing also exist (CAN/BNQ 2501-130-M-88, CAN/BNQ 2501-135-M-88). The calculation of hydraulic conductivity using pumping tests is based on the rate of drawdown of water levels in a network of observation wells due to removal of water from a test well. The pumping test is generally used to determine bulk or average hydraulic conditions. Pumping tests are expensive because they require a number of installations and are normally carried out over a period of several days.

(ii) **Laboratory Techniques**

Remoulded and recompacted, or non-remoulded soil samples can be tested in a constant head permeameter or a falling head permeameter. The test may be conducted at a given void ration (compaction) that is judged representative of field conditions. A schematic representation of the required apparatus is shown on Figure 2.2.5. For the constant head permeameter, the hydraulic conductivity (K) is obtained from (Freeze and Cherry 1979):

$$K \quad \frac{QL}{AH} \tag{2.2.3}$$

Error! Switch argument not specified.

where:

Q = steady volumetric discharge through the system.
L = soil sample length.
A = soil sample cross-sectional area.
H = constant head applied over the soil sample.

For the falling head permeameter, the hydraulic conductivity (K) is obtained from (Freeze and Cherry 1979):

$$K \quad \frac{aL}{At}\log_e\left(\frac{Ho}{Hi}\right) \tag{2.2.4}$$

Error! Switch argument not specified.

where:

a = tube cross-sectional area.
t = time required for hydraulic head to drop from H_o to H_i.
H_o = initial head.
H_i = head a period of time (t) after beginning of test.

Low permeability soils (i.e. clays) can also be tested in a triaxial permeability apparatus under different gradients.

(iii) **From Grain Size**

These empirical methods would only be used for very approximate estimates and would be supplemented using either laboratory or *in situ* techniques. It should be noted that these equations should generally be used with soils having low silt and clay content (i.e. sandy soils). This is particularly true for the Hazen equation and the Masch and Denny equation which were established based on tests on unconsolidated sand samples.

Hazen Equation

$$K \quad A\left(d_{10}\right)^2 \tag{2.2.5}$$

Error! Switch argument not specified.

where:

K = hydraulic conductivity (cm/sec)
A = normally taken as equal to 1
d_{10} = grain size diameter at which 10% by weight of the soil particles are finer than and 90% are coarser (mm)

FIGURE 2.24

SCHEMATIC REPRESENTATION OF SLUG TEST AND DATA PLOT

$$K = \frac{r^2 \log_e (L/R)}{2 L T_0}$$

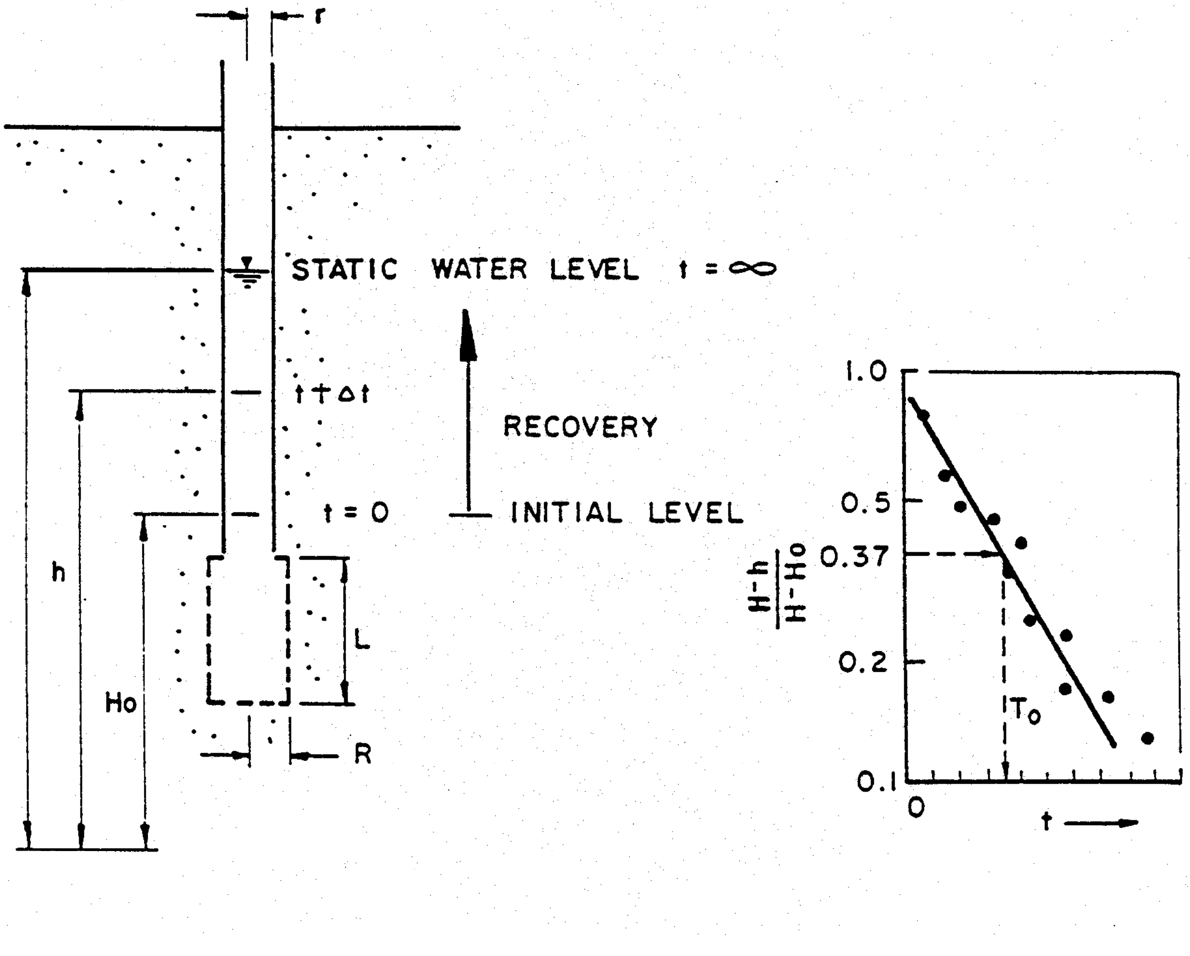
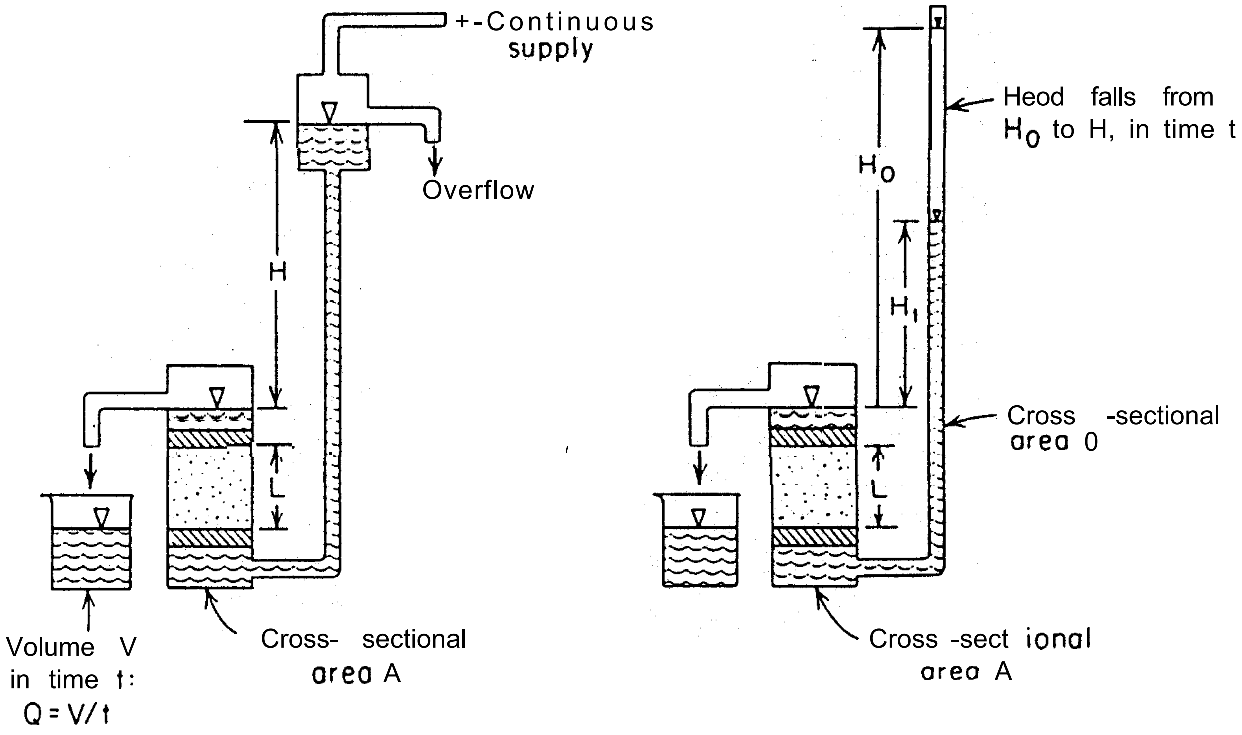


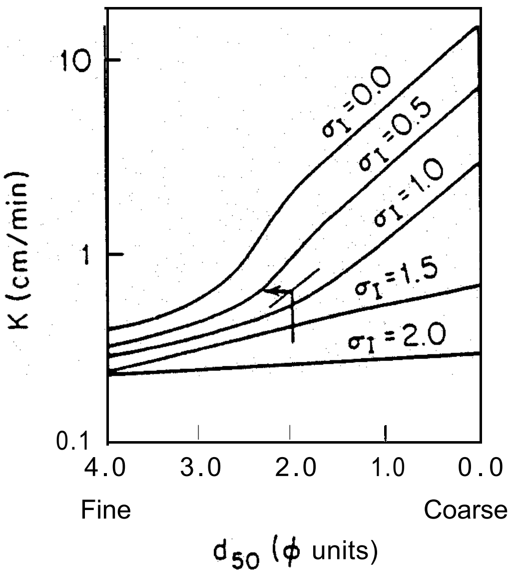
FIGURE 2.2.5

CONSTANT HEAD PERMEAMETER AND FALLING HEAD PERMEAMETER



(a) (b)

(a) CONSTANT-HEAD PERMEAMETER; (b) FALLING HEAD PERMEAMETER (AFTER TODD, 1959)



Masch and Denny Equation $\sigma_I \quad \frac{d_{16} - d_{84}}{4} + \frac{d_5 - d_{95}}{6.6}$ **Error! Switch argument not specified.** (2.2.6)

where:

σ_I = inclusive standard deviation.
d_n = grain size diameter at which n% by weight of the soil particles are finer than and 100%-n% are coarser in Krumbein's units
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Once σ_I and d_{50} (in Krumbein's units) are established, the hydraulic conductivity (K) value is obtained from a chart (Figure 2.2.5).

Faire - Hatch Equation $K \quad \left(\frac{\rho g}{\mu}\right)\left[\frac{n^3}{(1-n)^2}\right]\left[\frac{1}{m\left(\frac{\theta}{100}\sum\frac{P}{d_m}\right)^2}\right]$ **Error! Switch argument not specified.** (2.2.7)

where:

K = hydraulic conductivity (mm/s)
ρ = water density, 0.001 g/mm^3
g = gravitational constant 9,800 mm/s^2
ρ = dynamic viscosity (at 10 C) 1.31 10^{-3} $g\ mm^{-1}\ s^{-1}$
n = porosity (0 to 1)
m = compaction coefficient (experimentally found = 5)
θ = shape factor 6.0 (spherical grains) to 7.7 (angular grains)
P = percentage of sand held between adjacent sieves (%)
d_m = geometric mean of the rated sizes of adjacent sieves (mm)

Bedrock Permeability (Hydraulic Conductivity)

Methods used to estimate soil hydraulic conductivity can be used for bedrock, though some modifications may be required and some methods are not applicable.

Slug testing through open casing (or rods) cannot be performed in rock. The technique has to be modified in order to avoid loss of water between rods and hole sides or rods and casing when the slug test is performed. A relatively water tight connection between the open end of rods on surface and tested hole interval can be achieved using a single or a double packer arrangement. Figure 2.2.6 shows how inflated packers can be used to perform a slug test along a specific interval. Slug tests are then carried out the same way as in soils.

A slightly different method (Lugeon testing) using packers has also been developed and basically consists of the injection of water in a tested interval under various pressures. Lugeon values can be transformed into hydraulic conductivity (K) values.

Laboratory permeability testing of rock samples is also possible but would probably not be considered representative since hydraulic conductivity in bedrock is generally fracture controlled.

Waste Rock Permeability (Hydraulic Conductivity)

The *in situ* methods used to determine hydraulic conductivity in soils are normally not appropriate for waste rock dumps.

While it may be possible to evaluate the hydraulic conductivity of waste rock in the laboratory using permeameters, there are obvious serious limitations on these techniques with respect to the size of apparatus required given the probable sample size. Laboratory techniques are therefore much less practical.

Air Permeability Testing

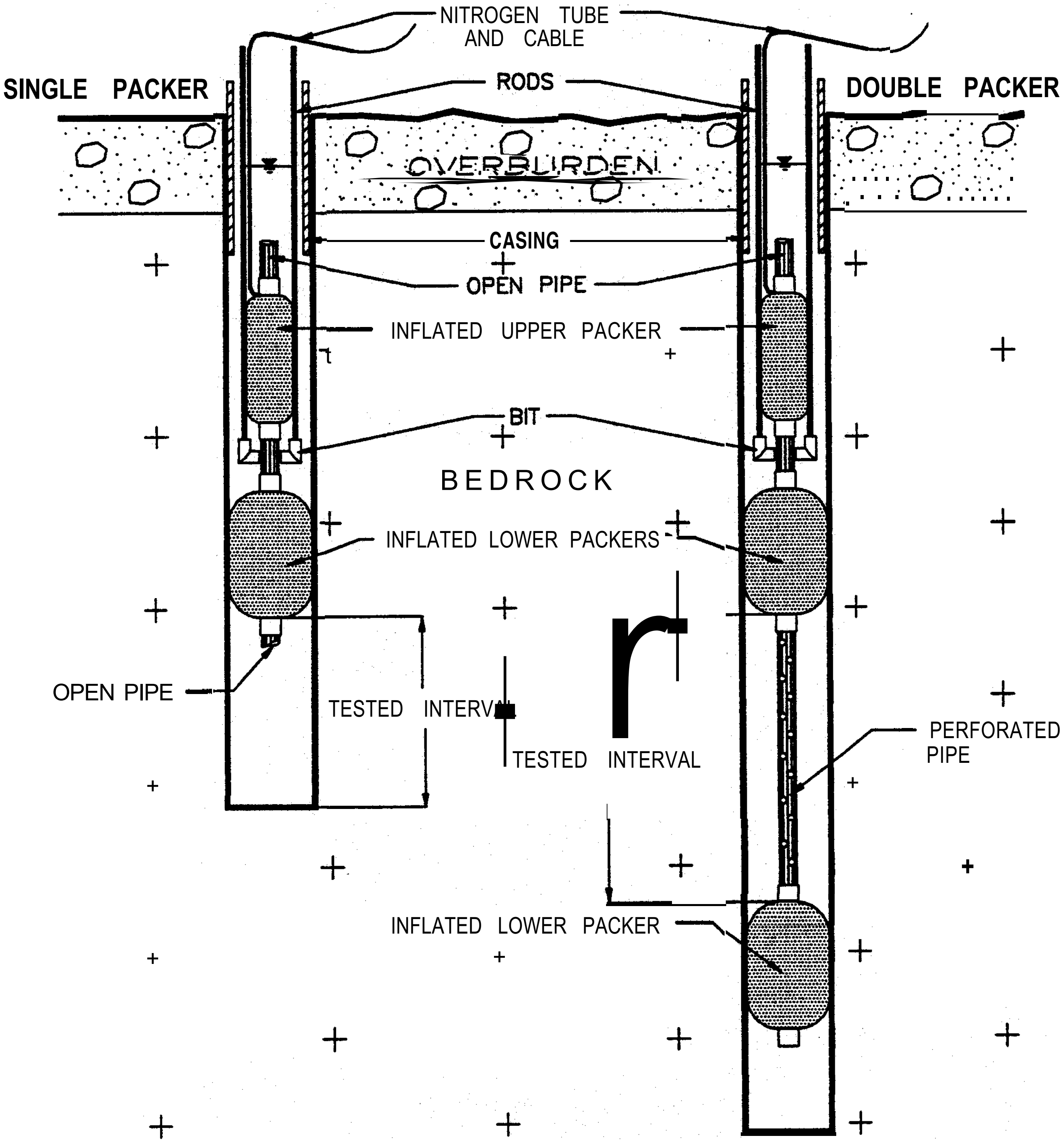
Any quantitative modelling effort requires the measurement or a good estimate of air permeability. Recent publications (Massman and Farrier 1992; Thorstenson and Pollock 1989) discuss the influence of atmospheric pressure variation on gas transport in unsaturated materials. Field measurements of permeability (in darcies or cm^2) or equivalent hydraulic conductivities (in metres/day) are described by Weeks (1978).

Three approaches are used in air permeability testing: air pumping tests, air injection tests and air permeability estimates from natural barometric gradients. Air pumping tests are carried out through a series of boreholes used for pumping or monitoring of air pressures, similar in design to pumping tests used in saturated aquifers. At depth, this experimental setting may prove much too expensive for waste rock monitoring. Lacking advance knowledge about the behaviour of the unsaturated waste rock, boreholes equipped with manometers may be too far from the pumping well to register any change at all. Critical distances may be in the order of only a few metres away from the pump. Large air volumes have to be pumped for significant air pressure drop in observation boreholes. Injection tests are not recommended in waste rock research since it modifies the gas composition in the surrounding rock and introduces unwanted oxygen into the system. Risks of test failure are high in both cases, especially for very coarse dump materials.

Field determination of vertical permeability to air in the unsaturated zone is best achieved by the natural gradient method (Weeks 1978). This method does not require different field installation than what is needed for gas sampling. Essentially, multilevel gas sampling tubes can be used to measure air pressure

FIGURE 226

SCHEMATIC REPRESENTATION OF PACKER TESTING



NO SCALE

differences with respect to atmospheric pressure at surface (see Figure 2.2.7). Daily variations in barometric pressure are recorded at the passage of frontal weather systems or associated with rainfall and storm events. Air sampling tubes are connected to a manometer where pressure differences of less than one millimetre of water (1 mm H_2O = 10 Pa) may be recorded. Significant air convection currents may establish in unsaturated materials for pressures differences as small as 1 Pa. Typical storm events may show barometric variations of 1,000 Pa within a few hours. Air tubes terminating at different depths can be used to record barometric pressure gradients with time. Recordings of such events are used to determine intrinsic permeability (in darcies or cm^2) (see Figure 2.2.8). Cost can be less than $1,000 per test if suitable boreholes with gas sampling ports are already installed.

Since pressure differences may be quite small for high permeability waste rocks, precision manometers able to measure to 0.1 mm water should be used. A pressure transducer may also be used for continuous monitoring of air pressure in the range of 0 to 25 mm water. The latter solution is preferred since barometric variations associated with storm events are highly unpredictable. Temperature data and porosity estimates are needed to calculate permeabilities. Using different spacing intervals between air sampling ports, it is possible to derive mean permeability of the dump and local variations with depth.

