# REVIEW OF IN-PIT DISPOSAL PRACTICES FOR THE PREVENTION OF ACID DRAINAGE - CASE STUDIES

## MEND Report 2.36.1

This work was done on behalf of MEND and sponsored by
Hudson Bay Mining and Smelting Company Limited
as well as the
Ontario Ministry of Northern Development and Mines and
Canada Centre for Mineral and Energy Technology (CANMET)
through the CANADA/Northern Ontario Development Agreement (NODA)

**September 1995**

# EXECUTIVE SUMMARY

Open pit mines that have ceased production are increasingly being considered for the permanent and environmentally acceptable disposal of mine waste rock and tailings that are, or have the demonstrated potential to become, sources of acidic drainage. This report addresses key aspects that need to be taken into consideration when evaluating the in-pit disposal of wastes and presents 12 case studies of actual and planned in-pit disposal of mine wastes.

There are four basic concepts for the placement of wastes in pits:

Option 1 - Underwater disposal
Option 2 - Elevated water tables
Option 3 - Dry disposal
Option 4 - Perched water tables

The four options are described in terms of the theoretical concepts and practical aspects; selected examples of research and field applications are provided from the published literature.

Not all pits are suitable for the in-pit disposal of wastes. The success of an application would depend on many technical factors, including:

- the acid generation potential of the wastes and pit walls;
- the geotechnical characteristics and properties of the wastes and the pit walls;
- predicted pore water, pit water, and groundwater quality;
- hydrogeology of the open pit; and
- the hydrology of the open pit.

Mine related constraints must also be taken into consideration. These include: limiting access to remaining mineralization below the pit; wall stability and related safety concerns; available access; and the proximity of underground workings to the open pit.

Consideration must be given to both the short term and long term implications of the in-pit disposal concept; these include ecological and human health protection and closure planning perspectives. Each site is unique and may have special constraints with respect to the quality and use of surface water and groundwater, land use, and sensitive ecological communities.

The potential costs for future in-pit disposal of wastes should be considered in the preliminary economic evaluations that are used to establish final pit limits. Greater than expected waste disposal costs could have an unfavourable impact on the future profitability of some open pit mines.

Volume 2 of this report presents twelve case studies: seven case studies describe in-pit disposal programs that have been implemented; two case studies describe proposed in-pit disposal programs; and three case studies provide technical information from other pits which will likely be of interest to persons evaluating in-pit disposal programs.

The following case studies describe pits that have been used for in-pit disposal of mine wastes:

> ***The Owl Creek pit*** - To prevent discharge of acidic drainage from waste rock piles, the waste rock was relocated to the pit and flooded.
>
> ***The Rabbit Lake pit*** - This pit is likely the first application of an engineered pit disposal concept, which involved the use of a bottom rock drain, an engineered pervious envelope, placement of tailings as a dry filter cake, and closure with a surface lake and a soil/sand diffusion barrier.
>
> ***The Collins Bay B-Zone pit*** - Following extensive decommissioning studies, the special waste (which contains elevated arsenic, nickel, sulphur, or uranium content) was placed in the bottom of the pit and the pit was flooded, creating a pit lake.
>
> ***The Solbec pit*** - A crown pillar pit was filled with reactive waste as a means of inhibiting further acidic drainage.
>
> ***The Udden pit*** - The pit was backfilled with reactive waste rock and allowed to flood.

***The Stratabound CNE pit*** - The in-pit disposal of reactive waste rock was planned at the design stage, and the waste rock has been relocated to the pit and clay capped.

***The Cluff Lake "D" Zone pit:*** The pit flooded after the end of mining operations, and an extensive monitoring program has been carried out to evaluate the physical and chemical changes occurring in the pit lake water column.

In-pit disposal programs have been proposed at the following case study sites:

***The Island Copper pit*** - As part of planned closure, it is proposed that the pit be flooded to create a meromictic lake.

***The Deilmann pit*** - Insufficient capacity exists within an existing surface tailings management facility to accommodate future tailings production therefore tailings disposal options are being reviewed; one option involves the conversion of the Deilmann pit to a full side drain and under-drain tailings management facility.

Additional case studies which may provide useful information to persons evaluating in-pit disposal programs are:

***Robinson Mining District*** - Extensive numerical modelling was carried out to evaluate the hydrogeochemistry and to support the prediction of environmental impacts from several pit lakes.

***The Gunnar pit*** - This pit lake is interesting because of unique and well-documented limnological characteristics.

***The Berkeley pit*** - This mine site is part of a U.S. Superfund site and is a well-known example of a serious acidic drainage problem in a flooding open pit.

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On envisage de plus en plus d'utiliser les fosses des mines à ciel ouvert désaffectées pour l'élimination permanente et acceptable au point de vue environnemental des résidus et des stériles qui produisent ou sont reconnus comme pouvant produire des eaux de drainage acides. Le rapport qui suit porte sur les principaux éléments dont il faut tenir compte lorsqu'on étudie une telle possibilité et présente 12 études de cas de mines où un tel entreposage est prévu ou déjà en cours.

Il existe quatre possibilités de base pour l'entreposage des déchets dans les fosses :
1re solution - entreposage sous l'eau
2e solution - nappe d'eau surélevée
3e solution - dépôt de matériaux secs
4e solution - nappe d'eau perchée.

Pour chaque solution, les aspects théoriques et pratiques sont décrits; des exemples de travaux de recherche et d'applications concrètes tirés de publications sont fournis.

Les fosses de mine ne se prêtent pas toutes à l'entreposage des déchets miniers, c'est pourquoi il faut examiner certains facteurs techniques :

- le potentiel de production d'acide dans les déchets et sur les parois de la mine;
- les caractéristiques géotechniques et les propriétés des déchets et des parois de la mine;
- les prévisions concernant la qualité de l'eau interstitielle, de l'eau de la mine et de l'eau souterraine;
- l'hydrogéologie de la mine à ciel ouvert
- l'hydrologie de la mine à ciel ouvert.

Il faut aussi prendre en compte les contraintes liées à la mine, notamment : la réduction de l'accès à la minéralisation qui se poursuit sous la mine, la stabilité des parois et les mesures de sécurité connexes, l'accès possible, et la proximité des travaux souterrains par rapport à la fosse.

Il ne faut pas ignorer les répercussions à court et à long terme de l'entreposage des déchets dans les fosses, tant du point de vue de la protection de l'environnement et de la santé du public que de la planification de la fermeture du site. Chaque emplacement étant unique, les contraintes quant à la qualité et à l'utilisation de l'eau de surface et de l'eau souterraine, à l'utilisation du terrain et aux écosystèmes fragiles.