Gaseous Diffusion

It is generally accepted, that the diffusion of oxygen is an important, often rate-limiting step for acid generation. The macroscopic oxygen transport in one dimension through porous solids can be described by the following differential equation:

$$\frac{\partial C}{\partial t} + D_e \frac{\partial^2 C}{\partial z^2} + v_z\, h \frac{\partial C}{\partial z} + \rho\, R_{0_2}(C) \quad 0$$

Error! Switch argument not specified. (2.2.8)

where:

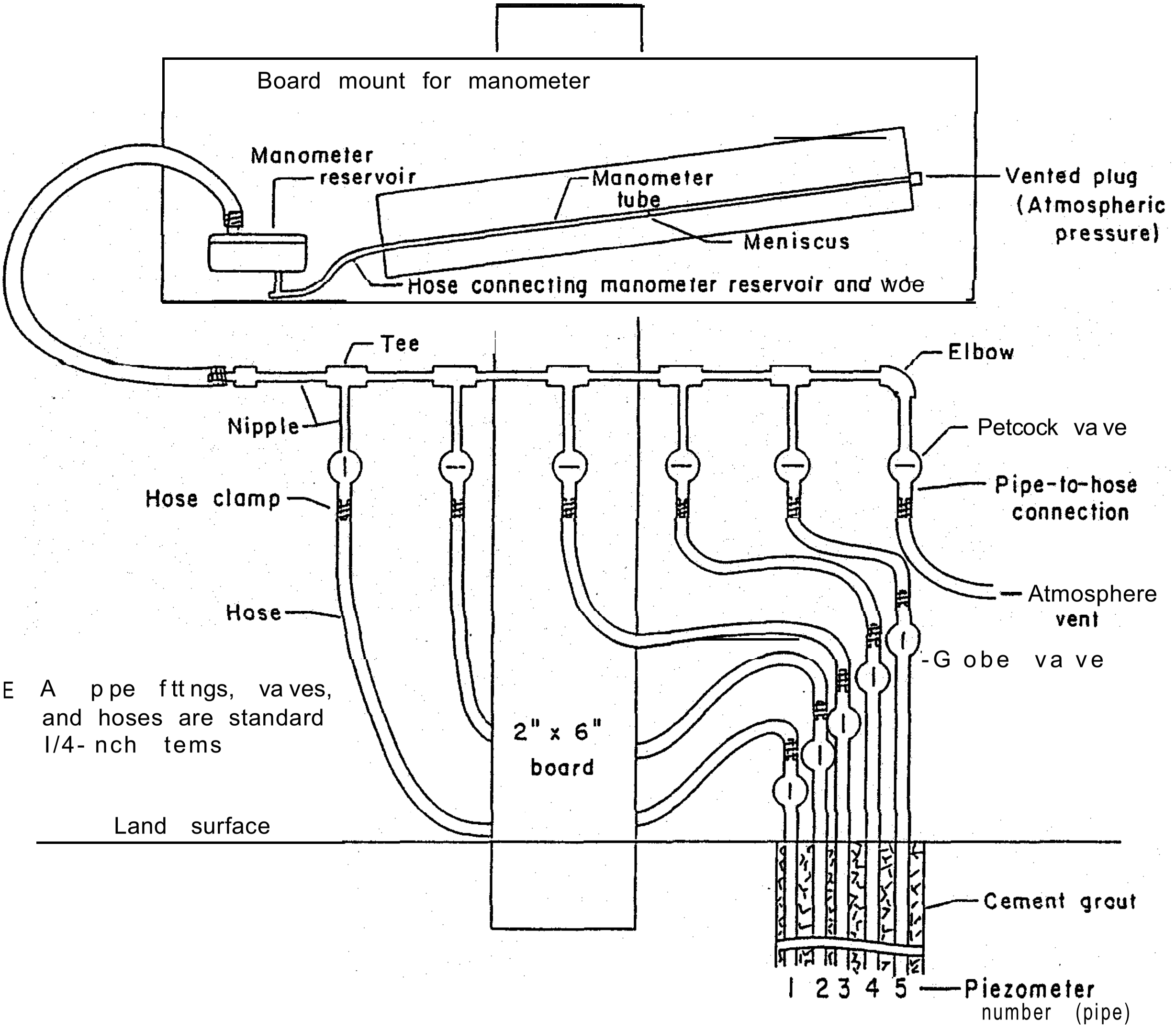
C = gaseous oxygen concentration (mol/m^3)
t = time (s)
z = distance into the solid (m)
D_e = effective diffusion coefficient of oxygen (m^2/s)
v_z = water (liquid) infiltration velocity (m/s)
h = Henry's coefficient (mol/m^3 O_2 in liquid per mol/m^3 O_2 in gas)
ρ = bulk density of the sample (kg/m^3)
$R_{O_2}(C)$ = oxygen consumption rate mol kg^{-1}/s

In equation (2.2.8), the distance, *z*, is taken positive in the direction of transport. In virtually all experimental work through mine waste, this transport has been constrained to be uni-dimensional.

The parameter to be estimated by the oxygen transport studies is the effective diffusion coefficient, D_e. In

FIGURE 2.2.7

SCHEMATIC OF MANIFOLD FOR AIR PERMEABILITY TESTING

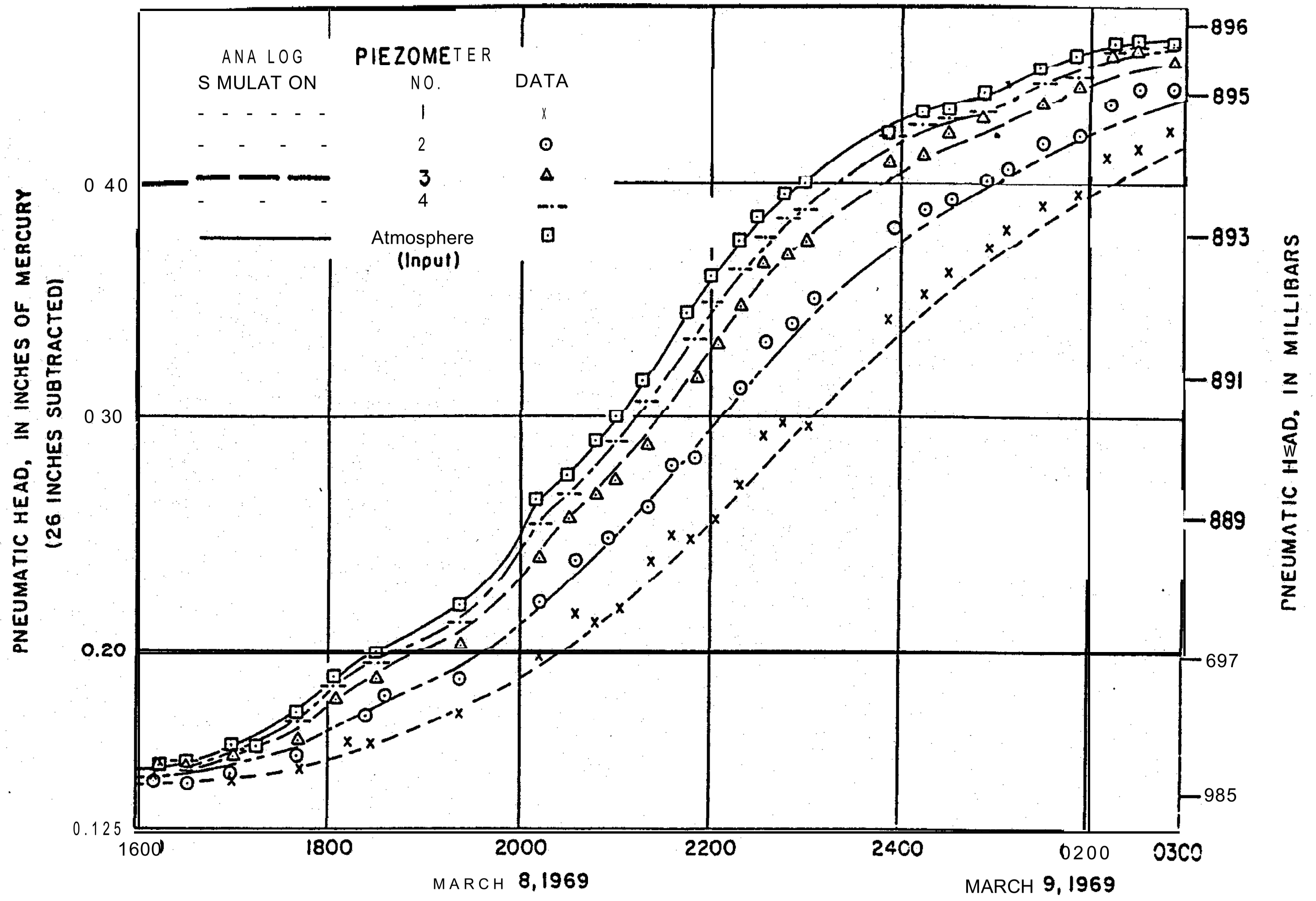


NOTE All pipe fittings, valves, and hoses are standard 1/4-inch items

SOURCE AFTER WEEKS **(1978)**

FIGURE 2.2.8

MEASURED PNEUMATIC HEADS AND BEST - FITTING ANALOG SIMULATION



SOURCE AFTER WEEKS (1979)

nature, the numerical value may range from 10^{-10} m^2/s to 2 x 10^{-5} m^2/s, depending on soil structure, porosity, and moisture content. It has been shown (Scharer et al., 1991), that this range can account for some 500-fold differences in acidity. Therefore, the tests are designed to minimize processes other than diffusion. For example, eliminating liquid flow and maintaining constant (100%) humidity in the test solid eliminates the convective term in equation (2.2.8). In some soils, the specific consumption of oxygen may be high. Moreover, the oxygen consumption rate is concentration dependent. These compound the difficulty of estimating the true value of D_e. For these reasons, often a non-reactive tracer gas (CO_2, organic vapours) are employed in the gas permeation studies. A final simplification involves steady state approximations. The combinations of these simplifications greatly reduces both the complexity of the experimental procedures and calculations. The heterogeneity of the waste sample remains the problem. Since diffusive transport is a relatively long process, the studies usually involve relatively small samples of fine grained material, such as tailings rather than waste rock. Laboratory program to assess diffusion into waste rock or cover materials is approximately $5,000/sample.

Nolan, Davis and Associates (N.B.) Limited (1993), in association with ANSTO (Australian Nuclear Science and Technology Organisation), describe field procedures for measuring and monitoring the principal gas transfer mechanisms associated with the oxidation of pyritic waste rock. Their work provides the rationale and describes the various techniques and procedures proven to be effective for measuring the bulk physical parameters of gas diffusion, gas permeability and thermal conductivity which are recognized as the principal parameters required to define gas transfer (Nolan Davis and Associates (N.B.) Limited 1993).

Reardon and Moddle (1985) employed carbon dioxide gas as a tracer for oxygen diffusion in pyritic uranium tailings. The apparatus consisted of a short column containing well-packed tailings to reduce wall effects. A gas stream containing a known concentration of gaseous carbon dioxide is introduced at one end. A solution containing dilute sodium hydroxide is placed at the other end of the column. The gaseous CO_2 absorbs in the liquid and reacts to form sodium carbonate. The extent of the reaction is monitored by a conductivity probe in the NaOH solution. The diffusion coefficient may be calculated from either dynamic or steady state data.

A variation of the column diffusion test involves the vapour diffusion of a highly volatile organic liquid (ether, chloroform). The organic liquid is placed at the bottom of the column. The temperature is strictly maintained at a constant value, hence, the vapour pressure of the organic liquid remains constant. The organic vapour diffuses upward through the soil sample and exits via a slow-moving, regulated air stream introduced to the top of the column. The concentration of the organic vapour in the air stream is monitored by gas chromatography. The vapour diffusion experiment is relatively simple to perform; the disadvantages include the long experimentation time, the exacting temperature control, and the difficulty in maintaining constant moisture content throughout the experiment.

Yanful and Nicholson (1991) used dynamic measurements to estimate the parameter D_e through tailings covers. The column of soil was first de-oxygenated with nitrogen gas. Oxygen is allowed to diffuse through the soil column and the oxygen concentration is recorded by a dissolved oxygen probe located in a small gas-filled chamber at the end of the soil column. The gas diffusion coefficient is calculated by regression analysis of the analytical solution of the simplified diffusion equation:

$$\frac{C}{C_\infty} \quad 1 - \exp - \left(\frac{D_e}{h^2} t \right)^{0.5} \textbf{ Error! Switch argument not specified.} \qquad (2.2.9)$$

where:

C = concentration of oxygen in the bottom chamber (mol/m^3)
C = final concentration of oxygen (mol/m^3)
h = height of the soil sample column (m)
t = time (s)

The dynamic technique is best suited to estimate the diffusion coefficient at 50% or less hydraulic saturation. At higher saturation, the rate of change of the oxygen concentration is excessively low for meaningful parameter estimation.

Chao et al. (1991) have developed an experimental setup for the rapid measurement of the oxygen diffusion through soil samples at any moisture content. The experimental system consists of a three compartment diffusion cell, a mass spectrometer, and a gas flow regulator assembly. The diffusion cell is comprised of a cylindrical sample holder at the middle with stainless steel screens at the top and the bottom. Nitrogen and air pass through the two outer compartments. A mass spectrometer (VG Pegasus) is used to monitor both inlet and outlet gas compositions. Pre-humidified gases are introduced continuously at measured flow rates to the two chambers. The pressures of the two gases are kept equal by a pressure regulator (less than 0.5 mm H_2 pressure difference). Composition of the gas streams is continuously monitored and the data logging is performed by an on-line computer coupled to the mass spectrometer. At steady state, the diffusion coefficient may be calculated by the equation:

$$D_e \quad \frac{Qh}{A} \frac{Y - Yo}{Y_{air} - Y} \textbf{ Error! Switch argument not specified.} \qquad (2.2.10)$$

where:

Q = nitrogen flow rate (m^3/s)
h = thickness of soil sample (0.02 - 0.03 m)
A = surface area of the sample (m^2)
Y = mole fraction of oxygen in the exiting nitrogen stream
Y_o = mole fraction of oxygen in the entering nitrogen stream
Y_{air} = mole fraction of oxygen in the ambient air

The mass spectrometer is capable of measuring differences in the oxygen mole fraction as low as 0.2%. The apparatus gives very reproducible results. Measurements could be made within five hours at moisture content as high as 90%.

2.2.8 Porosity Testing

Soils

The usual method used to determine soil porosity is based on the following relationship from Vomicil (1965):

$$n \quad 1 - \frac{\rho_b}{\rho_s}$$ **Error! Switch argument not specified.** (2.2.11)

where:

n = porosity

ρ_b = bulk mass density

ρ_s = particle mass density

The bulk density is the oven-dried mass of the sample divided by its field volume. The particle density is the oven-dried mass divided by the volume of the solid particles, as determined by a water-displacement test. In cases where great accuracy is not required, ρ_s = 2.65 g/cm^3 can be assumed for most mineral soils (Freeze and Cherry 1979). Cost is approximately $200/test.

Waste Rock

Standard procedures to determine aggregate porosity exist (American Society for Standards and Testing 1983). Although these procedures apply to aggregate with maximum particles size of 10 cm, it would be possible to perform the same test on waste rock samples containing larger blocks or particles. Some components of the testing material (balance, tub, etc.) would have to be built on larger proportions to match the sample particle size. The standard method is as follows: knowing the rock relative density (R_d), as established by a water displacement test, the void percentage (or porosity) can be obtained. The procedure basically consists of filling a metal box of known volume with the sample. The sample can be compacted or not, depending upon which option is more representative of field conditions. From this, the bulk density (ρ_d) can be obtained. The porosity (n) is the calculated using the following relationship:

$$n \quad \frac{(R_d \, \rho_w) - \rho_b}{R_d \, \rho_w}$$ **Error! Switch argument not specified.** (2.2.12)

where:

R_d = rock relative density (dimensionless)

ρ_W = water density (g/cm^3)

ρ_b = sample bulk density (g/cm^3)

(ASTM C29-91, ASTM C127-88)

Cost is approximately $100/test.

2.2.9 Water Content and Moisture

Soils

The standard procedures used to estimate water content are quite simple. The wet soil sample is weighed and then oven-dried and weighed again. The difference in weight between the two measurements is used to establish water content. It should be noted that special care is required for sample preservation. The sample should be put in a jar or wrapped in plastic in order to avoid loss of gravitational water or retained water, depending on whether the sample is saturated or under-saturated. Water content is defined as the ratio of the weight of water in the sample (as determined above) to the weight of solids in the sample (ASTM D2216-90).

Waste Rock

The method as described above to measure water content in soils could be used for waste rock, provided a representative sample can be taken. It is the most common method used, and is recommended because it is simple and cost-effective. Cost for analysis is approximately $20/sample.

Because of the lack of standard methods for estimating water content for unsaturated samples containing large size particles (over 15 cm), consideration could be given to a two step procedure as follows. Sample the waste material with particle size smaller than 15 cm and perform a standard water content determination (as for soils); then select and mechanically reduce a representative amount of the bigger blocks (larger than 15 cm) from the waste to particles smaller than 15 cm, and use this sample to do a second water content determination using the standard method. A global water content for the waste rock material could be obtained by making a weighted summation of the two previous water contents that would be multiplied by the percentage of each material size (smaller than 15 cm, and larger than 15 cm) as obtained from a grading curve (see sub-section 2.2.10).

Since it would be virtually impossible to sample saturated waste rock without loss of entrained water, porosity, as estimated with the method presented in sub-section 2.2.8, should be used in conjunction with rock density to estimate the water content (W%). The following relationship can be used assuming 100 percent saturation:

$$W\,(\%) \quad \frac{n\,\rho_w}{n\,\rho_w + (1-n)\,\rho_R}\,100 \tag{2.2.13}$$

Error! Switch argument not specified.

where:

n = porosity (0 to 1)
ρ_W = water density (g/cm^3)

ρ_R = rock density (g/cm^3)

2.2.10 Grain Size Analysis

Grain size analysis is a critical component of any ARD assessment. The production of ARD is directly proportional to the specific surface area of the sulphidic minerals available for oxidation. The specific surface area is approximately twice the ideal surface area (calculated from spherical geometry) to about 1 mm particle size; above this size, the ratio of surface areas becomes considerably larger. It is essential that the sulphide mineral content be correlated with grain size to obtain an accurate estimate of the total surface area of sulphidic minerals. Many forms of mineralization are associated with altered or fractured zones, therefore, upon blasting and excavation, sulphide minerals can concentrate with the finer fractions. These fractions are most susceptible to oxidation therefore it is important to both obtain data on mass fractions for various grain sizes as well as sulphide content in each fraction.

Determination of the particle size distribution for waste rock requires a non-standard testing procedure. It is recommended that the distribution of very large particles be established using "Grizzlys" or large scale sieves. A grading curve for waste rock material should be obtained by combining a series of representative weighed waste samples with the use of both a Grizzly and standard sieve and hydrometer analysis.

Costs range from between $60 to $100/test for simple sieve analyses. Costs can be much higher for coarse waste as machine time, labour for hand picking etc. will be required. This raises cost to $500 to $1,000/sample.

A second and less accurate method that could be used to determine the grain size distribution of waste rock involves visual estimates. Grain size analysis for waste rock made with this method have to be made in two steps. The estimate is made by placing a measuring tape over the waste material and adding up all the sections of the tape running across a pre-determined particle size range (for example: 1,500 - 1,000 mm, 1,000 - 500 mm, 500-150 mm, 150 mm and less). An average percentage of each particle size range can be obtained from several estimates made using the measuring tape. The finer material (less than 15 cm) can be submitted for standard soil sieve and hydrometer analysis. (ASTM D422-63). As sulphidic mineral surface area is a major concern in the acid generation mechanisms special care should be taken to determine sulphide content as a function of grain size. For that purpose, each fraction of the sample retained in the sieves (or in the pan) should be sent separately for chemical testing and mineralogical examination.

The reader is cautioned that knowledge of grain size alone is not adequate in itself. A knowledge of construction procedures utilized to build the rock dump is also necessary. If dumps are built in small lifts, various rocks sizes will be relatively well distributed throughout the dump. However if waste dumps are constructed by end dumping from a high face, substantial segregation of the rock sizes will occur with the larger rocks located in the lower horizons. This will affect rock porosity, permeability etc. throughout the dump.