Les coûts de l'entreposage éventuel des déchets dans les fosses devraient faire partie des évaluations économiques préliminaires à partir desquelles seront établies les limites définitives des mines. Un dépassement des prévisions pour l'entreposage des déchets pourrait nuire à la rentabilité future de certaines mines à ciel ouvert.

Vous trouverez, dans la partie 2 du rapport, douze études de cas; sept décrivent des programmes d'entreposage des sites déjà utilisés, deux pour des projets de programmes d'entreposage proposés, et trois fournissent des renseignements techniques sur d'autres fosses, renseignements susceptibles d'intéresser les personnes chargées d'évaluer les programmes d'entreposage dans les fosses.

Les fosses des mines suivantes servent à l'entreposage des déchets miniers :

> **La mine Owl Creek** - afin de prévenir la production d'eaux acides dans les haldes, les stériles ont été déplacés dans la fosse et couverts d'eau.
>
> **La mine de Rabbit Lake** - Cette mine est vraisemblablement la première à

utiliser un concept d'entreposage aménagé; on a utilisé un drain de pierres dans le fond et une enveloppe poreuse sur les parois, ensuite les résidus sont placés comme gâteau de filtration sec et on a couvert le tout d'un lac de surface et d'une barrière de diffusion sol-sable.

**La mine de Collins Bay - Zone B** - Après des études poussées sur la fermeture de la mine, on a placé les déchets spéciaux (contenant de fortes concentrations d'arsenic, de nickel, de soufre ou d'uranium) au fond de la fosse, avant d'inonder cette dernière, créant ainsi un lac.

**La mine Solbec** - Un pilier de couronne a été rempli de déchets réactifs afin de contrer le drainage acide.

**La mine Udden** - La fosse a été remplie avec des stériles réactifs et on a permis son inondation.

**La mine CNE, de Stratabound** - L'entreposage des stériles réactifs dans la fosse était prévu dès le moment de la conception; les stériles ont été redéposés dans la fosse et recouverts d'une couche argileuse.

**La mine de Cluff Lake - Zone D -** Une fois les travaux d'exploitation terminés, la fosse s'est inondée et un programme de surveillance intensive a été entrepris dans le but de déterminer les changements physiques et chimiques survenant dans la colonne d'eau du lac de la fosse.

Des programmes d'entreposage des déchets dans des fosses ont été proposés aux sites suivants :

**La mine Island Copper** - Dans le cadre des travaux de fermeture, on propose d'inonder la fosse pour créer un lac méromictique.

**La mine Deilmann** - L'installation de gestion des résidus à la surface ne pouvant suffire à l'entreposage des résidus supplémentaires, d'autres possibilités sont donc envisagées, dont la conversion de la mine Deilmann en une installation de gestion complète des résidus à l'aide de drains latéraux et souterrains.

Voici d'autres cas dont l'étude pourrait fournir des renseignements utiles aux personnes chargées de l'évaluation des programmes d'entreposage des déchets dans des fosses :

**Le Robinson Mining District** - On s'est beaucoup servi de la modélisation numérique pour évaluer l'hydrogéochimie et étayer les prévisions sur l'incidence environnementale de plusieurs lacs de fosses.

**La mine Gunnar** - Ce lac est intéressant en raison de ses caractéristiques limnologiques uniques et bien documentées.

**La mine Berkeley** - Le site, couvert par le fonds de dépollution américain *Superfund*, est un exemple bien connu des graves problèmes de drainage acide associés à une fosse inondée.

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| 4 | Island Copper |
| 5 | The Solbec Open Pit |
| 6 | The Udden Open Pit |
| 7 | The Stratabound CNE Open Pit |
| 8 | Robinson Mining District |
| 9 | The Gunnar Pit |
| 10 | Cluff Lake "D" Pit |
| 11 | Deilmann |
| 12 | The Berkeley Pit |

# 1.0 INTRODUCTION

## 1.1 STUDY SCOPE AND BACKGROUND

Mine waste disposal is becoming an increasingly scrutinized environmental issue. The legacies of inappropriate past mine waste disposal practices are constant reminders of the serious environmental damage that can occur. Some of the key public and environmental issues relate to: long term stability of impoundment sites; long term leaching; and erosion of surface disposal sites. One method of mine waste disposal which often mitigates these concerns is the disposal of mine wastes in mined-out pits.

The use of pits for waste disposal is not new. Historically, industrial residues, municipal refuse, excavation spoils, etc. were placed in disused aggregate quarries and pits. Specific use of pits for mine waste disposal has been common, however, the utilization of the pits was generally a matter of convenience rather than a conscious environmental decision.

Disused pits are often considered an environmental legacy, and a potential resource. Pits can provide geochemically stable environments for wastes, are often an aesthetic focal point in rehabilitation plans, may serve as habitat for both terrestrial and aquatic plants and animals, and have potential recreational value.

The current study focuses on the historic practice of using mined-out pits as a depository for potentially acid generating and non-acid generating wastes. This practice is becoming well accepted in many jurisdictions and it is understood that in some locations the backfilling of mined out pits is becoming a requirement. In recent times mine operators have even proposed excavating pits for the sole purpose of mine waste disposal.

One of the major deficiencies that currently exists is a central file of data (case studies) relating to the use of mined-out pits for mine waste disposal. The objective of this study is to thoroughly review the published literature and to make contact with national and international private and public sector groups to complete this review.

With the data in hand, both industry and governments will be in a better position to comment upon the advantages and issues related to pit disposal.

Waste disposal in pits is not a universally good waste management strategy; site-specific factors will often dictate when the practice is appropriate. Some of the key factors to consider when assessing the applicability of in-pit disposal will include site hydrogeology, geochemistry of wastes, pit morphology and relevant alternatives.

In theory, wastes disposed in pits below the water table are not subject to oxidation. Furthermore, contaminant release may be substantially reduced by either making diffusion the controlling transport mechanism or by reducing the hydraulic gradient across the pit to near zero, thus restricting convective outflow. In either event, controlling oxidation greatly reduces the contaminant potential.

Some of the most important factors supporting increased utilization of pits are:

- effective control of acid generating wastes;
- placement of contaminated mine wastes back into the geochemical environment from which they were extracted;
- virtual elimination of long-term geomorphological/erosional concerns;
- reduction of need for long term care and maintenance;
- virtual elimination of the potential for accidental release;
- waste placement as part of the pit stabilization plan;
- potential for major reduction in contaminant release;
- potential to eliminate future land use controls for the site; and
- potential for a substantial cost savings when calculating the *"total"* waste management costs (short term, long term, closure, bonding, etc.).

## 1.2 METHODS OF DATA COLLECTION

A computerized technical literature search was carried out by reviewing the databases listed in Table 1.1. A total of 138 technical articles and reports were identified; selected articles were obtained and are listed in the references.

## Table 1.1

## ON-LINE LITERATURE SEARCH

| Database File Searched | Database Name and Time Period |
|---|---|
| 6 | NTIS 1964-1994/Dec B1 |
| 8 | Compendex*Plus(TM) 1970-1994/Dec W1 |
| 89 | GeoRef 1985-1994/Nov B2 |
| 103 | Energy SciTec 1974-1994/Oct B2 |
| 144 | Pascal 1973-1994/Sep |
| 156 | TOXLINE(R) 1965-1994/Oct |
| 117 | Water Resour.Abs. 1968-1994/Mar |
| 624 | McGraw-Hill Publications Online 1985-1994/Nov 03 |
| 5 | BIOSIS PREVIEWS(R) 1969-1994/Nov W3 |
| 40 | Enviroline(R) 1970-1994/Oct |
| 308 | CA Search(R) 1967-1971 |
| 310 | CA Search(R) 1977-1981 |
| 311 | CA Search(R) 1982-1986 |
| 69 | Energyline(R) 1970-1993/Dec |
| 35 | Dissertation Abstracts Online 1961-1994/Oct |
| 44 | Aquatic Sci & Fisheries Abs 1979-1994/Sep |
| 96 | FLUIDEX 1973-1994/Oct |
| 63 | TRIS 1970-1994/Sep |
| 354 | APILIT 1964-1994/Aug |
| 648 | Trade & Industry ASAP(TM) 1983-1994/Oct W5 |
| 148 | Trade & Industry Index(TM) 1981-1994/Oct W5 |
| 669 | Fed.Register 1988-1994/Nov 04 |
| 88 | Academic Index(TM) 1976-1994/Oct W4 |

**Search Statement:**

OPEN()PIT()(MINE?? OR MINING) AND (MINE()(WASTE?? OR TAILING?? OR CLOSURE?? OR DECOMMISSIONING??) OR ACID()(MINE OR ROCK)()DRAIN?)

As a quality assurance measure, an inquiry was made to the research section of the library at the Colorado School of Mines in Boulder, Colorado to determine if there were any relevant databases concerning open pit mines that had not yet been reviewed. No additional databases were identified.

Communication with contacts was made for the most part by telephone and facsimile. These contacts were representatives from mining companies, industry associations, research organizations, consulting firms, and regulatory agencies. The contacts were located in Canada, the United States, Australia, South Africa, Norway, Sweden, Finland, and Germany. The distribution of contacts in Canada is shown in Table 1.2, the United States in Table 1.3, and international contacts are shown in Table 1.4.

People contacted were asked to provide relevant data if available. The response was excellent and a wide array of information respecting the many aspects of in-pit disposal was received. These reports and communications are listed in the references.

Several people and organizations made a special effort to provide information to the study team. The following contributions are noteworthy:

- Noranda Technology Centre (Luc St. Arnaud of NTC and Vern Coffin of Noranda Minerals) for taking the time to meet us to discuss in-pit disposal and Noranda's experience in this area;

- The Ontario Ministry of Northern Development and Mines and the Québec Ministère des Ressources naturelles, Service du développement minier, for providing a hardcopy of their databases concerning open pits and glory holes;

- Mining companies that contributed to the development of the case studies by supplying information, and reviewing and providing their commentaries of draft case studies; and

- Robert McCandless of Environment Canada, Vancouver for providing files regarding the sampling of the water column in several flooded open pits and comments regarding the British Columbia Mine database.

Table 1.2

## DISTRIBUTION OF CONTACTS IN CANADA

| Location | Organization | Regulator | Mine | Consultant |
|---|---|---|---|---|
| Federal | CANMET, MEND | ✓ |  | ✓ |
| British Columbia | Cominco |  | ✓ |  |
|  | Island Copper |  | ✓ |  |
|  | Ministry of Energy, Mines and Petroleum Resources | ✓ |  |  |
|  | Environment Canada | ✓ |  |  |
| Manitoba | INCO Thompson |  | ✓ |  |
|  | Department of Energy and Mines | ✓ |  |  |
|  | UMA Engineering |  |  | ✓ |
|  | Hudson Bay Mining + Smelting |  | ✓ |  |
| New Brunswick | Department Natural Resources, Minerals and Energy | ✓ |  |  |
|  | Stratabound Minerals |  | ✓ |  |
| Newfoundland | Asarco, Buchans |  | ✓ |  |
| Ontario | Ministry of Northern Development and mines | ✓ |  |  |
|  | Algoma Ore |  | ✓ |  |
|  | Kinross Gold Corp |  | ✓ |  |
|  | St. Andrew Goldfields |  | ✓ |  |
| Québec | Noranda Technology Centre |  | ✓ |  |
|  | Ministère des ressources naturelles | ✓ |  |  |
|  | Ministère de l'environnement et de la faune | ✓ |  |  |
| Saskatchewan | Cameco |  | ✓ |  |
|  | Environment and Resource Management | ✓ |  |  |
|  | Cogema |  | ✓ |  |