2.2.11 Flow Monitoring

Water balances are key requirements in assessing ARD potential, performing mass balances and calculating contaminant loadings. Flow data for surface water flows, run-off, infiltration, seepage etc. are often inadequate. There are numerous flow monitoring devices available. Golder and SENES (1985), describe flow monitoring for tailings impoundments; many of these methods and considerations are relevant for waste rock piles.

Surface flows in and around waste rock piles may include streams, channels, ditches and pond outflows. In all instances, the basic technique used to estimate flow is to develop a *rating curve* at each specific location which correlates the depth of flow and flow rate from repeated measurements of both water depth and flow over a wide range of flows. Depth readings are made using a staff gauge, float, pressure or electronic sensor. Flow measurements are normally made using current velocity meter-stream area calculations for the development of rating curves. Procedures for this method of stream flow measurement are described in ASTM (3858-90). Velocity-area methods can also be used for periodic point measurements.

Staff gauges are relatively inexpensive and require little in the way of maintenance. When a staff gauge is used, flowrates are only known for those times when the gauge is visited and the depth read. To obtain more frequent or continuous measurements of flow, float, pressure or electronic depth measuring devices can be connected to automatic recorders. Recorders are more expensive but the information they provide can be used to better understand flow behaviour and they are useful for remote locations that cannot be accessed or measured frequently, and where flow is intermittent and associated with precipitation events. Regardless of whether manual or automatic depth reading methods are used, the location of a flow measuring station must be such that backwater effects or other conditions that can induce errors into measurement are avoided.

Seepage from waste rock piles does not lend itself to easy measurement because flows are generally low, and there is a large potential for dilution by other surface waters. In the case of both distributed and localized seepage, the seepage flow must in some way be contained or collected for a flow measurement while excluding other sources of water. This may involve the construction of collector ditches or sumps in the areas of seepage. High volume seepages which result in significant surface water flows can be measured using surface water flow measurement techniques as described above. Low volume seepages can sometimes be estimated using seepage-meter techniques.

Seepage meters have been used to investigate shallow groundwater discharge to surface water streams and lakes (Lee and Cherry 1978; Lee et al. 1980). Seepage meters consist of collection devices installed on the stream or lake bed which intercept and measure the rate of discharge of groundwater into the surface water. In areas of groundwater discharge or seepage, water flows upward into the seepage meter and fills the collection bag. The rate at which the collection bag fills is monitored, and the rate of groundwater discharge or seepage is calculated. The identification of groundwater discharge or seepage zones for the installation of seepage meters can be complemented by the use of mini-piezometers. Mini-piezometers consist of small diameter (<1 cm) piezometers installed manually to shallow depths (<1 m) below the stream or lake bed. Groundwater discharge or seepage zones are identified where water levels in the mini-piezometers are higher than the water level in the stream or pond.

Overall continuous flow monitoring is recommended as run-off events from waste dumps tend to be highly related to rainfall/snowmelt events. For many instances, run-off only occurs during heavy precipitation or snowmelt periods.

Installation costs are from $200 to $2,000 for V-notch weir and staff gauge. Electronic flow meters range from $1,500 to $2,000 and up.

2.2.12 Infiltration Modelling

Sampling Techniques

In order to estimate actual infiltration of precipitation in a waste pile or any other zone of interest, two basic techniques are available.

The first one uses basic meteorological data in which the only data necessary to estimate potential infiltration are average monthly precipitation and temperature over a representative period of time (more than 10 years). This data is available through federal or provincial agencies and the data should originate from the nearest meteorological station to the study area. Also available through these agencies is the monthly potential evapotranspiration data calculated from the monthly average temperature. If not available, monthly potential evapotranspiration can be calculated using the Thornthwaite method. The Thornthwaite equation gives a reasonable estimate of potential evapotranspiration (the data obtained from meteorological stations is calculated through the same method).

$$ET_{Pi} \quad 16 \left(\frac{10\, T_i}{I} \right)^a F_i$$ **Error! Switch argument not specified.** (2.2.14)

where:

ET_{Pi} = monthly potential evapotranspiration for month "i" (mm of water)
T_i = average monthly temperature for month "i" (^{o}C)
F_i = latitude factor for month "i" (dimensionless) at a given latitude

$I \quad \sum \left(\frac{T_i}{5}\right)^{1.514} \quad for\ T_i > 0° C,\ and\ i \quad 1\ to\ 12$ **Error! Switch argument not specified.**

a = **Error! Switch argument not specified.**

Other data that could be used are the daily average pan evaporation rate, solar radiation and temperature, depending on the level of accuracy required and the pile (or basin, etc.) geometry and characteristics (i.e. ponding water, presence of vegetation, etc.). This data can also be used in predictive models such as the HELP model, discussed below (Shroeder et al. 1989).

Infiltration (and evapotranspiration) can also be measured directly using lysimeters. These are basically impermeable cells or basins established in the ground or waste rock pile. The volume of water from precipitation collected in these cells is regularly measured and, with a knowledge of the collection time and collection area (i.e. area of the cell), an infiltration rate can be calculated. This information is usually correlated with precipitation data for the site; and with precipitation data, evapotranspiration (ie water loss) can also be calculated. A lysimeter can be as simple as a buried tub or as sophisticated as a geomembrane lined area. Sampling tubes and ports are usually part of the installation. Barrel lysimeters cost approximately $1,000 to install per lysimeter.

Predictive Techniques (HELP Model)

The Hydrologic Evaluation of Landfill Performance (HELP) Model was designed to evaluate different aspects of water flow over and through landfills. Given the similarities between engineered landfills and waste rock piles, the HELP model can be used as a powerful tool in predicting the performance of waste rock piles with respect to acid leachate generation.

HELP is essentially a water budget model dealing with quasi two-dimensional flow. The model simulates vertical flow for saturated and unsaturated conditions using Darcy's Law and Darcy's Law modified for unsaturated conditions. Lateral drainage is based on quasi-steady flow assumption (Schroeder et al. 1989).

The data required to run the HELP program includes (Schroeder et al. 1989):

- site area
- slope of cover layer and slope of top of each layer
- average daily precipitation
- average daily solar radiation
- soil data: porosity, field capacity, wilting point, hydraulic conductivity, evaporation coefficient, layer thickness, initial soil water content, maximum drainage distance for lateral draining

layers, position of impermeable layers, leakage fraction for synthetic membrane (if applicable)
- maximum leaf area index (function of vegetative cover)
- evaporative depth

The model output will include (Schroeder et al. 1989):

- precipitation and run-off
- evapotranspiration
- hydraulic heads
- percolation
- lateral drainage
- soil water content in evaporative zone
- soil water and snow water in storage at a given time

The model will also compute statistics over different time intervals for several of the output parameters. Costs for HELP model are approximately $2,000.

None of the above methods are clearly preferred. Use of more than one method will improve confidence in estimates. Uncertainty in infiltration estimates may translate to uncertainty in model predictions of contaminant loadings.

Many other infiltration models have been developed but few have been applied to modelling infiltration in waste rock dumps.

2.2.13 Biological Monitoring

The goal of these procedures is to confirm the presence and oxidative activity of bacterial isolates on waste rock particles in the unsaturated zone and in groundwater adjacent to waste rock in the saturated zone. Bacteria may be isolated at conditions (low or no oxygen, high temperature) which are known to inhibit the growth of collected strain or wild type *Thiobacillus ferroxidans*.

Experimental results have shown that a variety of acidophilic bacterial strains can be recovered from solid rock samples and evidence is available that a number of different microorganisms thrive in saturated aerobic and microaerophilic environments (circulating or stagnant groundwaters). These may affect the sulphide oxidation rate. For example, *Thiobacillus sulfoxidans* is known to enhance the oxidation of sulphide minerals by *Thiobacillus Ferrooxidans*.

Sampling Solids in the Unsaturated Zone

The sampling of waste rocks can be carried out by hand picking from the surface of the dumps, from exploration trenches to several metres from the surface, or during conventional drilling operations. Samples in the form of drill cuttings can be obtained in the unsaturated zone from air drilling methods. Water content is modified during recuperation but enough moisture is still present to preserve most bacteria. Collected samples are rapidly transferred to the laboratory in bottles containing prepared nutrient solutions.

Field personnel responsible for sampling should wear plastic (surgical) gloves to prevent contamination of the rock samples or drill cuttings with grease, oil or water.

To minimize field operations, 500 mL collection bottles are prepared in advance and filled to 50% capacity with sterile nutrient solution. This solution contains per litre: 3.0 g $(NH_4)_2SO_4$, 0.5 g KH_2PO_4, 0.5 g $MgSO_4$, 0.1 g KCl, and 0.0125 g $Ca(NO_3)_2$; pH is adjusted to 2.5 with 10 N H_2SO_4 and the medium is sterilized by autoclaving.

Rock fragments and cuttings are introduced into the wide mouth bottle until the nutrient solution overflows a little and the cap is screwed back on. The samples are kept on ice or in a refrigerator until the microorganism isolation procedure is carried out.

Sampling Liquids in the Saturated Zone

Liquid sampling can be done by filling bottles with acid mine drainage from the base of waste rock dumps.

In an attempt to obtain more information on the *in situ* status of the microorganisms activity in groundwater, a sampling device was designed to trap acidophilic microorganisms. It is made of high density polyethylene screw type centrifuge tube. Holes are drilled in the tube wall to ensure circulation of groundwater. Each trap is filled with sulphide minerals such as pyrite, pyrrhotite, sphalerite, chalcopyrite or any sulphides which can be used to support the growth of the microorganisms most likely to adhere to its natural substrate surface. Fused sulphur pellets can also be used successfully as substrates. About one third of the total length of a centrifuge tube is left intact in order to collect a small volume of groundwater.

Depending on the depth of groundwater in the drill holes, a number of these *bacterial traps* can be installed in a string to evaluate the relative efficiency of each sulphide substrate. Polyethylene strings should be used to hold the tubes that are left in place for a few days to several weeks.

Bacterial colonization of selected substrates can be visualized by light or scanning electron microscopy. Colonies can be grown in the laboratory using procedures that may have to be specifically developed for each locality. Lafleur et al. 1993, and Ragusa and Madgwick 1993 describe methods for enumerating iron oxidizing bacteria which are difficult to enumerate using conventional bacteriological methods.

Biological monitoring is normally not required for ARD assessment. It can be assumed the dominant sulphide oxidizing bacterium is Thiobacillus Feroxidans, for which kinetic rates for growth and biological oxidation are well-established.

2.2.14 Meteorology

Meteorological data that may be required as part of the monitoring program for a mining facility include wind direction, wind speed, rainfall, snowfall, relative humidity, solar radiation and air temperature. Some of this data may be available from a nearby or an on-site meteorological station. This data will be necessary for carrying out detailed research investigations and modelling.

For typical monitoring of waste rock dumps, the most important meteorological data are air temperature and surface soil temperature, rainfall and evaporation. If representative data are not available from a nearby climate station, then instruments for measuring these parameters should be installed on-site. The selection of appropriate locations for meteorological measuring devices is important, should consult with climatologist.

Cost for an automated weather station ranges from $5,000 to $10,000, depending on measurements required, power source, etc. Cost for monitoring is variable, depending on how much of data collection and recording is automated.

Temperature

A high quality measurement of the average annual ambient air temperature can be obtained with an aspirated temperature sensor, which requires a source of power to continuously operate the aspirator fan. A continuous recorder or data logger can be used to record the temperature measurements. If power is not available, a thermistor or a platinum resistance thermometer could be used. These will need a passive radiation shield to counteract wind effects. Air temperature measuring instruments are normally located 1.5 m above the ground surface. If a continuous recorder is not available, readings with a data logger should be taken on a frequent basis to obtain an accurate average annual temperature. Soil temperature can be measured using a thermistor buried in the shallow surface soil, and recorded with a data logger.

Rainfall

Measurements of rainfall can be obtained with a tipping bucket precipitation gauge. These are available in various capacities, depending on the level of precipitation at the site. The rain gauge is not suitable for frost or freezing conditions. If an estimate of average annual precipitation is required, i.e. both rainfall and snowfall, then a heated tipping bucket precipitation gauge can be used to the melt snow or ice that accumulates in the gauge. For temperatures down to -25 C, propane gas heating and a double wall case will be required. If power is not available to heat the bucket, a weighing precipitation gauge can be used, although this instrument requires additional maintenance (e.g. oil, antifreeze) and a special wind shield. The precipitation gauges can be equipped with automatic recorders or accessed with a data logger.

Evaporation

Measuring evaporation can be difficult. Large evaporation pans are required to obtain an accurate estimate. Instruments for measuring evaporation include a recording evaporation balance, a Piche type evaporation gauge, and an atmometer.

2.2.15 Thermal Analysis

Air and heat convection are key mechanisms controlling oxygen flow through waste rock dumps. Temperature profiles suggest that strong upward thermal gradients and oxygen profiles in rock dumps are often not typical of transport mechanisms by diffusion alone. Model studies suggest that convection is the dominant air transport mechanism in waste dumps (Cathles and Apps 1975; Cathles and Schlitt 1980; Davis and Ritchie 1986 1987; Harries and Ritchie 1985; Jaynes, Rogowsky and Pionke 1983 1984; Pantelis and Ritchie 1991).

Field observations during cold seasons show the presence of "hot spots" in different parts of a dump, frequently near the edges on the top of slopes. Often fumes, caused by vapour condensation, are observed during cold days. Snow-free spots may be observed at the surface of several waste rock dumps for part of the winter. Local measurements between rock fragments indicate temperatures of 10 to 20 C even when the air temperature is below 0 C. Theory also predicts the presence of convection cells inside the dumps with warm spots away from the slopes (Combarnous and Bories 1975; Domenico and Schwartz 1990).

Infrared Monitoring

Large-scale temperature surveys can be obtained by infrared imagery. The thermal infrared transmission spectrum emits in the 2-5 µm and 8-14 µm frequency bands. Infrared sensors detect radiation in a given frequency band according to the emissivity of the medium. Prior field calibration procedures must be carried on to determine waste rock emissivity.

On small surfaces, temperature measurements can be done using hand-held "infrared guns" that give spot values of temperature at distances of a few metres. Guns can be used to map small areas on the field around known heat sources.

Aerial surveys are done using an infrared thermographic camera. False colours or 128-level black and white thermal images can be obtained using a video cassette recorder to register the information. Emissivity has to be known before the survey and air temperature must be known during the flying period. If the survey is carried out using a helicopter, an estimate of elevation above ground must be made. Oblique images of the ground are obtained by adjusting levels of sensitivity of the camera. The AGEMA Thermovision 400 infrared camera, sensitivity level 1, gives a span of 6 C between scale ends and sensitivity level 2 gives a span of 14 C. Depending on the sensitivity level, terrain emissivity, ambient temperature and distance between camera and the dump surface, accurate temperatures can be determined within an interval. All temperatures higher or lower than the interval appear as white or black points. With appropriate calibration and camera settings, all field temperatures can be represented within maximum and minimum values.

Aerial surveys should be done during a period of the year when maximum difference exists between air and dump surface temperatures. These conditions usually exist in May and October in most mining areas. An ideal time of the day is before sunrise or shortly after if the sky is cloudy but no precipitation occurs. Direct solar radiation interferes with the picture quality.

Infrared images recorded on tape can be extracted using a videoprinter that gives a photograph of part of the dump in black and white or false colour (see Figure 2.2.9). Photographs can be scanned and analyzed using appropriate software. For quantitative work, corrections must be made for image distortion caused by oblique images or variations in topography. Ground control markings can be located by unrolling wide aluminum foil at the dump surface. Emissivity of aluminum is very low (0.1-0.2) so that the markings appear black on infrared images. Figure 2.2.9 shows a print of a warm area of the south dump of La Mine Doyon and a treated image shown as shades of grey for different temperature zones.

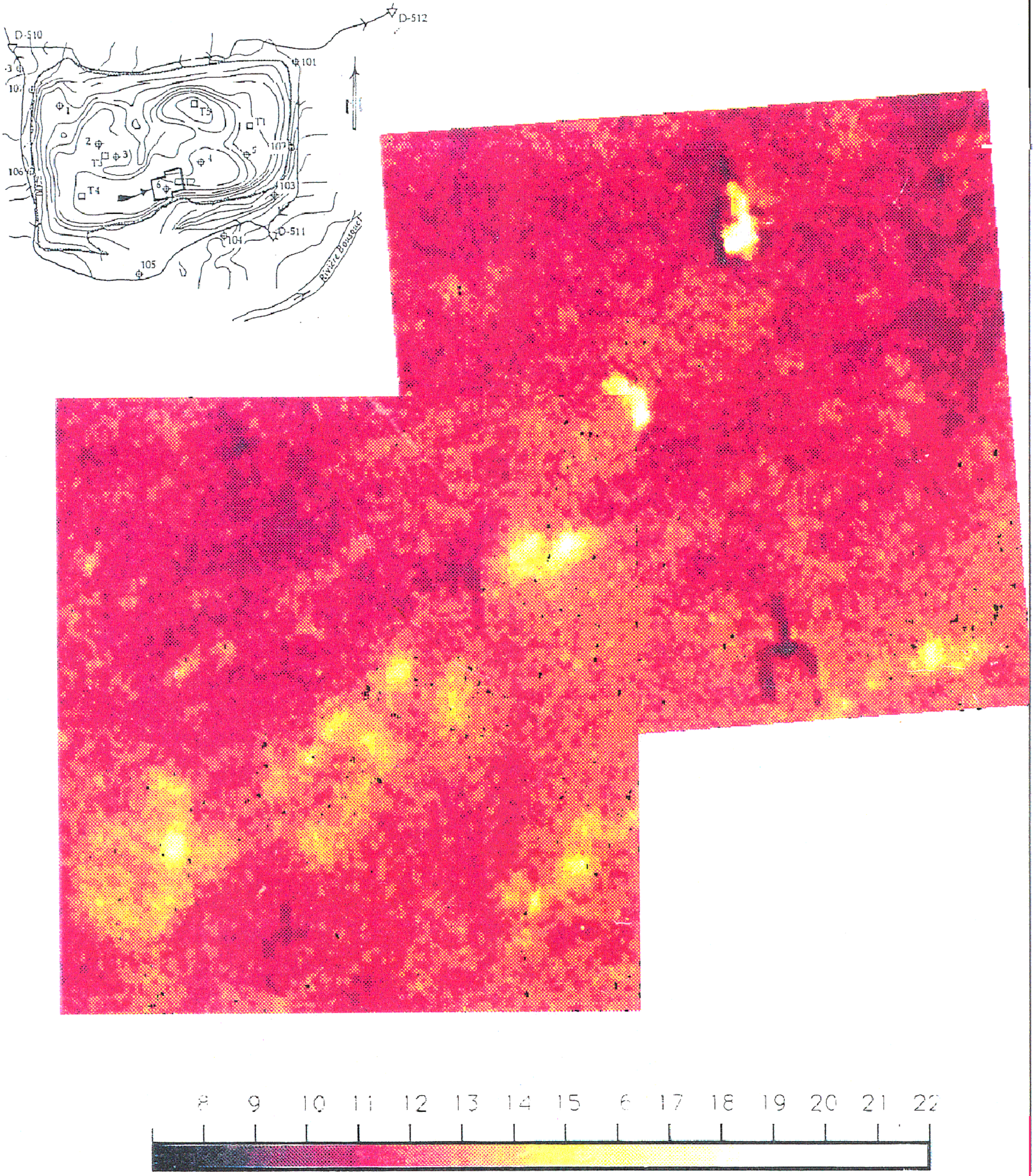
Temperature measurements may be affected by several factors, including the following: wind, heat capacity and thermal conductivity of the medium, surface to volume ratio, moisture content and evaporation, sky cover and its effect on radiation exchange, topography, elevational differences, dewfall and precipitation. For these reasons, infrared monitoring is still in the developmental stage and is used semi-quantitatively. Improvement of the method can be obtained by detailed field mapping using a 0.5-1.0 m square grid to cover anomalies detected through air surveys.