Table 1.3

## DISTRIBUTION OF CONTACTS IN THE UNITED STATES

| Location | Organization | Regulator | Mine | Consultant* |
|---|---|---|---|---|
| Arizona | ● Magma Copper | | ✓ | |
| California | ● Bureau Land Management | ✓ | | |
| | ● U.S. Geological/Survey | ✓ | | |
| | ● California Asbestos Monofill | | ✓ | |
| | ● Condor Earth Technologies | | | ✓ |
| Colorado | ● PTI Environmental | | | ✓ |
| | ● U.S.B.M. | ✓ | | |
| | ● Department Natural Resources | ✓ | | |
| | ● Pintail Consultants | | | ✓ |
| | ● Office Active/Inactive Mines | ✓ | | |
| Federal Capital | ● U.S. EPA | ✓ | | |
| Florida | ● Condor Earth Technologies | | | ✓ |
| Idaho | ● Bureau of Minerals | ✓ | | |
| | ● Kinross DeLamar | | ✓ | |
| | ● Coeur d'Alene | | ✓ | |
| Montana | ● Bureau of Mines + Geology - U.S.B.M. (Butte) | ✓ | | |
| | ● Department of Reclamation | ✓ | | |
| | ● Bureau Land Management | ✓ | | |
| | ● Golden Sunlight | | ✓ | |
| | ● Montana Mining Assoc. | | ✓ | |
| | ● MSE Inc. | | | ✓ |
| | ● Montana Resources | | ✓ | |
| New Mexico | ● Laguna Native Band | ✓ | | |
| Nevada | ● U.S.B.M. (Reno) | ✓ | | |
| | ● Glamis Gold Inc. | | ✓ | |
| | ● University of Nevada at Reno | | | ✓ |
| Oklahoma | ● Open Pit Haul Truck Manufacturer | | | ✓ |
| Pennsylvania | ● Consol | | ✓ | |
| | ● U.S.B.M. (Pittsburgh) | ✓ | | |
| | ● Open Pit Mining Association | | ✓ | |
| South Carolina | ● University South Carolina | | | ✓ |
| South Dakota | ● Brohm Mining | | ✓ | |
| | ● Richmond Hill Mine | | ✓ | |
| Utah | ● U.S.B.M. (Salt Lake City) | ✓ | | |
| | ● Abandoned Mines Department | ✓ | | |
| Virginia | ● University West Virginia | | | ✓ |
| Washington | ● Pegasus Gold | | ✓ | |
| | ● U.S.B.M. (Spokane) | ✓ | | |
| | ● Echo Bay Mines | | | ✓ |
| Wyoming | ● Department of Environmental Quality | ✓ | | |

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[*] or researcher, supplier.

Table 1.4

## SUMMARY OF INTERNATIONAL CONTACTS

| Country | Organization |
|---|---|
| Australia | Australian/Asian Institute of Mining and Metallurgy (AIMM), and Australian Mineral Foundation |
| Finland | Outokumpo Research Oy. |
| Germany | Bundesministerium Für Umwelt, Naturschutz and Reaktorsicherheit. |
| Norway | Norwegian Institute for Water Research (NIVA). |
| South Africa | CSIR, Division of Forest Science and Technology. |
| Sweden | Boliden Metall AB. |

## 1.3 REPORTING ORGANIZATION

This report is organized as follows:

Chapter 2.0, Considerations for In-Pit Disposal, provides a review of theoretical considerations respecting the generation of acidic drainage, and concepts and methods for its abatement, as well as a discussion of the technical considerations and practical aspects of in-pit disposal. Environmental aspects and regulatory constraints and considerations are also addressed.

Chapter 3.0, Pit Disposal Concepts, describes methods of inhibiting the production of acidic drainage from reactive wastes (waste rock, tailings) deposited in pits. The discussion addresses the variation in physical conditions (e.g. pit layout, water table elevation, etc.) that may affect a proposed in-pit disposal program.

Chapter 4.0, Case Studies, summarizes the sites identified in the study and presents a key to the detailed Case Studies. The identified sites include both completed and proposed in-pit waste disposal programs. Twelve detailed Case Studies are included in Volume 2 of the report.

Chapter 5.0, Discussion of Findings, assesses and summarizes the key findings of this study. It also provides readers with a listing of basic data required to prepare and assess an in-pit disposal program. Priorities for further technology development in this area are also presented.

# 2.0 CONSIDERATIONS FOR IN-PIT DISPOSAL

## 2.1 WASTE CHARACTERIZATION

Characterization of the wastes is extremely important for defining appropriate methods for in-pit placement. Key factors requiring characterization will include:

- acid generation potential;
- leachate quality, leachable mass and future geochemistry of pore water, pit water and groundwater;
- grain size;
- permeability; and
- consolidation characteristics.

Several MEND reports have been prepared to assist practioners in the characterization of reactive mine wastes (e.g. SENES, 1994b; Coastech, 1989; SRK, 1992; CANECT, 1989).

The key factors requiring characterization are briefly addressed below.

### 2.1.1 Acid Mine Drainage Potential

Acid mine drainage (AMD) is the result of the combined chemical and biological oxidation of sulphide minerals and the concomitant release of associated metals, such as iron, aluminum, manganese, uranium and other toxic heavy metals. The oxidation of pyrite, the predominant sulphide mineral, can be expressed by the following stoichiometric equations.

*Pyrite Oxidation:*

$$FeS_2 + 7/2O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+ \qquad (2.1)$$

$$or,\quad 2FeS_2 + 7O_2 + 2H_2O \rightarrow 2FeSO_4 + 2H_2SO_4 \qquad (2.2)$$

Ferrous iron ($Fe^{2+}$) is oxidized to its ferric state as follows.

$$2\,Fe^{2+} + \tfrac{1}{2}O_2 + 2H^+ \rightarrow 2\,Fe^{3+} + H_2O \qquad (2.3)$$

The reaction given by Equation 2.3 is dependent upon the pH of the solution and presence of catalysts such as *Thiobacillus ferroxidans* and other acidophilic bacteria. Under acidic conditions (pH 2 to 3), the biological oxidation rate is approximately 16 to 35 fold greater than the chemical rate.

The dependence of the dissolved ferric ion to variations in pH is shown in Figure 2.1. Ferric iron does not remain in solution much above pH 2 to 3 where it is hydrolyzed to $Fe(OH)_3$. Under more alkaline conditions $Fe(OH)_3$ is formed as indicated in Figure 2.1:

$$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3 + 3H^+ \qquad (2.4)$$

Ferric ion is also an excellent oxidant.

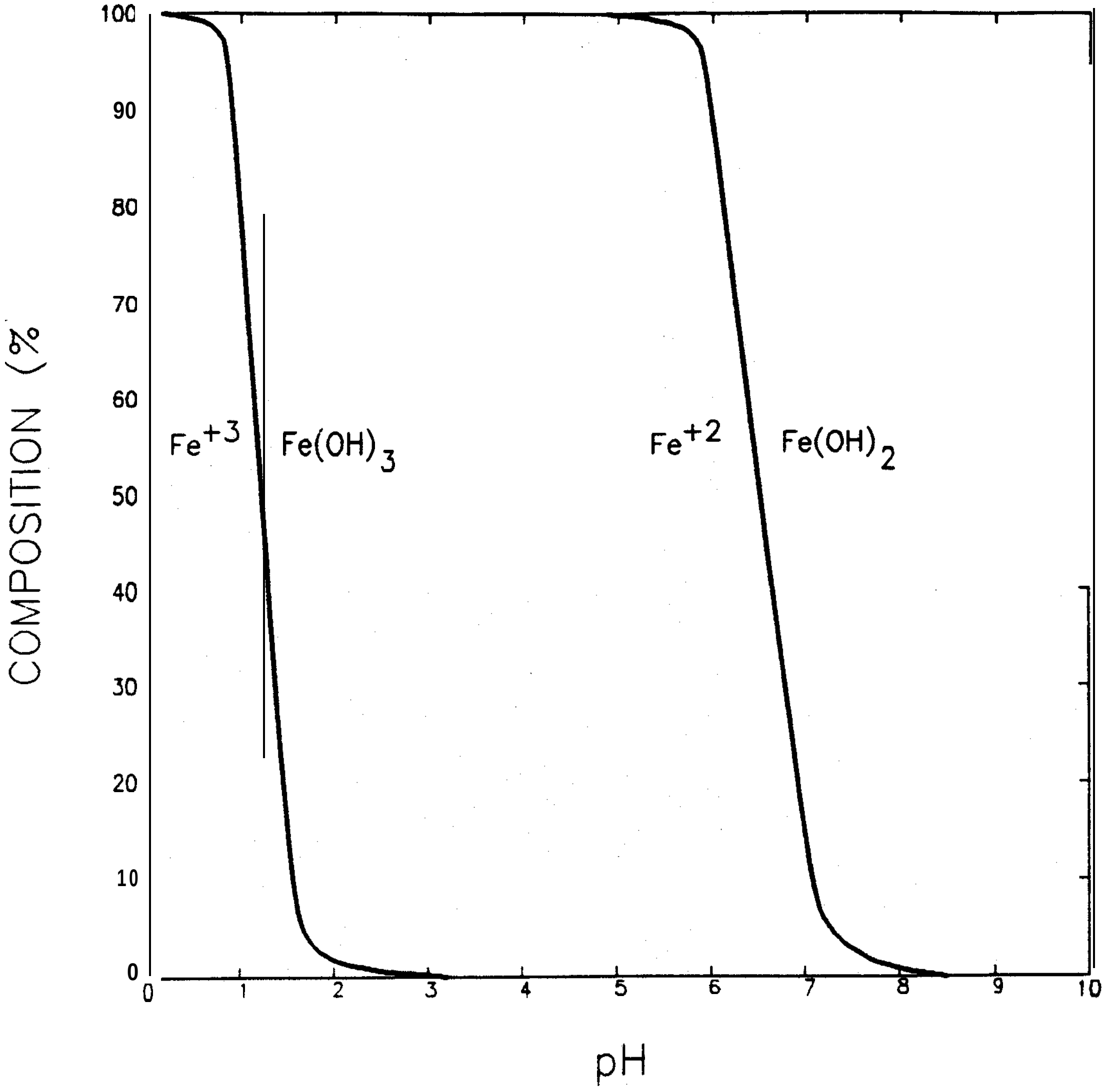
Under low pH conditions, available ferric ion acts as an oxidizing agent to produce additional sulphate and hence sulphuric acid. The anoxic oxidation of pyrite is as follows.

$$14\,Fe3+ + FeS_2 + 8H_2O \rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+ \qquad (2.5)$$

Sulphide minerals, other than pyrite, may have different reaction mechanisms, stoichiometries, and reaction rate limiting factors.

## FIGURE 2.1

## DISTRIBUTION OF FERROUS AND FERRIC IRON AS A FUNCTION OF pH



SOURCE: TAKEN FROM FIGURES 11.7 AND 11.8, RITCEY (n.d.)

The acid generation potential of a waste is determined through conventional acid base accounting (ABA) and kinetic testing. If wastes are currently acid generating or potentially acid generating according to ABA and kinetic testwork, the pit disposal option will have to allow for AMD control. This could be provided by:

i) below water disposal to control oxidation by restricting oxygen diffusion;
ii) incorporation of buffering minerals to consume acidity;
iii) controlling infiltration of water and oxygen by providing an impervious cap;
iv) controlling oxygen entry by providing perched water tables or through placement of an oxygen-consuming layer (e.g. wood chips); and
v) promotion of sulphate reduction to precipitate metals and produce alkalinity.

The concepts and experience with these applications are reviewed below.

#### 2.1.1.1 Underwater Disposal

The placement of reactive waste under water cover has proven to be a highly effective method for AMD control. Water cover is an effective barrier to the gaseous diffusion of oxygen. The prime mechanism for oxygen entry into saturated reactive waste is by convective transport of dissolved oxygen in groundwater or infiltrating water. At the typical flows of water entering the submerged waste, oxidation rates are normally very low and of minor consequence. However, the flow of waters through the submerged wastes will slowly dissolve precipitates, buffering minerals and secondary minerals which will gradually release contaminants over time.

#### 2.1.1.2 Addition of Buffering Minerals

The chemical and biological oxidation of sulphide minerals results in the production of sulphuric acid and the concomitant release of heavy metals. Alkali materials can be used to neutralize the acid and precipitate the metals. The alkali may be limestone added to the waste or other waste products with high neutralization potential. The most common additive is limestone.

The reaction of limestone (calcium carbonate) and sulphuric acid is as follows.

$$2H_2SO_4 + CaCO_3 + H_2O \rightarrow CaSO_4 \bullet H_2O + CO2 \qquad (2.6)$$

The reaction product gypsum ($CaSO_4 \cdot 2H_2O$) is present in soluble and/or precipitate form depending upon solution concentration.

Limestone for the most part consists of calcite ($CaCO_3$) with naturally occurring impurities. Reactivity is assessed based on available $CaCO_3$ or CaO and particle size; generally, limestones with a high calcium content provide more efficient neutralizing capability than dolomitic limestone ($Ca_x\ Mg_{2-x}\ (CO_3)_2$).

The reaction between limestone and sulphuric acid occurs slowly due to coating of reactive limestone surfaces by reaction products, and the limited reactive surface area of limestone. Neutralization reactions with dolomitic limestone having a higher proportion of magnesium produce both magnesium sulphate and gypsum.

As the neutralization reaction using limestone approaches neutral pH, the reaction slows considerably. As such, limestone is considered useful in applications where acidic pH is raised to near neutral conditions (pH 4 to 6). Therefore, a concern with limestone treatment as a sole neutralization reagent is the inefficiency in the precipitation of several heavy metals, in particular, nickel, manganese, zinc, copper, and cadmium, which are not effectively precipitated at pH levels below 6.0.

Field tests in Canada, the United States, and elsewhere have shown that the mixing in of alkaline materials with waste rock containing sulphides that have already started to produce acid does not stop the acidification process. Rather, the oxidation continues at a slower rate, and in a localized manner. However, the oxidation products are neutralized *in situ*, and satisfactory water quality is produced. The addition rate of alkaline material can be determined through accelerated kinetic tests.