2.2.16 <u>Geophysical</u>

Geophysical surveys conducted during mineral exploration can also be used to detect sulphide minerals in rock surrounding a mineral deposit that may become waste rock. The use of geophysical survey methods could be more economical than closely spaced boreholes, as the geophysical survey can provide continuous information on rock strata between boreholes. These geophysical surveys may be performed as part of the

FIGURE **2.2.9**

INFARED IMAGES



exploration program and the results can be used for both exploration and for characterization of ARD potential.

Two methods are Induced Polarization (IP) and Self-Potential (SP). The data obtained from an IP survey include:

PFE - Percent Frequency Effects,
R - Resistivity, and
MF - Metal Factor (derived from PFE and R).

The following information can be inferred from these response (Byerly 1990):

- PFE > 10% indicates high concentrations of sulphides or other polarized materials;
- R > 10,000 ohm metres indicates presence of easily weathered rocks (i.e. interstitial space and/or water); and
- MF > 1 indicates easily weathered sulphidic material.

Geophysical methods historically have been used to detect and characterize the distribution and location of sulphide minerals within *in-situ* rock, as described above. The application of these methods to tailings, and the subsurface in the vicinity of tailings is described below:

> "Acid drainage is generally more electrically conductive than natural groundwaters. This conductivity contrast can be used to detect acid drainage remotely using electrical geophysical methods originally developed for resource exploration and engineering applications. Four geophysical techniques for detecting acidic sources from tailings and subsurface migration paths are currently being evaluated as a MEND project: ground-based electromagnetic (EM) surveys; airborne EM; induced polarization; and self potential surveys.
>
> With modifications, these techniques can be used for detection and monitoring of acidic drainage. Further ground-truthing of surface EM data at known AMD sites is being carried out. Also, data inversion software is being developed to process and present EM data already available. Variations in conductivity with time are also being measured to evaluate applications to long-term monitoring.
>
> The conductivity of the subsurface can also be measured using electrodes in contact with the ground to transmit direct current through the earth. Although less popular than EM, a number of enhancements of this method have been developed which may also have applications to acidic drainage problems. Two of these, induced polarization and self potential, are being assessed for use as indicators of sulphide content and electrochemical

> activity in tailings, respectively.
>
> The application and evaluation of these geophysical techniques is being carried out in the Sudbury basin, at the Copper Cliff and Levack tailings. Results to date show excellent potential to reliably track AMD from tailings at very low cost." (MEND 1993).

These experiments are being conducted on and in vicinity of tailings. To date it is unknown whether these geophysical techniques can also be applied successfully to waste rock sites.

2.3 SAMPLE COLLECTION

2.3.1 Drilling Techniques

Exploration Drilling

There are basically three different core drilling techniques: single tube (or standard drilling), double tube and triple tube.

The single tube technique is the oldest one and is currently not commonly used. The method involves pulling out all the drill rods following each run that is drilled to recover the core in the bottom rod.

The double tube and triple tube methods are both widely used. Both are referred to as *wire line drilling* and allow recovery of a core tube locked inside the bottom rod with a device commonly called an *overshot* which snaps on the upper core tube extremity. The core tube is then winched (hoisted) up to surface with the wire line inside the rods.

The difference between the double and the triple tube comes from the two part liner inside the triple core tube. For the double tube, the core is extruded directly from the tube. With the triple tube, the core is extruded (inside the liner) from the core tube using pressurized water.

Rock Dumps (Waste Rock Piles)

Though a wide variety of drills and drilling techniques are currently available, past experience suggests that powerful, large diameter drills are required to drill through waste rock piles. Well drills usually match those requirements.

Several well drill bit types are sold commercially and can be categorized as follows (see Figures 2.3.1 and

2.3.2):

1) Drag bits (unconsolidated or semi-consolidated sediments)

2) Cone-type bits (soft to moderately hard rocks)

3) Down-the-hole hammer with button bits or roller bits which are either concentric or eccentric with the drill casing (hard, dense rocks and rockfill).

Because of very difficult drilling conditions in waste rock and, in particular, problems with maintaining drillhole alignment, category 3) above, the down-the-hole hammer is considered to be the most suitable type of equipment for waste rock piles. In addition, with the down-the-hole hammer, cuttings can be collected continuously as drilling processes. Cuttings from waste rock, which is usually drained, are brought back to surface through the casing using pressurized air forced through the bit. There would, of course, be a problem where large voids are encountered since the voids would tend to cause a loss of air circulation and would make sample recovery impossible.

Of the various down-the-hole hammer type drills available, the eccentric (off centred) button bit is particularly well suited for drilling in waste rock. This type of bit mounted on a hammer will ream the borehole so that the borehole is slightly larger than the hole casing. This has two major advantages:

1) significantly reduces the potential for an irregular piece of waste rock falling into the drillhole against the drill rods and blocking casing advance; and

2) the casing follows the bit and rill rods by gravity or requires only modest vibration or driving to advance in the borehole.

With the eccentric down-the-hole bit, the hole is thus drilled and cased in a single drilling pass. After the hole is drilled and cased, the drill string is rotated in a counter clockwise direction and the eccentric bit is withdrawn into the casing. The drill string and bit are then lifted from the hole and the casing is left in place. Other drilling techniques, including other down-the-hole hammer bits, require that the casing be installed by driving in a separate operation which can be difficult and is certainly less efficient.

With respect to the other types of drill bits for well drills, drag bits are suitable only for unconsolidated or semi-consolidated formations (i.e. overburden or very soft sedimentary rocks). Cone-type bits can be used in waste rock drilling but are more suited to bedrock drilling. Depending on the nature of the waste rock (i.e. dimensions and relative hardness) a cone-type bit would be expected to experience more difficulty in maintaining drill hole alignment and a significantly lower rate of advance than a down-the-hole hammer type drill bit.

2.3.2 Field Monitoring

There are several tests which must be performed at the time of sampling. These include several water quality measurements (e.g. pH, conductivity and dissolved oxygen). Often, it is not possible to measure data in the field, in which case rapid transport for analysis is necessary. Paste pH determination is a field test used to assess the readily available acidity or alkalinity of a soil. This test can be conducted on waste rock fines collected in the field. An equal volume of deionized water is mixed with the natural rock fines (i.e. not a crushed sample). The conductivity of the leachate should also be measured to assist with interpretation of the paste pH results (Renton et al. 1988).

Another field determination is the "fizz test" where dilute (10%) hydrochloric acid is used to test for presence of carbonate minerals. The fizz test can suggest relative reactivities of rocks (Coastech 1991) and has also proved useful in distinguishing siderite from calcite (Brady and Hornberger 1989).

Neither the paste pH nor the fizz test can provide an adequate prediction of potential acidity/alkalinity, but may be useful for field comparisons.

2.4 QUALITY ASSURANCE

Quality assurance/quality control (QA/QC) procedures are an important part of environmental monitoring programs. QA/QC protocols are well established for analyses of samples but are not well defined for sample collection procedures. Norecol Environmental Consultants Ltd. have prepared a review of QA/QC protocols for the components of environmental monitoring programs that are related to predicting or detecting acid rock drainage and its environmental effects (Norecol 1992).

Common elements of a field QA/QC program (Beak 1991) include:

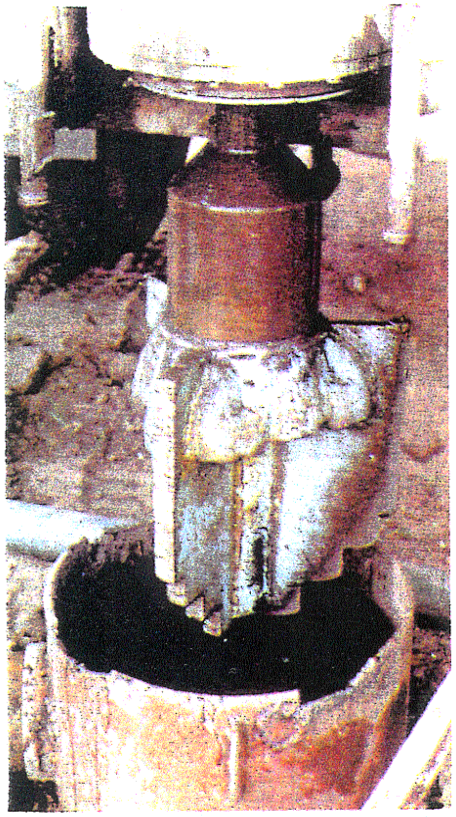
- maintenance of field notes
- technician training and evaluation; and
- standardization of sample collection.

The draft report by Norecol (1992) addresses each of these elements; however, the following sections are centred on the sample collection function. The reader is referred to Norecol (1992) for additional considerations and approaches.

2.4.1 Flow Measurements

FIGURE 2.3.1

WELL DRILL BIT TYPES



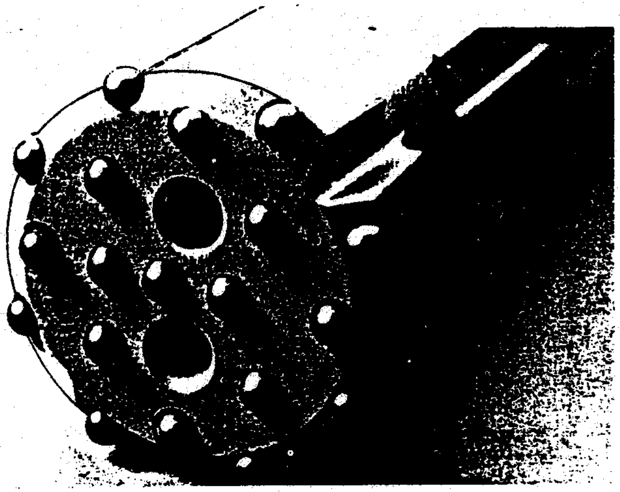
TYPE 1 (DRAG BIT)

TYPE 2 (CONE-TYPE BIT)

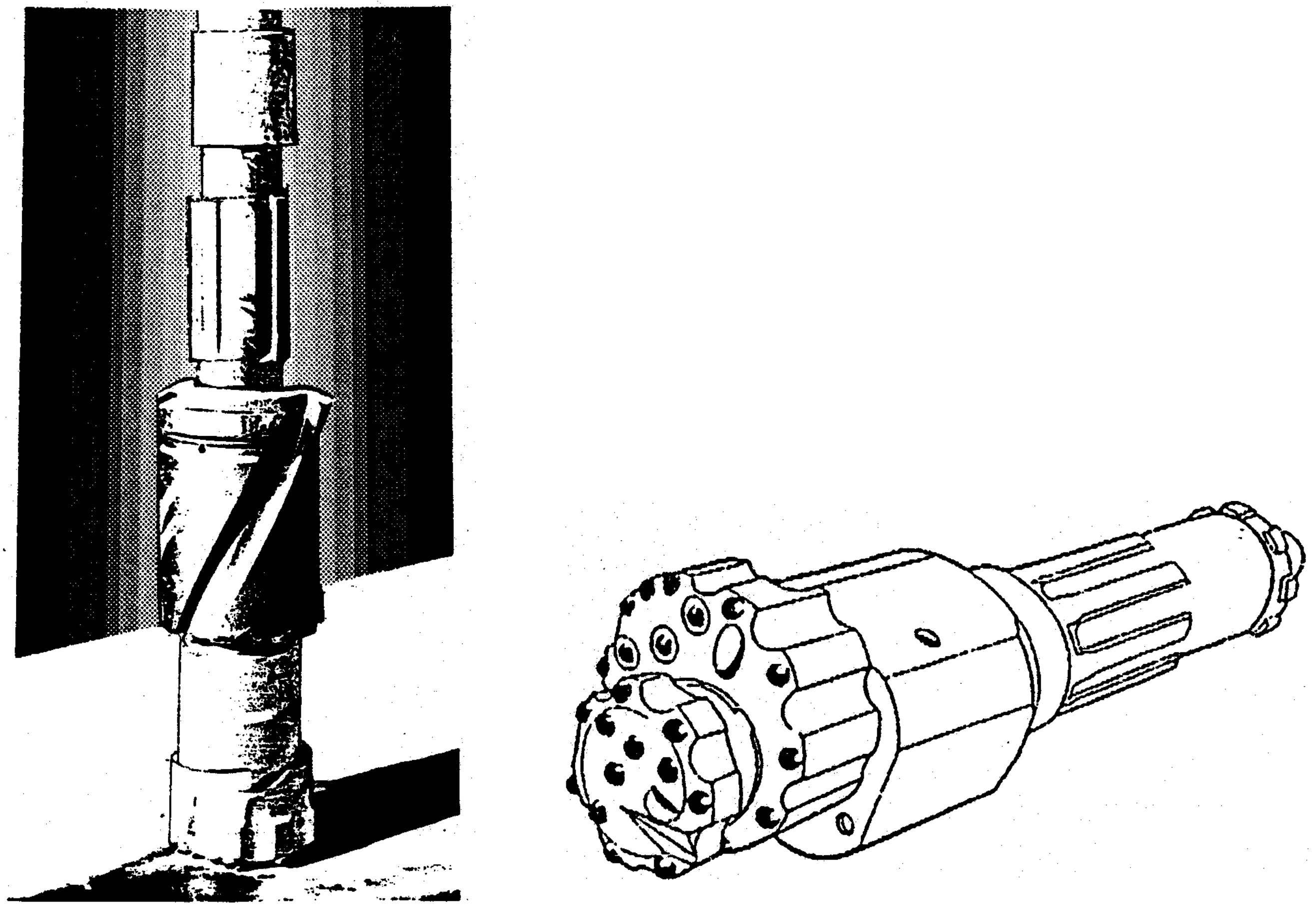
TYPE 3 (STANDARD BIT WITH DOWN-THE-HOLE-HAMMER)

FIGURE 2.3.2

WELL DRILL BIT TYPES



TYPE 3 (STANDARD BIT WITH DOWN THE HOLE HAMMER)



TYPE 3 (ECCENTRIC BIT WITH DOWN-THE-HOLE HAMMER)

Instantaneous flow measurements in a stream/channel should be conducted at a selected location that has the best cross-section for measurement. If the recommended procedures (Norecol 1992) are followed by experienced technicians, the flow measurements should have an accuracy within five percent of the true value 95% of the time (Terzi 1981).

Continuous stage (water level) measurements are converted to streamflow using a stage-discharge relationship. The accuracy of streamflow data depends on the accuracy and stability of the stage-discharge relationship at the measurement location and the frequency of discharge measurements. About 10 stage/discharge measurements should be made to establish a curve (Terzi 1981). Replicate measurements at the same stage level will indicate the degree of instability of the stream (Norecol 1992).

2.4.2 Waste Rock

There are few options for sampling waste rock (grab sampling, chip sampling, drilling) and virtually no information on the relative benefits of each of these options (Norecol 1992). The methods and locations selected for sampling are significant as these should be representative of the method used for construction of the dump. Waste rock dumps are extremely heterogeneous and may have variable water conditions. Duplicate samples would be preferred but these are very expensive.

Waste rock sampling is usually conducted to evaluate ARD potential. Two factors will affect the value of acid-base accounting, the representativeness of the sample obtained, and the procedures used to ensure the sample does not alter prior to analysis (e.g. storage). Representativeness is controlled by the number and size of samples collected; quality control is ensured through the use of duplicate samples (see Norecol 1992). The waste rock samples collected should be appropriate for the analyses to be performed (i.e. unweathered, fresh rock for ARD tests). Waste rock samples should be analyzed within two weeks, or if necessary, stored in a dry, cool location (preferably frozen). All sampling should be supported by detailed observations of geology, mineralogy and weathering (Norecol 1992).

2.4.3 Pore Gas

Techniques for pore gas sampling in the unsaturated zones of tailings and waste rock have been compiled by CANECT Environmental Control Technologies (CECT 1989). Samples of gas from monitoring ports are either analyzed on-site using an autoanalyzer or stored in syringes under carefully controlled conditions for later analyses. Biases will result if the sampling interval is not adequately sealed from the atmosphere, which is difficult for waste rock dumps (Golder 1989).

Variations in gas composition in waste rock dumps are usually larger than in tailings. Barometric pressure differences, wind velocity and thermal gradients induce air convection currents. In the first few metres near surface significant changes in oxygen content may be recorded during the same day (Harries and Ritchie 1985); therefore field data should be carefully recorded to help further interpretation of the gas data.

Field data from a gas sampling program will include sample identification numbers, sampling station numbers, and depth of sampling port. Date and hour of the day should be noted as well as weather conditions: air temperature, barometric pressure (if available), qualitative estimate of wind velocity, and special events such as storms or rapid weather changes. If samples are collected, purge time or volume should be noted along with type of pump used (peristaltic, hand bulb pump, etc.). Temperature at sampling port location should be recorded and if an air pressure cell or manometer is available, differential air pressure should be noted.

Because of inherent variability due to weather conditions, some steps must be taken to insure that gas concentrations measured are significant. With meters, three independent readings can be taken; this is done by disconnecting the tubes and starting over after purging. Odd data is rejected and the mean is calculated. For control and calibration, a few samples should be taken for chromatograph analysis.

Duplicate samples may be taken at given depths especially in low oxygen concentrations. This procedure will help detect problems due to aging, leakage or diffusion. For major atmospheric gases, a simple procedure is to check if the sum of components adds to 100%; this means that nitrogen also has to be analyzed.

In order to avoid mistakes in interpretation, it is important to establish the natural variability in gas composition at the beginning of a monitoring program. Weather conditions such as cold and warm seasons, barometric fronts, storm events, wind velocity may affect variability; daily variations should be noted for near surface sampling ports.

2.4.4 Water Chemistry

Surface Water

QA/QC planning includes selection of sampling sites and sampling frequency and replication. A control (unaffected) sampling location is required. The sampling design must address the range of natural variability of water quality (seasonal or flow-related). Sample contamination by the technician, sampling device, or sample container is the major source of bias. This can be assessed through use of sample blanks (e.g. transportation, sampler, pre- and post-filtration blanks). Sample containers should be compatible with the parameter to be analyzed (i.e. non-metal for ARD), and rinsed in site water prior to sampling (Norecol 1992). Morin (1990b) presents a case study of routine data quality in water analyses for five sets of seven replicates distributed to three different laboratories.

A calibrated field pH meter should be used to record pH prior to sample transportation. Appropriate sample preservation techniques should be used, and samples should be analyzed within the recommended time frame for the various parameters (e.g. within 24 hours for acidity and alkalinity) (Norecol 1992).

Groundwater and Pore Water

These water samples require special procedures because they are not usually in equilibrium with the atmosphere and may be altered (e.g. formation of precipitates, change in pH) if exposed to oxygen. CECT (1989) described and evaluated 20 different methods for obtaining groundwater/pore water samples for monitoring acidic drainage from tailings; some of these methods have general application to ARD monitoring. Groundwater is sampled upgradient and downgradient. General guidelines for water quality replicates should be followed. Water blanks should be included at the beginning, and at several random positions within a sample batch. The sampling method selected will depend on the specific sampling interval and the acceptable level of sample disturbance. All equipment should be carefully washed between sampling stations to prevent contamination. Groundwater samples for metal analysis should be filtered and preserved as soon as possible (Norecol 1992).

2.4.5 Bacteria

Methods for sampling of bacteria (*Thiobacillus ferroxidans*) in waste rock have been adapted from appropriate procedures for soil bacteria. Waste rock samples collected for ARD assessments should be suitable for bacterial analysis. A sterilized, sealed container containing sterile distilled water and aseptic sampling techniques are recommended. Conditions which affect bacterial growth should be noted (e.g. temperature, moisture, paste pH, nutrients). Storage conditions that may alter bacterial growth should be avoided. Ideally, samples should be refrigerated at 4 C (not frozen) and sent for analysis within 24 hours (Beak 1991).

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PART B

3.0 WASTE ROCK SAMPLING - EXPLORATION PHASE

3.1 DATA REQUIREMENTS

3.1.1 Overview

The objective of this chapter is to provide a road map or suggested guide to addressing waste rock sampling for an exploration property.

Exploration by definition covers a broad range activities. Initial stages include aerial surveys, literature evaluation, prospecting, trenching, geological mapping, geochemical surveys, etc. This may lead to drilling and eventually advanced stages of exploration which could include bulk sample extraction and test mining. Exploration activities often produce waste rock and mine waters.

The implementation of a waste rock sampling program during the exploration phase of a project is essential. The data collected can have a substantial effect on environmental management practices during advanced exploration phases and should include key data required for the design and feasibility evaluation of the mine development.

3.1.2 Generic Data Requirements

In order to develop a mining project, a developer needs to demonstrate the projects financial and environmental feasibility. The data collected from the exploration phase is the information upon which these decisions will be based. Therefore adequate levels of data must be collected to support the viability of the project.

A major cost incurred for all mining projects is waste management and "closure". The ultimate feasibility of a project may well be related to the costs for reclamation and long-term care and maintenance of the closed-out facility. Therefore, the sampling and data collection program during the exploration phase must consider the information required for mine development and the data required to support a credible closure plan. In this regard, jurisdictions such as the provinces of British Columbia and Ontario will require mines to post bonds prior to operations which will cover the ultimate costs of closure. The value of these bonds can easily reach tens of millions of dollars.

3.1.3 Specific Data Requirements

A typical project which progresses to a detailed exploration phase will require the following information.

i) Geology and Mine Plan - A detailed geological assessment is required to identify rock types, potential mineralization, and potential concerns. Other related data on nearby properties or developments in a similar type of deposit are of value. Preliminary concepts for potential mining methods and waste production and management are also required. This data will scope the need for further study.

ii) Chemical Characterization - All potential waste samples should be chemically and mineralogically characterized. These samples should include all waste rock and "low grade ore", as low grade materials are often stockpiled but never processed. In addition, mineralized waste is often difficult to separate from barren wastes. Therefore, barren material, mineralized waste and low grade ore should all be characterized with respect to their potential for creating a contamination problem.

iii) Leaching Data - Leaching data is necessary for all waste materials to determine environmental concerns. The degree of study and types of tests (static and dynamic) should be determined by a staged evaluation. These data scope out potential problems and allow for assessment of remediation techniques and evaluation of closure options.

iv) Borrow Material - Data on subsurface conditions, potential cover materials, etc., are required in order to develop closure options and cost estimates as well as suitable designs for ARD control during operations. Data collection on borrow materials may include physical characteristics (e.g. permeability to gas and water), and chemical characteristics such as buffering capacity.

v) Baseline Environmental Data - Baseline data are required for meteorology and climate, hydrology, hydrogeology, and surface water and groundwater quality. These data along with ecological studies are essential for determining the potential environmental impacts of the proposed facility and are necessary to confirm the environmental feasibility of the project.

Environmental monitoring programs typically begin in the exploration phase, with the collection of baseline data. The need for specific monitoring programs will vary from site to site and project to project. The primary concern for this manual is monitoring of waste rock. The following methodology is directed towards the ARD component of the data requirements during the exploration phase.

3.2 ARD ASSESSMENT METHODOLOGY

3.2.1 Rock and Soil Sample Collection

The sampling program required in the exploration phase of a potential orebody should normally include sampling of core from exploration drilling and samples of overburden material. As exploration drilling progresses, ore deposit shape, ore grade and possible exploitation schemes (underground or open pit) will be established. As shown on Figure 3.2.1, ore deposit shape and type of exploitation (underground or open pit) are key factors that will determine both the type and the volumes of waste rock (for simplicity, low ore grade will be referred to as waste rock) to be handled on surface.

Samples of core obtained during the exploration phase are submitted for testing to characterize rocks which may eventually be placed in waste rock dumps. Characterization of the overburden on the property is suggested in order to assist in siting the waste dumps and to provide information related to the availability of cover soils.

Waste Rock Sampling

Potential waste rock samples from exploration drill core should be collected as the drilling program progresses (see Figure 3.2.1). Waste samples are simply collected from split core from the zones of interest. If exploration involves surface rock sampling through bulk samples or channel samples, again grab samples or sub-samples should be used for waste characterization studies.

Soil Sampling

A general survey would include gathering of information from different sources (government maps, surficial geology, reports, etc.) and photo-interpretation over the study area. Once a rough picture of the overburden material distribution is obtained, field verifications should be made. The field verifications would typically involve test pits with a backhoe and the collection of grab samples of representative soil stratigraphy.

Standard grain size analysis and moisture content material determination (Section 2.2.10 and 2.2.9) on the collected samples should complete the overburden data acquisition at this stage. The geotechnical data obtained in this initial verification program would be used to supplement surficial geological data in order to prepare a surficial soils map for the area of the site. This data summary map would be used for siting of potential waste rock stockpiles and could be useful in evaluating the potential availability of cover soils for future consideration.

Exploration drilling using diamond drilling techniques normally precludes the collection of overburden samples for characterization. Some exploration work does, however, include some reverse circulation drilling to establish overburden thickness and the nature of the overburden. In this case, soil samples could be obtained for some soil classification testing.

3.2.2 The ARD Sampling Program

The ARD sampling program has three components:

- screening
- assessment and prediction
- related studies and investigations

An example procedure as required for the staged permitting of mining in British Columbia is provided for information in Figure 3.2.2.

Step 1 - Screening

Screening involves a series of monitoring programs which can be conducted quickly. Predetermined waste samples (see Section 2.1 and 2.2.1) are subjected to one or more of the test procedures outlined in Section 2.2.1 (Chemical Characterization) and Section 2.2.2 (ARD Assessment - Static Tests). For an exploration project, the samples would be chemically and mineralogically characterized, as a minimum. If the waste was barren of sulphide minerals, no further screening evaluation is required.

For samples containing sulphide minerals, an acid/base accounting is required. For samples with a large net buffering capacity, less concern should arise from the stockpiling of waste rock. Run-off and leachate from these piles could be contaminated since sulphide oxidation reactions can occur at alkaline pH levels and resultant dissolved metal species such as copper and zinc may not precipitate.

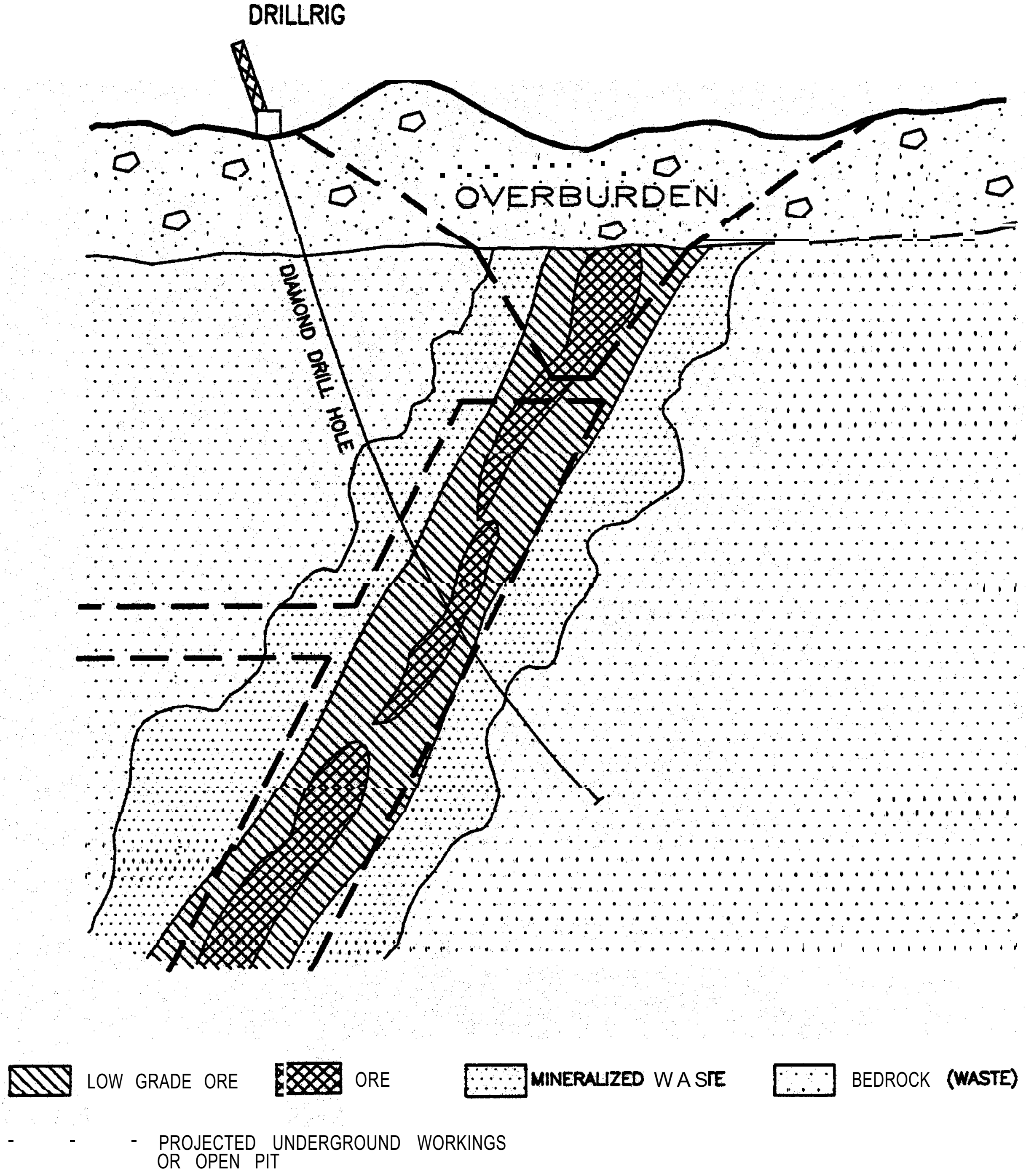
For samples with net acid generation capacity, it is correct to assume a potential ARD problem exists to proceed with further investigations.

Step 2 - Assessment and Prediction

The assessment phase is much more complex as there are a myriad of test procedures available. All these procedures have individual merit and no single test procedure is appropriate for all instances. The objective of this assessment phase is to confirm if a potential problem does exist and provide data which permits an

FIGURE 3.21

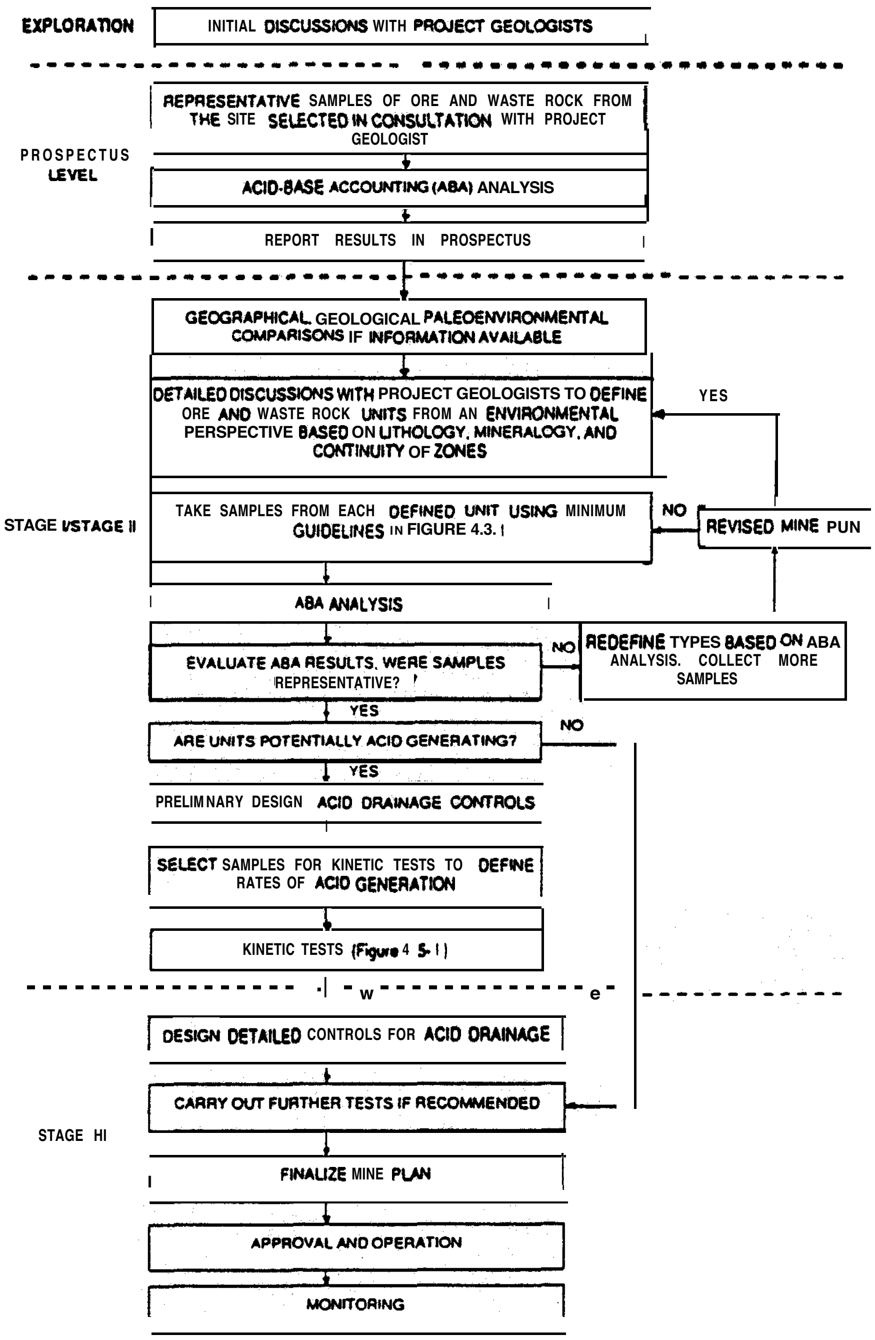
SCHEMATIC SECTION OF A TYPICAL ORE DEPOSIT



NO *SCALE*

FIGURE 3.2.2

PROCEDURE FOR EVALUATING THE POTENTIAL FOR ACID GENERATION IN BRITISH COLUMBIA



SOURCE: SRK INC., NORECOL AND GORMELY (1990). BC AMD TASK FORCE, DRAFT ARD TECH. GUIDE, VOL II assessment of the degree of the problem.

As discussed in Section 2.2.3, dynamic tests can provide the required data. As noted in Step 1, it is the writers opinion that any waste containing sulphide should be subjected to limited or preliminary dynamic testwork. This could include for example, column studies or humidity cell tests to determine if the leachate is likely to be contaminated. *It cannot be stressed enough* that effluent does not have to be acidic to contain elevated levels of heavy metals such as arsenic, nickel, copper, molybdenum, antimony, cadmium, iron (II) and zinc.

For the samples that have net acid generation potential, many different test procedures are required to allow for a predictive assessment of the problem. These tests include:

- detailed mineralogical analysis and determination of mineral forms (see Section 2.2.1);
- dynamic testing to address rates of reaction and identify contamination concerns (see Section 2.2.2);
- physical stability and weathering tests to assess crumbling rates and exposure of sulphide minerals over time;
- assessment of grain sizes including an estimate of the percentage of rock created greater than 10 cm and grain size distribution for rock particles below 10 cm (see Section 2.2.10);
- the correlation of sulphide content with grain size to assess whether sulphides are likely to concentrate in the fines (this test is only applicable to bulk samples and is not relevant for crushed core samples) (see Section 2.2.10); and
- detailed chemical analysis of leachate from dynamic tests.

The above data can be used as inputs for simplistic and complex models to predict the extent of an ARD problem. Current tools are not well developed but do generally allow an assessment of total quantity, rate, and duration of acid production.

Step 3 - Related Studies

At the exploration phase, the mining company is conducting drilling programs and related studies to determine the "best approach" to mining the orebody, (e.g. underground, open pit). These studies should also include an evaluation of potential management options for waste rock (e.g. surface stockpile with cover versus backfill into an open pit and flooding to maintain saturated conditions).

Other related studies are any additional programs which are essential for assessment of the financial and environmental feasibility of the proposed project. Some of these were discussed previously in Section 3.1.3 (Specific Requirements). Of these studies, the most important are:

- borrow materials evaluation (i.e. quantity and characteristics including porosity, gas and water permeability, moisture); and
- baseline environmental studies.

A borrow search for cover material (provided the characteristics of cover material is established at this stage) would use the data obtained from the general survey or simply be part of it. A series of test pits in more favourable identified zones would be excavated to provide additional information related to the engineering properties of the potential cover soils as well as available quantities. The level of detail of the investigation would depend on the design stage (i.e. conceptual or final design). Depending on the potential uses in cover design, the soil samples could be subjected to the following geotechnical testing:

- natural water content determination;
- grain size analyses;
- laboratory permeability testing;
- triaxial or direct shear; and
- testing for strength parameters.

4.0 WASTE ROCK SAMPLING - OPERATIONAL PHASE

4.1 DATA REQUIREMENTS

4.1.1 Overview

The operating phase of a mining project involves active extraction of ore and wastes. There are a few constraints related to sampling large quantities of waste materials being produced.

A modern operating mine would conduct a routine monitoring program of its waste. This program would be designed to: characterize the waste prior to stockpiling; ensure contaminated/noncontaminated wastes are not mixed; and, monitor environmental releases. These programs are often adequate for providing basic data and information but are inadequate for performing a thorough ARD assessment.

4.1.2 Specific Data Requirements

The types of studies completed for the exploration phase are equally applicable to the operating phase. The major differences are that actual waste samples are being produced from an operating mine, and the actual field conditions can be studied by monitoring the waste rock pile. Reliance on predictive tests is therefore of less concern. This is not to suggest that predictive tests are not valuable. These tests (e.g. humidity cell) can define if specific zones or waste types are of much greater concern and require special management. Most often, the various waste types are intermixed at a mine; therefore, the ability to measure effects from different rock types is not possible.

The major difference between the operating and exploration assessment is that for the operating phase, the monitoring programs are focussed on field data collection. With waste in place, data can be collected on leachate quality, temperature, biological factors, gas monitoring, physical characteristics, etc. These data are invaluable for calibrating predictive techniques (i.e. models) and increasing confidence levels in the overall ARD assessment.

4.2 ARD ASSESSMENT METHODOLOGY

The basic steps are analogous to the exploration stage.

Step 1 - Screening

As a general rule, screening tests in the early phases of mine development (i.e. exploration phase) will identify whether waste rock is a potential concern. In many mines, however, the geology changes with depth and orientation of the mine; therefore, the mine developer must ensure that all potential waste materials have been characterized and screened for ARD potential. Deposits may occasionally include oxide caps with sulphide mineralization at depth; thus waste produced during the early mine development may be clean but acid generating waste could be produced towards the latter stages of development.

A valuable source of data, which is often not fully utilized, is the numerical data obtained from blasthole analyses. Many mines obtain quantitative analyses for many key elements present in material from the ore and waste blastholes. This data often encompasses thousands of analyses in a database form which permits detailed characterization of all waste materials.