The following considerations regarding alkali amendments have been summarized from Schafer (1993):

- The efficiency of alkali amendments for neutralization of acidity is often indexed to pure limestone using the calcium carbonate effectiveness, for example:

| | | |
|---|---|---|
| limestone | $CaCO_3$ | 100% |
| hydrated lime | $Ca(OH)_2$ | 154% |
| process lime | $CaO$ | 174% |
| caustic soda | $NaOH$ | 125% |
| soda ash | $Na_2CO_3$ | 94% |

- Particle size is important as this determines the surface area which affects the rate of acid neutralization. Alkali amendments with grain size less than 0.25 mm diameter are considered reactive; particles larger than 2 mm are considered less reactive; intermediate grain sizes are considered to be 50% reactive.

- Hydrated lime and process lime are more soluble than limestone and react faster; however, in the environment, both these amendments will gradually react with water and carbon dioxide to form limestone.

- When limestone is added to acidic materials, gypsum ($CaSO_4 \cdot 2H_2O$) and metal oxyhydroxide coatings form which interfere with solubility and long term reaction rates.

- Calcite ($CaCO_3$) equilibrium maintains pH around 6.5 to 7.0. Limestone cannot increase pH above 8.3. Hydrated lime and process lime can temporarily increase pH to 11 or higher; however, in the environment, the pH will gradually decrease to 7 to 8 as the solution equilibrates with carbon dioxide.

Schafer (1993) recommends the combined application of lime and limestone. Use of hydrated lime initiates more effective pH control than limestone alone due to its higher solubility. Hydrated lime precipitates more sulphate as gypsum than limestone. The faster dissolution of the lime reduces the formation of coatings on the limestone, so the limestone remains more effective over the long term.

The actual requirements for buffering materials depend on the intended use, for example:

i) neutralization of existing acidic pore waters; or
ii) neutralization of existing acidic pore waters, and buffering for any future acid that may be generated.

The first case might be adequate for placement of currently acidic wastes into a pit which would later be flooded (or tightly covered). The second case would apply for placement of reactive wastes above the pit water table; as long as the wastes remain unsaturated there is potential for continued sulphide oxidation and acid generation therefore other means for controlling AMD should be investigated (e.g. application of a cover) and/or excess alkaline materials may be necessary to neutralize the generated acidity over the long term.

The alkaline materials can be mixed with the reactive wastes or placed in separate alkaline layer(s). Use of alkaline layers, downstream trenches, or barrier/buffer zone depends on a good understanding of the future flow conditions. Furthermore, use of separate alkaline zones for neutralization of acidic waters may not be entirely effective due to formation of coatings and precipitation of neutralization products within the void spaces which will restrict contact and thus reduce the availability of the remaining alkaline material.

#### 2.1.1.3 Infiltration Control

Sulphide oxidation requires both oxygen and water to occur. Sophisticated engineered covers can be designed to prevent infiltration and thus exclude fresh surface water from contacting the waste. However, unless truly impervious materials are available, (e.g. synthetic liners) some residual water will typically infiltrate through the cover. A barrier which effectively reduces infiltration is likely to have a high degree of saturation (e.g. compacted clay) which would also limit oxygen diffusion into the waste in a pit. As a general rule, it is much easier to control oxygen flux through an engineered (dry) cover than to control infiltration (synthetic liners excluded).

### 2.1.1.4 Oxygen Barriers

Oxygen barriers are fully addressed in SENES (1994a) report on dry covers. There are two basic types of oxygen barriers:

- i) saturated barriers which act to control the diffusive flux;
- ii) oxygen consuming barriers which serve to consume oxygen prior to entering the waste.

The primary mode of atmospheric oxygen transport to the surfaces of sulphide containing wastes disposed in a pit is by molecular diffusion through interstitial pore spaces. The diffusion of oxygen through the pore space is a strong function of the moisture content. From experimental data in tailings, which can be generalized to other porous media, a useful expression for the effective diffusion coefficient ($D_e$) as the function of the degree of saturation is as follows (Elberling et al., 1993):

$$D_e \simeq \frac{D_a (1 - S)^{\alpha}}{\tau} + \frac{D_w \tau S}{H}$$

where:

$D_e$ = effective diffusion coefficient in cover material ($m^2\ s^{-1}$)
$D_a$ = diffusion coefficient of oxygen in air ($m^2\ s^{-1}$)
$D_w$ = diffusion coefficient of oxygen in water ($m^2\ s^{-1}$)
$\tau$ = tortuosity factor
$S$ = degree of saturation (volume of water/volume of pore space)
$H$ = modified Henry's constant
$\alpha$ = experimental parameter

The dependence of the effective diffusion coefficient ($D_e$) on the degree of saturation indicates that the diffusion coefficient can vary over five orders of magnitude. However, significant attenuations in $D_e$ occur at saturation values above 0.6. This means, that the effective covers must remain nearly saturated to provide orders of magnitude decrease in diffusive oxygen transport. The maintenance of high moisture content depends, in turn, on both the hydraulic properties of the cover material and the hydrology of the pit.

The primary function of oxygen consuming barriers is the reduction of the ambient oxygen concentration at the reactive waste/cover interphase by consumption of oxygen. Almost invariably, the covers contain organic matter, primarily lignocellulosics such as wood chips, wood wastes, peat, sewage sludge, hay, straw, etc. The reduction of oxygen is achieved by microbial degradation of the carbohydrate fraction, (empirical formula: $CH_2O$) primarily celluloses (glucose polymer) and hemicelluloses (xylose/glucose/xylulose copolymer). The aerobic oxidation of organic matter proceeds according to the following stoichiometry (Germain et al., 1992):

$$\begin{aligned}&(CH_2O)_{106}\,(NH_3)_{16}\,(H_3PO)_4 + 138\ O_2 \rightarrow \\ &106\ CO_2 + 16\ HNO_3 + H_3PO_4 + 122\ H_2O \qquad (2.8)\end{aligned}$$

The oxidation is carried out by a consortium of microbial flora. Generally, two biochemical phenomena are recognized. The first step is the enzymatic hydrolysis of lignocelluloses to dissolved constituents. This is followed by the uptake and metabolism of the dissolved mono- and oligosaccharides.

In the absence of oxygen, organic matter can also be degraded as follows:

$$(CH_2O)_{106}\,(NH_3)_{16}\,(H_3PO)_4 \rightarrow 53\ CO_2 + 53CH_4 + 16NH_3 + H_3PO_4 \qquad (2.9)$$

This heterotrophic fermentation requires the interaction of three bacterial populations; hydrolytic, acetogenic, and methanogenic bacteria. Usually, methanogenesis is the rate limiting step. Evidence for fermentative biodegradation of lignocellulosics is provided by the accumulation of organic acids (acetic, propionic, and butyric acids) in the pore water and significant levels of methane ($CH_4$) in the gas phase.