Step 2 - Assessment

The assessment stage for the operating mine is analogous to the exploration phase. The operating phase permits the database to be extended by collection of field data. The sampling programs which can be included to extend the database are reviewed in Chapter 2.0 and include:

- ground and surface water quality monitoring (Section 2.2.4) of run-off, pore waters, seepage and surface waters to gather information on water chemistry, oxidation rates, and geochemical reactions;
- gas sampling (Section 2.2.5) to assess oxygen levels and consumption rates;
- temperature monitoring (Section 2.2.6) to evaluate rates of exothermic sulphide oxidation;
- permeability testing (Section 2.2.7) to provide data on both soil and rock permeability to water and gas which impacts oxygen transport and water infiltration;
- porosity testing (Section 2.2.8) which effects diffusivity of oxygen;
- water and moisture content (Section 2.2.9) which influence dump hydrology and oxygen diffusivity;
- mineralogy (Section 2.2.1);
- grain size distribution (Section 2.2.10) and sulphide mineral content which determine the sulphide oxidation rates;
- acid generation potential (Section 2.2.2)
- infiltration and flow monitoring (Section 2.2.11, 2.2.12) which permits detailed water balance calculations;
- biological monitoring (Section 2.2.13) which may assist in calibrating bio-oxidation controls for predictive modelling;
- meteorology (Section 2.2.14) to provide data for water balance and temperatures module

calibration for predictive techniques; and

- thermal analysis (Section 2.2.15) which may prove beneficial in identifying active zones for study but is not a useful technique for predictive analyses.

For both underground and open pit mines, geological sampling is performed as the pit or underground workings advance, to confirm ore grades, etc. Some of these samples, or composites made from these samples, could be used for ARD assessment. Sampling methods include: diamond drill coring, chip sampling, grab sampling and collection of cuttings from blast hole drilling.

Installation of Piezometers and Thermistors

The installation of piezometers and thermistors requires additional explanation. A usual way of installing piezometers in a waste rock pile consists of drilling of a cased hole down to the required depth (see Section 2.3.1 for drilling technique description). Screened piezometers are assembled and lowered inside the casing to the appropriate depth. Clean sand is carried down the hole and around the screen. Bentonite seals (when required, are put in place by very slowly dropping bentonite pellets directly in the casing. Bentonite pellets settle on sand, accumulate over a certain depth and swell to form an impermeable plug. The entire hole is alternately filled with clean sand and bentonite pellets up to surface as the casing is extracted.

Thermistor strings are usually tied to a piezometer riser pipe and positioned on it according to the desired temperature monitoring depth. Gas sampling tubes can be similarly installed.

Water level measurements in piezometers installed as described above are accomplished using a standard electrical water level indicator. Groundwater sampling is accomplished using either a standard down hole bailer or an inertial type pump such as a "Waterra" brand pump. Thermistor readings are taken using a standard OHM meter to measure electrical resistance and temperature values are obtained using instrument calibration charts.

It should be noted that piezometer and thermistor installation in a cased borehole as noted above, is really only practical in inactive (i.e. completed) waste dumps. It would be extremely difficult to maintain and raise the installations as the dump is being constructed. Information related to groundwater levels beneath or within the dumps and temperature data could, however, be obtained from remote installations installed prior to or during dump construction. In this case, thermistors such as those used in vertically cased boreholes would also be used. The piezometers, however could not be open tubing but rather could be either pneumatic or vibrating wire piezometers. The later type would be the most practical and are based again on electrical resistance readings on lead wires extending from the instrument and calibration charts. The lead wires from both thermistors and piezometers would extend laterally beneath or within the dump to the edges of the dump to a remote monitoring station. For practical reasons, the locations of these installations would probably be limited to near the extremities of the waste pile. Further, in order to protect the lead wires from the instrumentation to the remote monitoring station(s) the wires would have to be installed in steel or rigid plastic conduits placed in sand filled trenches.

Installation of Oxygen Sample Ports

Oxygen monitoring in the operating phase should start as early as possible after final grade has been completed. Depending on the geometry of the waste rock dump, most instrumented sites should be located near slopes or on benches when several layers are present. These areas are more subject to air convection due to air temperature and pressure gradients. In the central part of the dump, sampling sites should be located so as to be in line with points located on edges to permit drawing of cross-sections.

Boreholes should be drilled with a diameter large enough for installation of a nest of two or more piezometers, thermistors strings and 10 to 15 air sampling tubes.

In the top 10 metres, tubes should terminate at depths (in metres) of 0.3, 0.5, 1.0, 1.5, 2, 3, 5 and 10 m. Thereafter, sampling ports installation every 5 m is recommended. Field observations show oxygen concentration may be close to atmospheric to a depth of 10 m. In a few cases, oxygen profiles may be inverted with higher concentrations near the base of the borehole, especially near slopes bases. Each tube should be rigid enough to remain intact when backfilling with coarse sand in the annular space between the borehole and the tubes. Two-way valves are placed at surface to prevent dirt from entering and prevent air movement when sampling or pressure measurements are not done.

Sampling is done by adapting the sampling device described earlier before opening the valve. The sampling schedule should be adapted to modelling requirements. Short term variations (daily, storm events, weather fronts) may be assessed over periods of intense measurements (hourly monitoring with a gas-meter) to check the effects of barometric pumping, daily temperature changes and wind velocity. Otherwise the schedule of measurements may be monthly to quarterly until annual and seasonal patterns are recognized. Long term monitoring can be done once or twice a year at the same period.

Biological Monitoring

Biological monitoring can be performed from surface by digging shallow 3 to 5 m trenches to recover moist samples that are rapidly transferred to bottles containing nutrient solution. If drilling is done to install piezometers, air tubes or thermistors, small samples of drill cuttings are taken at every 1 to 2 m intervals and kept in prepared bottles containing nutrient solution.

Monitoring in the saturated zone can be done when boreholes have been completed. Strings of perforated sampling tubes are lowered below water level when possible. Sulphide minerals are used as substrates for bacteria. Pyrite and fused sulphur pellets are common substrates for that purpose. Samplers are kept in place for several weeks to permit bacteria to colonize sulphide substrates. Solids and groundwater samples are mixed in nutrient solutions and kept at low temperatures (2-4 C) until laboratory treatments are performed. Monitoring schedule is defined in terms of important changes noted in gas composition, water temperature or chemistry.

Step 3 - Related Studies

Related studies are any additional programs which are essential for assessment of the continued financial and environmental feasibility of the mining project. Some of these were discussed previously in Section 3.1.3 (Specific Requirements). Of these studies the most important are:

- evaluation of various waste rock management options (e.g. surface heap with cover, backfill in mine or open pit, placement underwater);
- borrow materials evaluation for use as a cover (i.e. quantity and characteristics including porosity, gas and water permeability, moisture);
- evaluation of neutralizing materials (e.g. ash, limestone) and investigation of material placement strategies to mitigate potential or existing ARD from the waste rock pile;
- environmental studies to detect downstream impacts, if any, and to plan for long-term monitoring;
- prediction of long-term ARD and potential treatment requirements.

5.0 WASTE ROCK SAMPLING - DECOMMISSIONING (CLOSURE)

5.1 DATA REQUIREMENTS

5.1.1 Overview

The monitoring data requirements for completing an ARD assessment for a nonoperating site are analogous to the requirements for both the exploration and operation phases. Additional studies such as selection of a waste rock management option, investigations of cover materials and long-term environmental monitoring will be extremely useful in planning for closure.

A major problem exists if ARD was not addressed during the previous phases, as the level of historical knowledge concerning the characteristics of the waste, placement, etc., may be minimal. In this case, the first step in designing a program is to go back to first principles. The initial data reviews would include:

- an overview of geology and waste types
- a detailed correlation of geology, mining methods, waste production and waste placement such that the dump construction and likely locations of key geological materials is understood
- a review of monitoring data available
- a review of chemical and mineralogical analyses from exploration and mining (e.g. blasthole data)
- a review of waste rock management options (e.g. covered surface heap, backfill in mine or open pit, placement underwater).

The most important consideration for the closure phase is planning for long-term treatment, care and maintenance of the selected rock management option.

5.1.2 Specific Data Requirements

The specific data requirements and monitoring programs are analogous to those for the operating phase. The primary difference is that active mining and waste production is not proceeding; therefore, all samples are likely to be extracted from the existing waste rock dump. The mine and historical drill core (if properly stored) may also be sources for samples.

The only possible studies that would be conducted for the nonoperating site, that may not be useful to an operating property, would be heat analysis (Section 2.2.15). Heat analyses is a good screening test for directing the forces of the monitoring programs and the reclamation/revegetation program.

The details of a recent state-of-the-art monitoring program for an inactive dump are reviewed in Chapter 6.0.

PART C

6.0 EXAMPLE PROGRAM - LA MINE DOYON

6.1 BACKGROUND

La Mine Doyon, a gold mine located between Rouyn and Val d'Or in Abitibi, Québec (Figure 6.1), has been operating since 1978. Exploitation was first done by surface mining methods and two pits were excavated along the strike of the orebody. Since 1989, mine operation is underground. Overburden was initially piled up on the north waste dump and so was part of the rock waste from the main pit until 1983. A greater portion of the rock waste is, however stored in the south dump which covers a total area of 53 hectares and has a volume of 11,500,000 cubic meters. The south dump contains the most reactive materials, namely sericite schists, that were in contact with the ore zone.

The south dump was built rapidly between 1983 and 1987 in thick layers by placing first a berm around the site and filling the centre with rock waste. The northwest part of the dump contains a pile of very low grade ore and the top of the dump is covered in places by less reactive rocks coming from the west pit. The dump occupies a stretch of land between the pits on the north and Bousquet River on the south (Figure 6.2). No special ground preparation was done below the south dump before receiving rock waste; natural sediments have a thickness between 2 m and 8 m above the bedrock. Acid drainage problems developed from 1985 and reached a peak in 1988.

The south dump contains larger volumes of waste rock than the north dump. Some of the waste rock in the south dump is also more reactive (acid generating) than the material in the north one. For those two reasons, the remediation program initiated in 1990 focussed on the south dump.

6.2 GENERATION OF ACID MINE DRAINAGE FROM THE SOUTH DUMP

The acid drainage problem became apparent only two years after the dump began receiving rock waste and reached a quite stable state from 1988 to present. Waste rocks contain variable amounts of pyrite depending on lithology. Diorites from the west pit contain 1.5% pyrite and the value for sericite schist from the main pit is about 7%; mean concentration in the rock waste is between 3.5% and 4.5% pyrite. However, pyrite content is not the main factor explaining the rapidity and intensity of the reaction at La Mine Doyon.

More likely, acid generation is linked to the brittleness of the sericite schists and its slaking in the presence of water. These schists form about half of the rock waste stored in the south dump. Fine grained pyrite is distributed in schistosity planes and it rapidly oxidizes in presence of atmospheric oxygen and bacteria.

Acid effluents produced by rock waste are collected by a network of drainage ditches laid around the dump and pumped to a water treatment plant where acidity is neutralized and heavy metals are precipitated. High density sludges are stored in basins built for that purpose; effluent water released to Bousquet River meets required environmental standards.

Restoration of the south dump is a major consideration at the mine. It is therefore necessary to study first the rate of acid mine drainage generation, its intensity, its concentration and its variation with time. Long-term management implies that maximal protection of the environment must be achieved with minimal costs. Two main options are being studied now: (1) to place the rock waste in the mine pits with progressive flooding, and (2) to cover the dump with a dry barrier able to control entry of air and water into the waste rock to reduce oxidation reactions and to minimize infiltration and the production of AMD.

6.2.1 South Dump Characteristics

The south dump has a total area of 53 hectares including side slopes. The average thickness of waste is between 30 m and 35 m and the mass of rock is 21 million tons assuming a porosity of 35% and an *in situ* unit weight of 1.85 tons/m^3. These values were obtained by comparing two topographic surveys done before and after the construction of the dump. Six boreholes in the dump have confirmed the thickness and nature of the materials.

Lithologic composition of the south dump may be estimated from the geologic maps of the mine pits at different steps during exploitation and from volumes of rocks extracted during specific periods. Three main zones are recognized in the dump: Zone 1 consists of rocks coming from the main pit and represents about 80% of the total volume of the dump; Zone 2, located on the northwest side of the dump, represents the very low grade pile (about 15% of total volume); and Zone 3, that represents material coming from the west pit, is spread as a thin layer over part of Zone 1 (estimated volume is 5%). Global composition is approximately the following: 50% sericite schists, 25-30% acid volcaniclastics, and 20-25% for all the other rock types.

Based on the composition of each rock type, the pyrite content for the whole dump varies between 3.5% and 4.5%. The most reactive unit is sericite schist because of its low resistance to weathering by water absorption (slaking), by freeze/thaw and dry/wet cycles. Under these conditions, the schists have a tendency to exfoliate, to swell and to easily expose pyrite grains.

FIGURE 6.1

LOCATION MAP

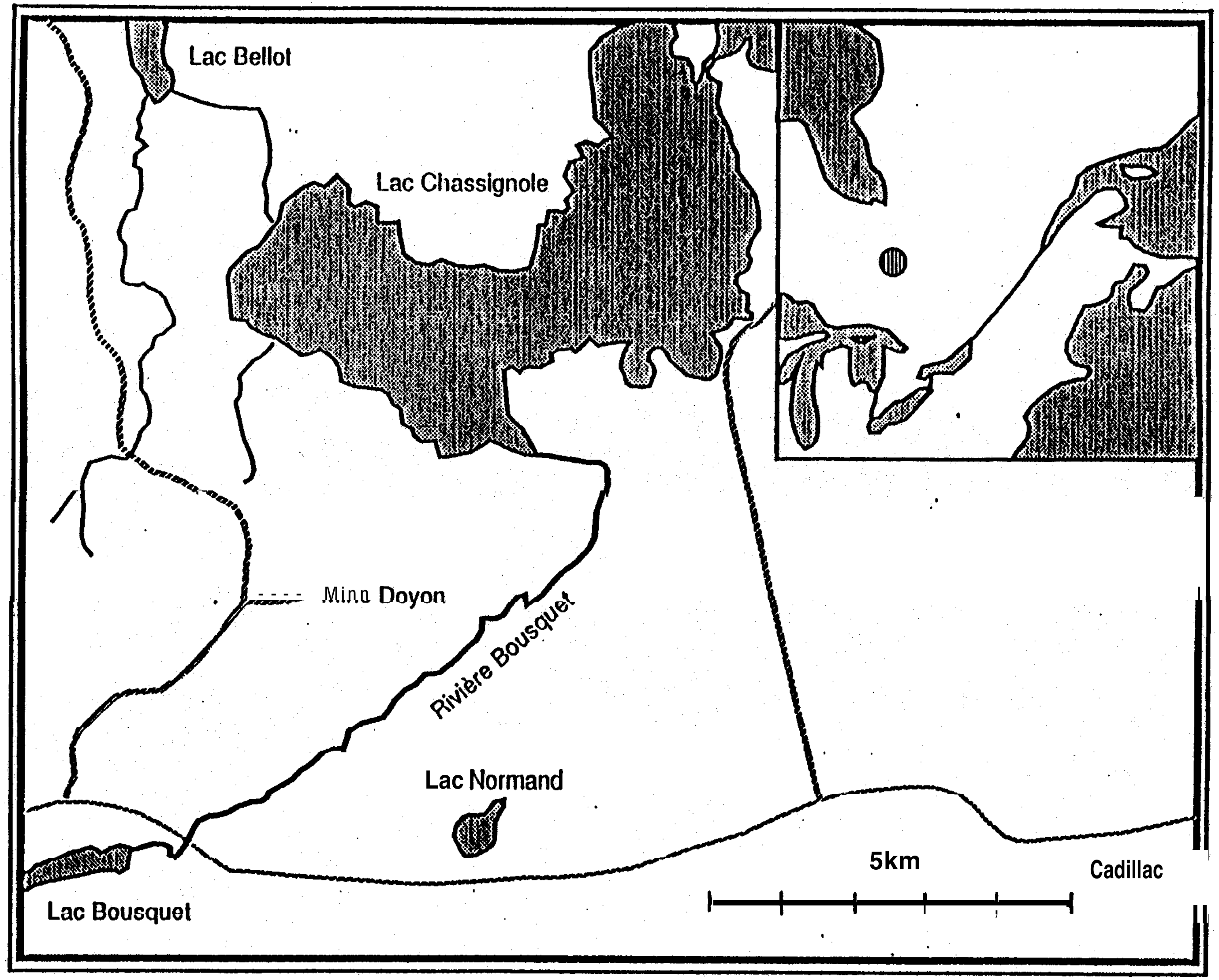
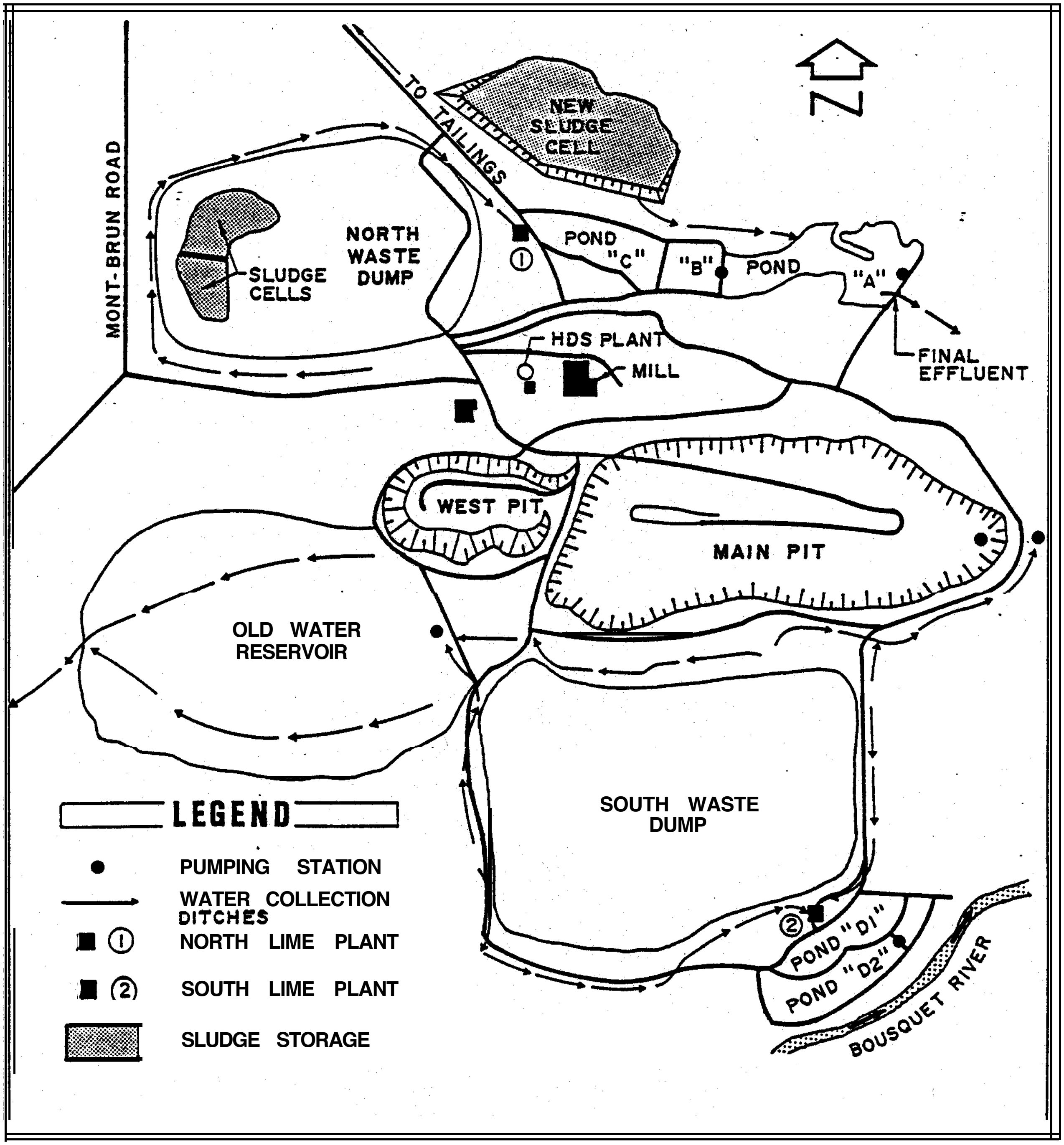


FIGURE 6.2

SURFACE INSTALLATION MAP



6.3 SOUTH DUMP EVALUATION PROGRAM

A main objective of this study was to determine the degree of alteration of pyrite in the south dump, to estimate the rate of acid generation and to calculate mass budgets indicating how reaction products are transported outside the dump. The evaluation program consisted of drilling and instrumentation of six boreholes penetrating the entire thickness of the rock waste, the unconsolidated sediments and the upper part of bedrock that lay below mine wastes. The six boreholes were instrumented with multi-level piezometers, thermistors and 6 mm diameter gas sampling tubes. Drill cuttings were sampled at regular intervals through the pile. Five exploration pits were dug at the surface of the dump to sample large blocks and observe alteration phenomena. Seven observation wells were drilled along the perimeter of the dump to sample groundwater (Figures 6.3 and 6.4). Periodic measurements of temperature, water levels and discharge rates were taken at three weir stations installed in the drainage ditches around the dump. Sampling of groundwater below and around the dump, of gases in the unsaturated zone of the dump, and water in the ditches was done on a regular basis starting in the winter of 1991.

Rocks and minerals were analyzed for their mineral composition, to determine the degree of alteration of pyrite at different depths and to determine whether alteration products such as gypsum, jarosite or ferric hydroxides were present in the dump. Temperature and gas measurements were used to estimate the intensity and rate of the oxidation reaction and to calculate by first approximation the potential life span of acid generation in the dump. Monitoring and water quality measurements of the effluents collected in the drainage ditches show an interesting relation between the mean concentration in dissolved solids and the rate of discharge.

Samples coming from drill cuttings, samples from exploration pits and from surface sampling were used for analysis. Each sample was described macroscopically and using stereomicroscopes. Contact paste pH, total rock chemical analyses and X-ray diffraction were also used to determine the mineralogy of materials.

6.3.1 Key Results

Examination and analysis of samples showed that typically alteration develops in successive layers from surface, somewhat similar to the development of soil horizons but traces of alteration are present at all depths to a different degree. The sequence of construction of the south dump, the initial state of the material and local heterogeneities can explain these departures from a general pattern. There is no clear evidence that the alteration proceeds from nuclei (or *trigger points*) inside the dump with propagation in the mass of rock waste.

The analysis of water quality below and around the dump was done using six boreholes (BH-1 to BH-6) inside the dump, each equipped with the two sampling levels, one in bedrock and the other at the limit between mine wastes and the original soil surface. Around the dump, seven observation wells (101 to 107) are used to sample groundwater at one or two elevations. Three drainage ditches bring leachate from the dump to weirs and sampling stations (510, 511 and 512). Water samples were taken from the ditches and boreholes.

Laboratory analyses on the water samples included the following parameters: acidity, conductivity, total dissolved solids (at 180 C to dehydrate sulphates), Eh, pH and the chemical components: Al, Ca, Cd, Cu, Fe (total, ferrous and ferric), K, Mg, Mn, Na, Ni, Pb, $S0_4$ and Zn. The most important parameters that determine water quality are acidity, sulphates, dissolved solids, pH and conductivity. Most important cations are Fe (total, ferrous and ferric), aluminium, magnesium and to a lesser degree calcium and manganese. Trace metals have no significant influence on mass budgets and are completely removed during neutralization processes in the HDS plant.

Concentrations of different components show wide variations according to the origin of each sample and usually reach maximum values in boreholes that penetrate sericite schists in the dump. For instance, sampling point BH-6R has total dissolved solids in the range of 153,000 to 200,000 mg/L. In the same piezometer maximum value of acidity reached 122,000 mg/L and sulphates reached 124,000 mg/L (as Ca CO_3 equivalent; see Figure 6.5). Total dissolved solids (TDS) have excellent correlation with all the major quality parameters for AMD so that measurement of it on a routine basis is a rapid and efficient way to evaluate and to check other parameters such as acidity, sulphates, total iron and aluminium (Figure 6.6).

Maximum concentrations are found along the former drainage network below the dump. Water samples showing highest acidities are located in the upper part of fractured bedrock where groundwater transport is more or less parallel to the original ground surface. Observation wells located around the dump show a different pattern. Wells 103 and 104 located south of the dump and upstream of drainage ditches are very acid and so is well 107 located at the northwest corner of the dump; wells 101, 102, 104, 105 and 106 show little or no acidity. Boreholes BH-2 and BH-3 show very high values of acidity (60-68,000 mg/L in BH-2 and 103-108,000 mg/L in BH-3) while rock waste at these locations are not very reactive. These two boreholes are located above the centre of a former stream that still drains a major portion of the dump to the northwest.

In drainage ditches, concentrations of total dissolved solids are high and variable with seasons. The main channel (station 510) has values of acidity varying between 35,000 and 62,000 mg/L, the southern ditch (station 511) has acidities between 14,000 and 61,000 mg/L and station 512 to the northeast has still lower values between 14,000 and 20,000 mg/L (equivalent $CaC0_3$). A dilution effect is noticed during spring snowmelt but this factor is not sufficient to explain adequately the observed data. The principal effect of spring infiltration is to flush out reaction products that slowly accumulated during winter when infiltration was

Table 6.3-1

MINE DOYON MONITORING PLAN

Monitoring Requirement	Method Selected
1) *Chemical Characterization*	
• **Elemental Analyses**	**Atomic Adsorption,** Ion Chromatography, XR Fluorescence
• Mineralogy	XR Diffraction, XR Fluorescence, EDX, Microprobe
. Mineral Forms	Scanning Electron Microscope, Petrographic Microscope
2) *ARD Assessment Procedures*	
• Static Tests	Acid-Base Accounting (Standard B.C. Task Force)
• Dynamic Tests	
3) ***Physical** Stability Tests*	
• Hardness	Los Angeles Abrasion Test, Micro-Deval
• Weathering	**$MgSO_4$** Adsorption, Compressive and Shear Wave Velocities Using an Accelerometer
4) *Water Monitoring*	
• Locations	Surface Water, Pore Water, Groundwater, Seepage
• Methods	Grab Samples, Core Washing, Core Squeezing, Piezometers
• Analyses Lab	**pH,** ICP, Major Anions, Acidity
Field	**Redox, pH,** Conductivity
5) *Gas **Sampling***	
• ☝♋⬧♏⬧	**O_2, N_2, CO_2**
• Method	Peristaltic Pump and 0, Sensor, Gas Chromatograph (Lab)
6) *Permeability*	
• *water*	Slug Tests
• Air	**(Modelling),** Pumping Test (94-95)
• Diffusion Rates	Derived from Gas Sampling, Temperature Gradients, and Model
7) *Rock Particle Size **Analyses***	
• Methods	Field: Sieving Very Coarse Fractions (1 ton sample), Lab: Sieving
8) *Porosity of Pile*	
• Methods	Detailed Survey to Measure Volume, Historic Data from Mine Operation (Mass-Volume Data), Microgravity (Bulk Density, Porosity, Water Content Data)
9) *Water Content*	Gravimetric Method (Trench Samples), Bulk Water Content (Microgravity)
10) *Flow Monitoring*	
• **Location**	Three Stations (NW, NE, SE) with Weir, Automatic Flow Recorder
• Methods	Weir Stations: Instantaneous Flow Rate and Cumulative Flow
11) *Infiltration Monitoring*	
• Methods	Gravity Lysimeters, Water Budget

Table 6.3.1, Continued

Monitoring Requirement	**Method Selected**
12) *Biological Monitoring* . Methods	*In Situ* Sampling (Traps), Bacteria Counting, Growth Experiments in Lab
13) *Meteorology* . Parameters . Methods	Precipitation, Temperature, Relative Humidity, Atmospheric Pressure Automatic Weather Station at the Mine and Environment Canada Stations (Rouyn/Amos/Val D'Or)
14) *Thermal Analysis* . Methods	Thermistor Strings in the Dump, Aerial Infrared Thermography, Modelling Air Convection
15) *Drilling Techniques* . Methods	ODEX Drilling, Trenches with Backhoe
16) *Geophysical Techniques*	Microgravity

FIGURE 6.3

BOREHOLE INSTALLATIONS, WEIRS AND TRENCH LOCATIONS

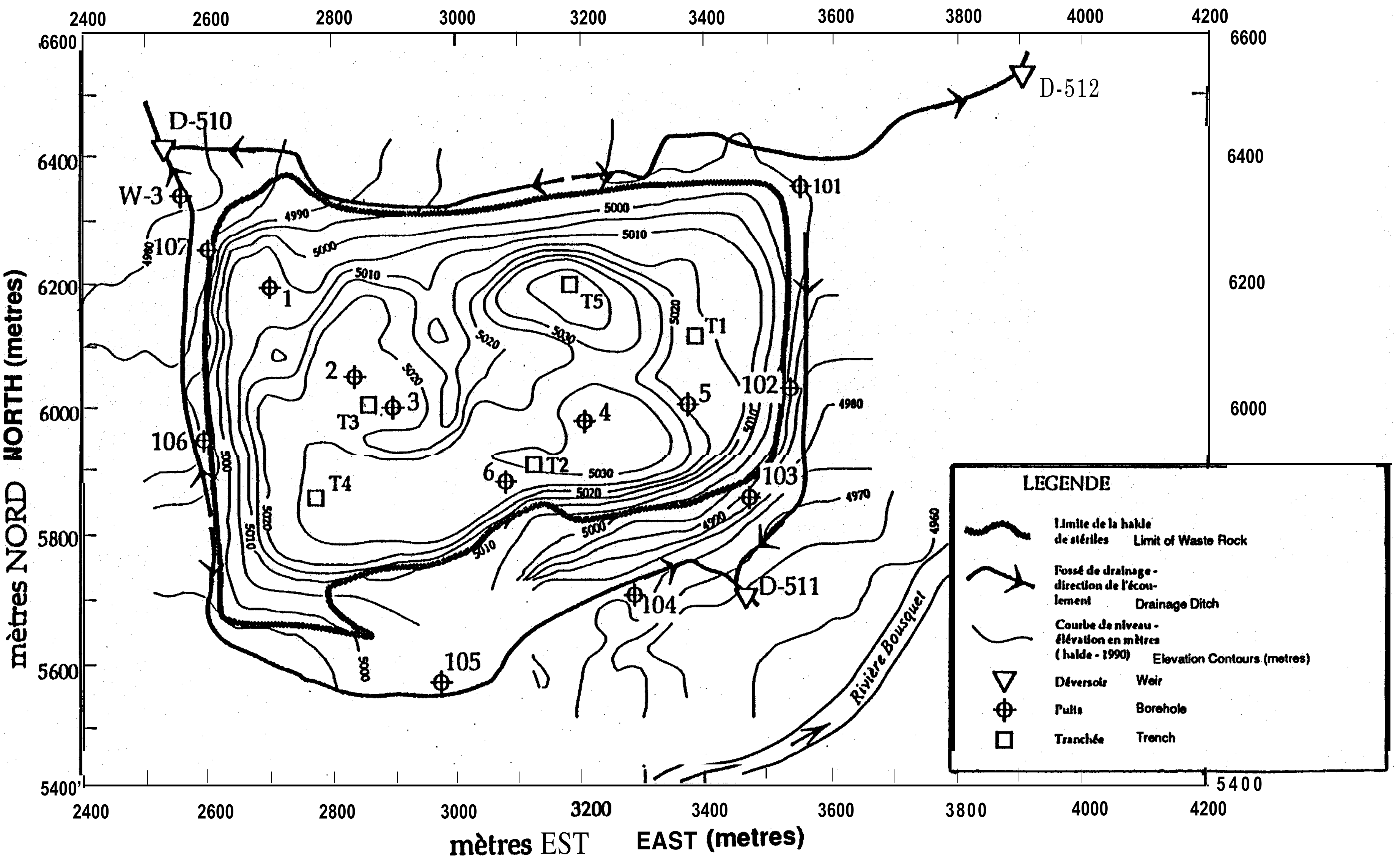


FIGURE 6.4

TYPICAL ON-DUMP INSTALLATION

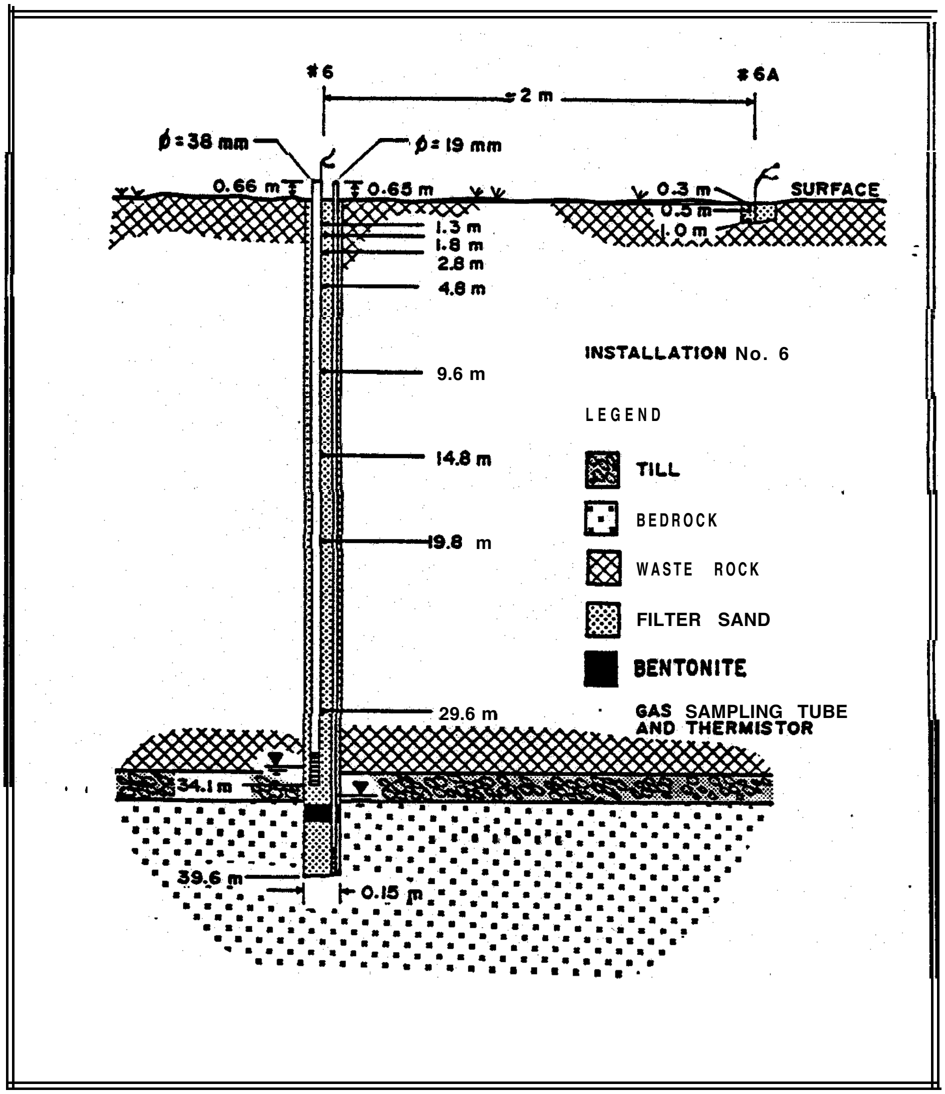


FIGURE 6.5

GROUNDWATER ACIDITY

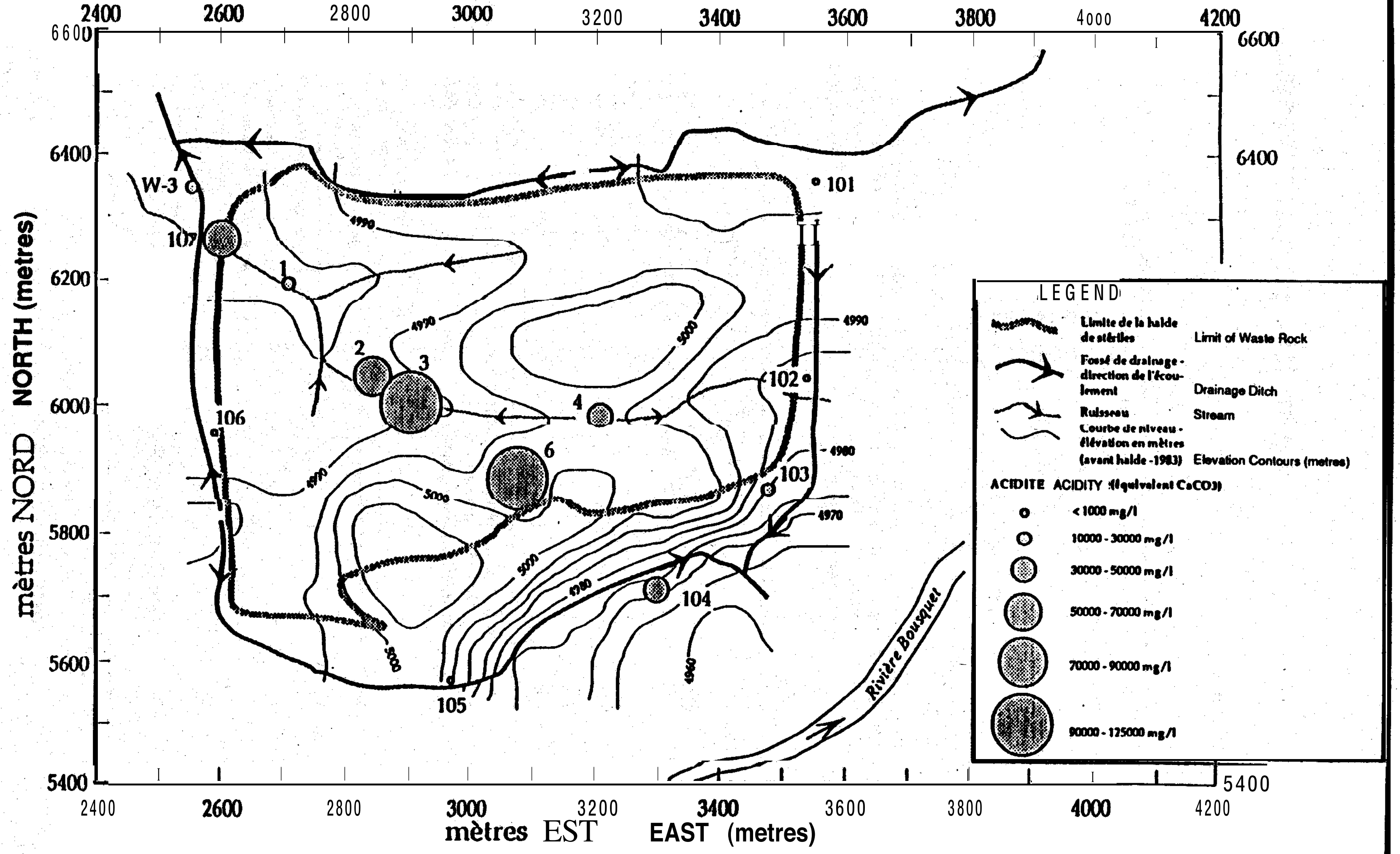
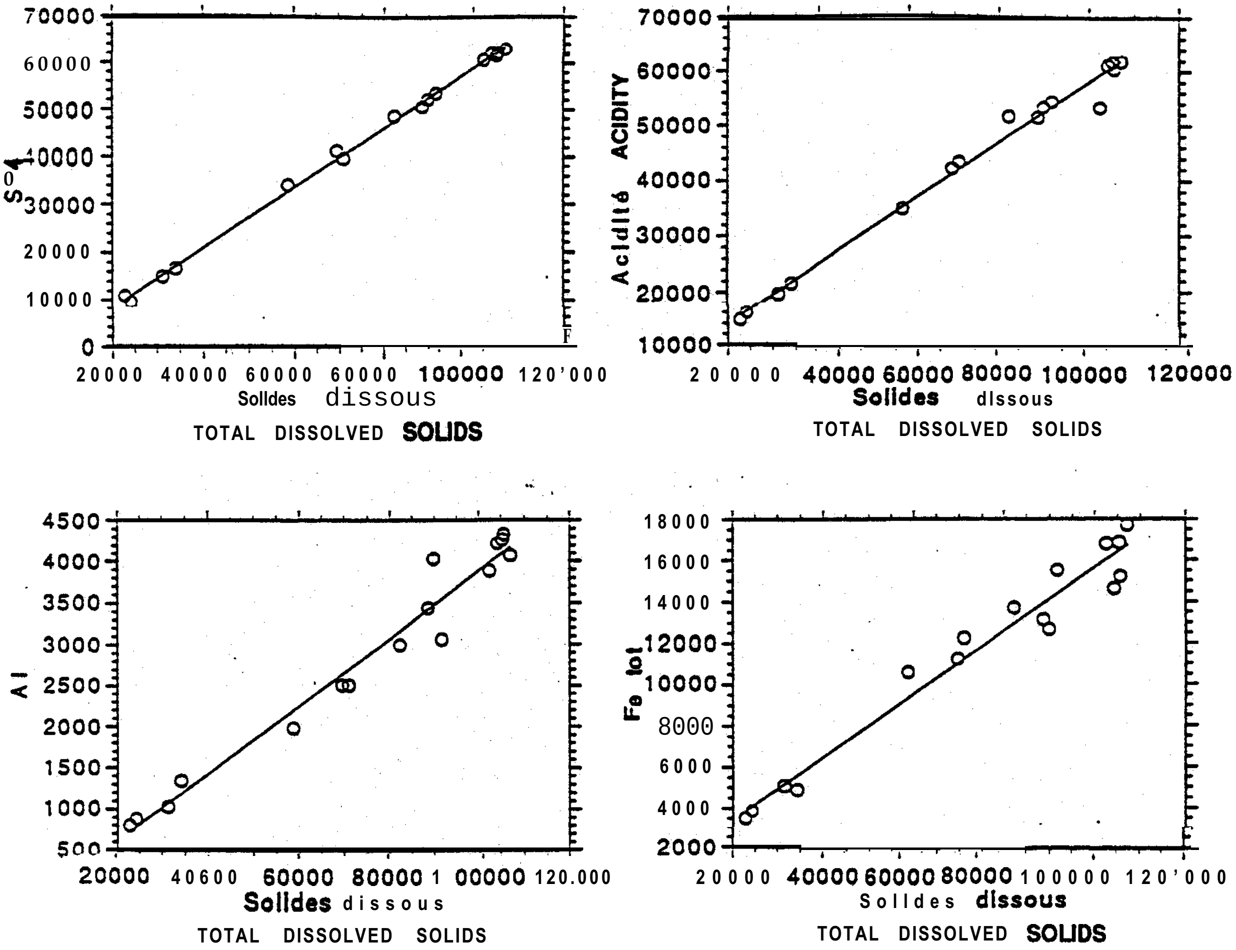
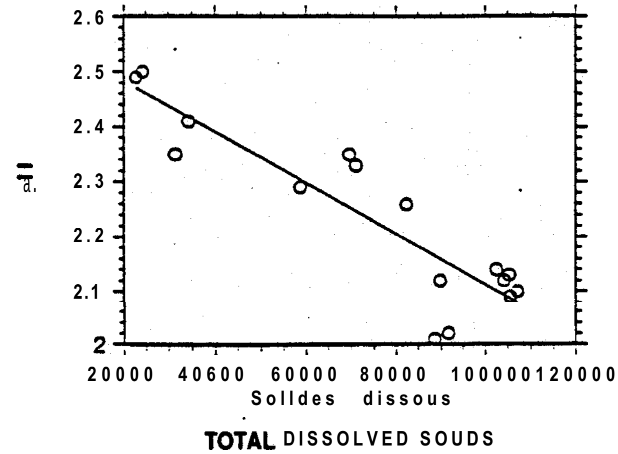