Although the biodegradation of the organic matter effectively consumes oxygen (see reaction 2.8), the organic acids produced by these fermentations may also result in release of easily dissolved metals and contaminants present in the deposited wastes.

#### 2.1.1.5 Sulphate Reduction

The biological reduction of sulphate to hydrogen sulphide or bisulphide occurs under anaerobic conditions and requires a source of decomposable organic carbon. In a mine environment, this carbon can be supplied by residues of oil and grease, the slow degradation of cellulose in timbers and from the dissolution or decay of other organic materials. The hydrogen sulphide reacts with dissolved metals such as copper, zinc and iron to precipitate metal sulphides.

The generalized equation for sulphate reduction is as follows:

$$2H^+ + 2CH_2O + SO_4^{2-} \xrightarrow[\textit{Bacteria}]{\textit{Anaerobic}} H_2S + 2HCO_3^- \qquad (2.10)$$

$$M^{2+} + H_2S \longrightarrow MS_{(S)} + 2H^+ \qquad (2.11)$$

where: $CH_2O$ represents the soluble organic carbon, and M represents metal ions.

The most common sulphur reducing bacteria are *Desulfovibrio* and *Desulfatomaculum*. These are strict anaerobes (e.g. grow in absence of oxygen) that are most active at pH levels from 4 to 7. In the natural environment, there is a synergism between three groups of microorganisms: the acidogens create the sulphate and acid mine drainage by oxidation of sulphide minerals under aerobic conditions; the methanogens convert organic materials into methane and degradable nutrients under anaerobic conditions; and the sulphate reducers use this organic carbon and convert sulphate to hydrogen sulphide which then precipitates metals from solution. Therefore conditions must be suitable for supporting growth and activity of three distinct groups of microorganisms.

Controlling the sulphate reducing process is the major difficulty of applying this *in situ* treatment in a mine or pit environment. For example: if too much organic carbon is present and reactions are rapid, excess $H_2S$ will be generated which is toxic to bacteria;

or if solutions are too acidic, the sulphate reducing bacteria are not active and sulphate reduction will not occur.

Sulphate reduction will generally occur for most application. The challenges are to design an inexpensive system for controlled addition of the organic carbon, as appropriate quantities of carbon are required to obtain the desired degree of sulphur reduction for successful and sustained *in situ* treatment. It is also important to prevent the substrate from becoming fouled by precipitates. The acidic waters should be directed towards the substrate in such a way as to ensure adequate contact and retention time for the reactions to occur. The theory is sound and the phenomenon has been observed within mine environments; however, no simple system has been demonstrated on a large scale.

For controlled systems the carbon source is normally a soluble sugar such as molasses. Other carbon sources such as mushroom compost, alfalfa and peat have been tested and shown to provide the needed organic carbon; however, the methodology to optimize the utilization of these carbon sources to supply adequate carbon for sulphate reduction has not been demonstrated.

### 2.1.2 Leachable Mass and Leachate Quality

The quality of pore water within the waste disposed in a pit is a key factor in determining the engineered controls necessary for a suitable pit disposal strategy. For example, if leachate quality is only marginally contaminated, predictive modelling of contaminant releases may well demonstrate that the potential environmental impacts are insignificant. Conversely, it may also demonstrate that engineered controls such as "pervious surrounds", diffusion barriers, engineered covers etc. are required to develop a satisfactory pit disposal option.

The pore water concentration data is important and so is the leachable mass fraction. One may find that the initial rates of contaminant release may be high; however, as the leachable fraction declines, the rate of release slows and the potential for environmental impacts becomes negligible and therefore acceptable.

Conventional testing such as pore water sampling, sequential leaching tests, and humidity cells can be used to establish pore water (source concentration) characteristics, leachable fractions, and possible long term (ultimate) concentrations. Empirical expressions can be developed to predict the change in contaminant concentrations over time.

Another key tool is geochemical modelling. Two types of models are currently available. These are pure geochemical equilibrium models such as MINTEQA2 and acid generation models such as RATAP.BMT3. For reactive waste flooded in a pit, MINTEQA2 can be a useful tool for predicting long term water quality and changes that may occur with pH modification or leaching by groundwaters. RATAP.BMT3 is useful for evaluating long term behaviour of unsaturated base metal tailings, with/without a dry cover.

### 2.1.3 Grain Size/Porosity

Grain size is an extremely important parameter as it affects several important processes:

- rate of acid production (surface area);
- reactivity of buffering minerals;
- permeability/porosity;
- moisture content; and
- mechanisms of contaminant transport (diffusive versus convective).

When characterizing wastes for pit disposal, mineralogical and chemical testing should be completed for various screen sizes. Of specific importance is acid base accounting data with grain size; one often finds that acid producing and acid consuming materials may be present in different particle size fractions. Experience has also shown that many geotechnical properties of wastes can be well correlated with grain size.

### 2.1.4 Permeability

Permeability is important to permit an assessment of the hydraulic transport of infiltrating water or groundwater through the waste. In selected cases, one may find backfilled waste materials have very low permeability in comparison with the fractured rock around the pit. Under these conditions, minimal infiltration may occur and groundwater will tend to pass around the pit through fractured zones rather than through the wastes deposited in the pit. This situation would result in a much slower release of metals and contaminants from the wastes. This feature has been developed into the concept of the "pervious surround" or "porous envelope", whereby materials with higher permeability are intentionally placed around the reactive wastes to direct groundwater flow away from the wastes.

In some situations, water barriers may be necessary to prevent convective transport and to create a diffusion controlled condition (e.g. by raising the water table or through creation of perched water table in the pits).

Conventional techniques using grain size analysis and conventional falling or rising head tests are normally suitable for determination of permeability (SENES, 1994b).

One concern that could potentially arise for backfilled pits is variations in permeability over time. Several phenomena often occur within backfilled mine wastes:

i) permeability is reduced due to secondary mineral precipitation (e.g. formation of sticky precipitates such as gypsum or impermeable layers known as hard pans);

ii) permeability is reduced due to consolidation of wastes over time;

iii) permeability increases due to dissolution of secondary minerals (e.g. gypsum $CaSO_4 \cdot 2H_2O$); and

iv) permeability decreases due to formation of additional fines and consolidation as result of weathering and/or alteration of waste material (e.g. sericite schists).