FIGURE 6.6

MAJOR IONS, pH, ACIDITY VERSUS T.D.S. PLOTS





Combined Data From 11/03/91 and 29/4/91
From Stations 510 and 511

Données combinées du 11/03/91 au 29/4/91
des stations 510 et 511

SO_4 = 0.633 Total Dissolved Solids - 4429 $r^2=0.998$

Fe tot = 0.153 Total Dissolved Solids + 351 $r^2=0.960$

Al = 0.041 Total Dissolved Solids - 214 $r^2=0.967$

Acidité = 0.552 Total Dissolved Solids + 2834 $r^2=0.987$

pH = 0.000004275 Total Dissolved Solids + 2.572 $r^2=0.903$

FIGURE 6.7

AVERAGE **TEMPERATURE** PROFILE THROUGH PILE
(WINTER CONDITIONS)

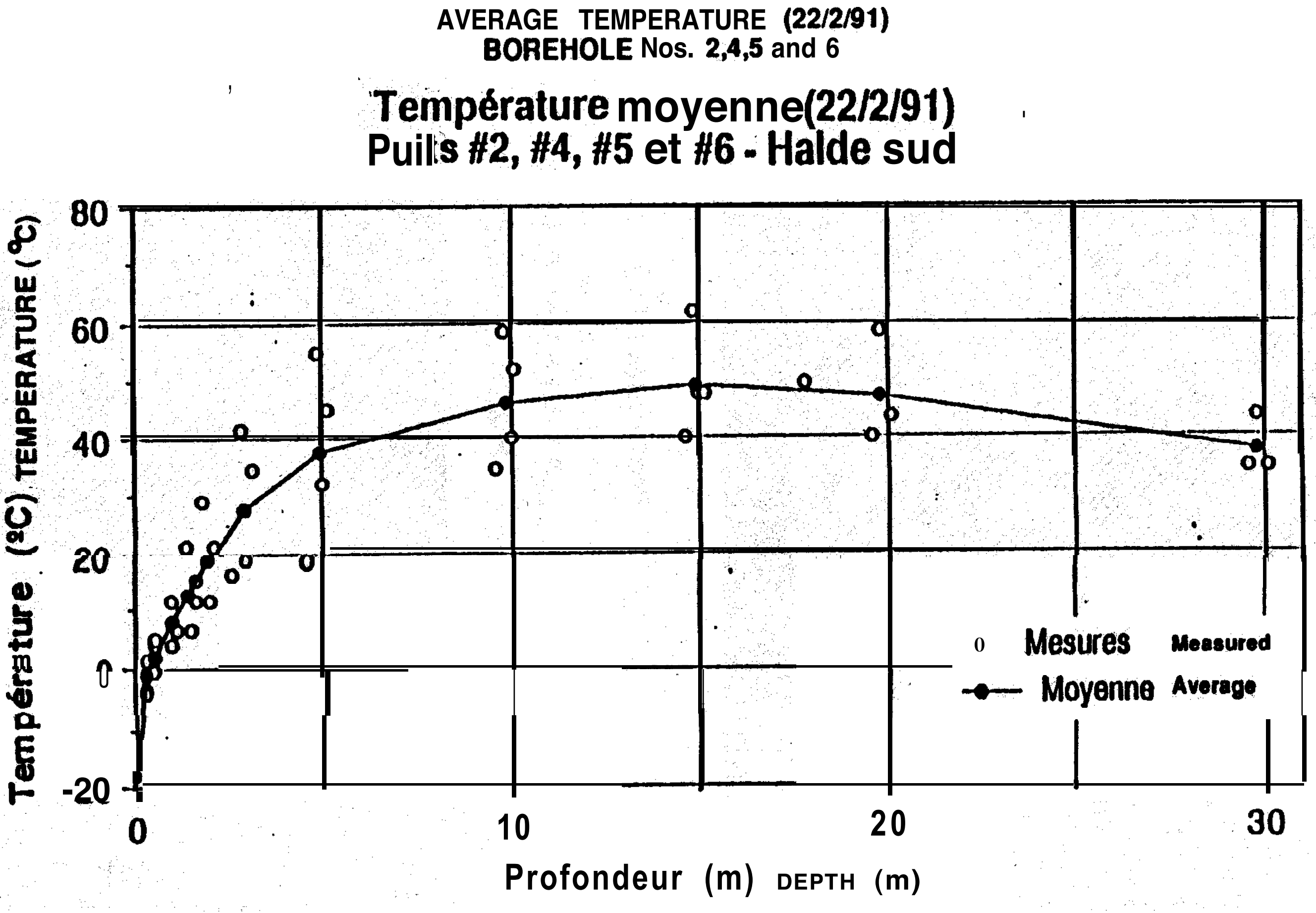
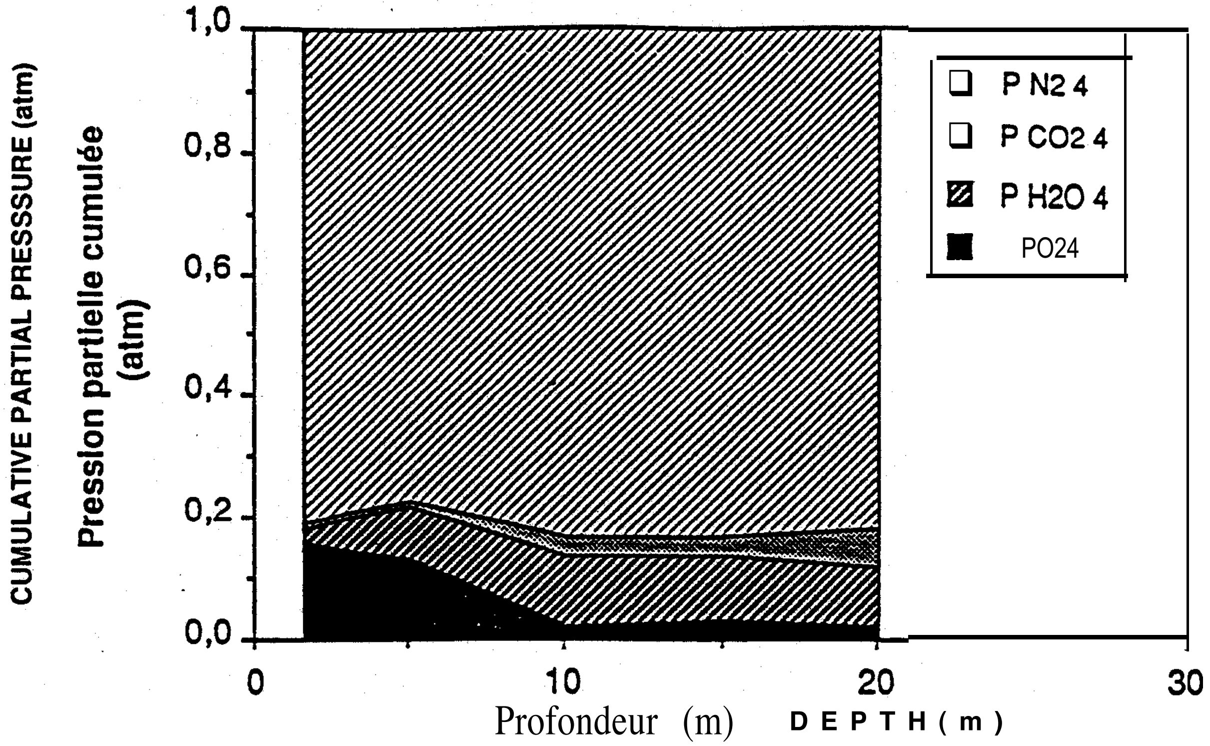


FIGURE 6.8

SAMPLED BOREHOLE GAS COMPOSITION

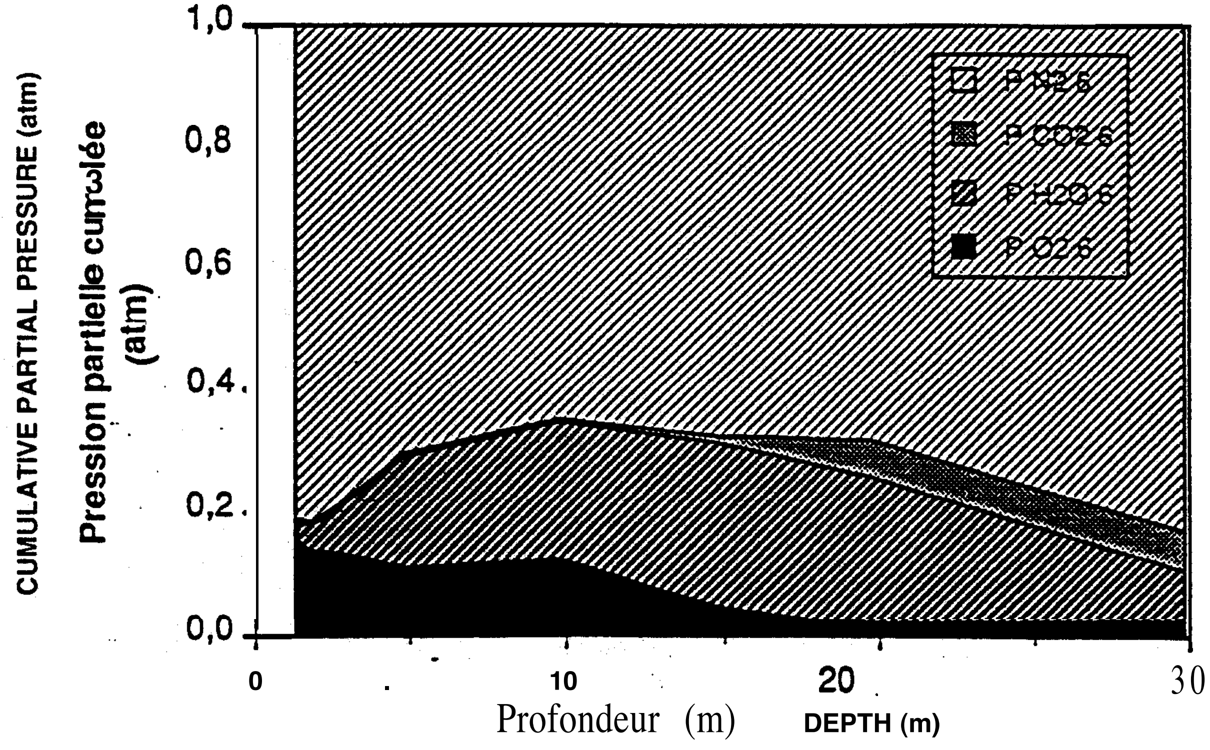
BOREHOLE No. 4 (APRIL 91)

Puits #4 (avril 91)



BOREHOLE No. 6 (APRIL 91)

Puits **#6 (avril 91)**



lower. The mass flow of sulphates, acidity, iron and other major constituents increases even if concentration is reduced because of the greater volume of effluents.

In the six boreholes thermistors record temperatures at eleven different depths in the south dump. Temperature data are essential to evaluate reaction rates since oxidation of pyrite is exothermic and the heat produced is an indication of the degree of reaction. In winter conditions, temperatures increase rapidly to a depth of 10-15 m and slowly decrease from 15 m to the bottom of the dump. Maximum values are higher than what is usually recorded in rock waste dumps (from 40 to 60 C on average and up to 66 C in BH-6). Borehole BH-3 is located in a non-reactive zone and its temperature is much lower (14-15 C). Below depths of 2-3 m temperatures are quite stable through time (Figure 6.7).

The chemical composition of gases in the non-saturated zone is important to determine the oxygen content at different depths as the fuel for AMD reactions and the CO_2 as a product of neutralization by carbonates. Sampling points were installed at eight levels corresponding to thermistors location so that corrections for air composition may be applied assuming that interstitial air is saturated with respect to water vapour at the given temperature. Gas chromatographic analyses show that only oxygen, nitrogen, carbon dioxide and water vapour are present in significant amounts (Figure 6.8). Hydrogen sulphide (H_2S) may be present at the base of borehole BH-4 where odours of H_2S have been noticed.

Oxygen content decreases rapidly with depth to reach stable concentration at a partial pressure of 0.025 atm (2.5%) which is nevertheless significant in the processes of oxidation at depth. CO_2 increased with depth to a value of 7% and it is probably related to leachate neutralization by dissolution of carbonates. Water vapour becomes more and more important with increasing temperature as it lowers air density and generates convection currents to the surface. Air convection is thought to be a major mechanism of oxygen transfer in waste rock dumps.

Infiltration of water in the south dump is estimated from 600 to 650 mm per year; that is a potential volume of 318,000 to 345,000 m^3/y of leachate reaching the drainage ditches if losses to groundwater are small. A preliminary flow model using the geometric parameters of the south dump, the original topography of the ground and values of hydraulic conductivity measured in bedrock suggests that groundwater flow may be in the order of 10,000 m^3/y only. Assuming that bedrock fractures are completely saturated, the model indicates that mass permeability is much lower than the local values obtained with slug tests. Preliminary estimation of groundwater losses through the floor of the dumps is 5% or less.

Thermal profiles, because they are quite constant with time are the best indicators of reaction rate in the dump. Temperature gradients in a porous medium rapidly redistribute heat produced by neighbouring reactions. Hence, at a given depth, temperature represents an equilibrium between generation of heat, the maintenance and activity of a bacterial population, acid formation from sulphides and amount of oxygen available for reactions.

Two boreholes show important temperature anomalies: borehole BH-6 has very high temperature (up to 66 C) at a depth of 15 m, and borehole BH-3 much cooler with a maximum not exceeding 15 C at the same depth. Other boreholes have maximal temperature between 40 and 50 C at depths of 10 to 20 m. Temperature profiles are stable with time at depth; in the first few metres near surface, seasonal fluctuations are recorded.

Heat generation is maximal near surface and is almost zero at a depth of 24 m; below that depth there is a loss of heat to the ground below. Down to an average depth of 14.3 m, the heat flux is directed toward ground surface and below that depth, heat flux is directed toward the base of the rock waste dump. With an analytical model, it is evident that most of the reaction is near surface with almost linear decrease of the reaction rate with depth. This model does not take into account water infiltration and oxygen convection inside the dump; only diffusive processes are considered.

Potential for generating acid may be estimated from the quantity of iron and sulphates that are transported to drainage ditches and by computing a mass balance to calculate the time remaining before all pyrite will be oxidized. Using a pyrite concentration of 3.5%, mean discharge in the ditches of 350,000 m^3/y and average concentrations of iron and sulphates, the life span of the acid generation problem is estimated at between 83 years (using sulphates) and 91 years (using iron).

Another independent method for evaluation of the acid generation potentials is derived from the analysis of heat produced by pyrite oxidation. Using a simple analytical model and seasonally corrected temperature data, heat generation linked to pyrite oxidation can be evaluated at 102 years. It is clear that these values indicate minimum duration associated with the more reactive rock (schists). At the end of this process, larger more intact rock will resist alteration since pyrite will not be readily available. The pyrite located below the rock surface would be oxidized at a lower rate. This oxidation may require a much longer time span.

6.4 POTENTIAL IMPROVEMENTS

Building of a low permeability cover on the waste rock is a potential solution to remediate the acid generating problem. A preliminary study covering this topic included: photo interpretation, field spot checks and mapping of overburden materials (10 km radius from La Mine Doyon); permeability and geomechanical laboratory testing of overburden materials, neutralization sludges and tailings; performance evaluation of cover designs using overburden materials and synthetic geomembranes using the HELP (Hydrologic Evaluation of Landfill Performance) model.

Another potential solution to eliminating acid generation from the south dump being considered includes backfilling the non-operating open pit with waste rock with either natural precipitation or diversion of surface run-off to the backfilled pit. Decisions concerning the best option have not yet been made. The second phase of the evaluation program which includes ongoing monitoring and reevaluation of reaction mechanisms and rates is underway.