### 2.1.5 Consolidation

The initial state of compaction and the potential for wastes to consolidate over time may have a substantial effect on the design of a pit disposal system. By the very nature of most pits, depths range from very shallow to very deep therefore consolidation effects will vary from place to place within the pit. Concerns include differential settlement and the overall integrity of any covers or barrier placed either over, under or around the reactive wastes.

## 2.2 PIT CHARACTERISTICS

Not all pits are suited for waste disposal and especially disposal of reactive waste. Some of the key considerations regarding suitability include:

i) mining constraints
  - future access to remaining ore reserves;
  - other nearby mining activities;
  - stability;
  - safety of workers during placement of wastes;

ii) mineralization of exposed pit walls; and

iii) hydrogeology/hydrology.

Other factors that also need to be considered include morphology, depth of overburden and potential benefits (e.g. future lake, recreation etc.). A brief review of the key issues is provided in the following section.

### 2.2.1 Mining Related Constraints

Few pits are ever "mined-out". Residual mineralization often remains and may prove to be economically recoverable at a future date. In addition concern is often raised regarding creation of flooded pits above existing or potential future mine workings.

Other factors which may impact on the use of the pit include interconnection with other nearby mine workings, and concerns regarding the stability of underground workings located under the pit.

Mine owners/operators have generally opposed backfilling of pits for one or more of the above reasons; however, it has recently been clearly demonstrated that there can be a net positive benefit to using an open pit for mine waste disposal.

There is also concern over the safety aspects of working in old pits. Pit walls may be unstable or degraded to the point where the risk of entry into the pit may preclude its use. For example, at several sites, it was indicated that helicopters had to be used for safe access to pit waters for sampling water quality. On the other hand, backfilling may well be a cost effective technique for stabilizing pit walls.

### 2.2.2 Pit Wall Mineralization

One concern with any pit is acid production from exposed mineralization on the pit walls. Leachates draining into the pit from joints, fractures, faults and exposed walls may be highly acid and could seriously impact on the utility of using pits for waste deposition. In these cases, concepts can generally be adapted to address this concern (e.g. grouting); however, cost effective solutions may not always be available.

### 2.2.3 Hydrogeology/Hydrology

The hydrogeology of the pit is by far the most critical factor in assessing the applicability of any pit for waste disposal. The hydrogeology of the site will often dictate what engineered controls are necessary to develop an acceptable disposal option.

Key factors regarding the pit include:

- presence of faults and major flow pathways;
- bulk permeability of the surrounding rock around the pit;

- hydraulic connections to other mining areas;
- groundwater flow path and potential downstream receptors (e.g. potable groundwater supplies, surface water streams);
- location and gradient of the groundwater table; and
- stratigraphy/permeability of overburden and bedrock.

The ideal pit for reactive wastes producing contaminated leachate would have the following characteristics:

- minimal to no groundwater gradient across the pit to ensure that no release of contaminants occurs as a result of groundwater transport;
- low permeability bedrock with few faults such that the pit effectively acts as a bathtub with no drain. All flows to the pit enter and discharge at the top resulting in no infiltration or groundwater discharge.

Few pits will ever have these ideal characteristics, but they may have some other hydrogeologic features that make them suitable for waste disposal. These include:

- minor groundwater inflows which result in modest contaminant releases but negligible downstream environmental impact;
- natural beneficial geochemical characteristics in surrounding rock that buffer acidity and retard contaminant migration.

For wastes that do not produce contaminated leachate, hydrogeology is not a major concern. For reactive wastes being disposed in non-ideal pits, many engineered controls can be applied to mitigate contaminant release. These are addressed in Chapter 3.0 and include such controls as use of liners, diffusion barriers, collection barriers and other technologies.

The hydrology of the surface region surrounding the pit may be a very important factor, as the surface flow conditions will affect:

- the flooding of the pit;
- the final water table elevation;
- the concentrations of contaminants leached from the wastes;
- the dilution provided for contaminated seepage/drainages from the pit which reach receiving water bodies; and
- the possible connection of a flooded pit with other surface water bodies.

For reactive waste disposal, assurance that the water cover will be maintained is critical for most applications. For pits with minimal watersheds and high water losses (e.g. seepage/evaporation), reactive waste disposal may not be practical. Most wastes and pits produce some level of contaminated seepage/drainage. If inflows from surface are very low and minimal dilution is provided in the receiving watershed, unacceptable water quality could be produced even though the net loading of contaminants from the pit into the environment is not significant. Another situation is also possible where a flooded backfilled pit with contaminated waters overflows into a nearby surface water body.

## 2.3 ENVIRONMENTAL ASPECTS

Consideration must be given to the short term and long term environmental implications of any pit disposal concept. Every site is unique and may have constraints related to groundwater quality and use, surface water quality and use, and sensitive ecological communities.

In selecting any waste management plan, it is essential that some evaluation of alternative disposal options is completed to justify pit disposal. Leaving mine waste on surface could well be a better option than in-pit disposal. The only way this can be reasonably assessed is to screen potential options, taking into consideration impacts and costs, in order to arrive at a sound and cost effective solution.

## 2.4 REGULATORY CONSTRAINTS/CONSIDERATIONS

It is reasonable to state that pit disposal of mine wastes is generally well received by regulators. The option of returning the waste rock into the ground is conceptually appealing. For example, the Province of British Columbia (BC RAC, 1993) released an Interim Policy for Acid rock Drainage at Mine Sites which states that:

> *"Secure underwater disposal of tailings of waste rock in man-made structures is currently an acceptable form of acid rock drainage prevention ... In cases where underwater disposal of tailings or waste rock is proposed, the proponent must show that:*
>
> - *the mine wastes do not contain significant readily soluble deleterious substances;*
> - *the water balance ensures that all potentially acid generating wastes will be continuously covered by water; and*
> - *there will be no significant impact as a result of wave action, ice, avalanches, flooding, earthquakes, thermal overturn and other relevant natural factors.*
>
> *A water cover is currently an acceptable form of acid rock drainage prevention for underground workings or open pits.*
>
> *The timing and inflow rate requirements in flooding open pits and underground workings will be based on the hydrologic conditions, the relative reaction rates of acid generation versus neutralization and the potential release of acid products. Proponents must demonstrate that any water released to the environment will be of acceptable quality."*

In at least one North American jurisdiction there is or will be a legal requirement to backfill pits. This type of regulatory decree is not required in Canada, is not a reasonable solution, and should never be universally applied. As already noted, backfilling pits may not be a suitable option at some sites.

The key regulatory issues identified through the study of several sites relate to groundwater and surface water quality, and future land use.

Groundwater quality may temporarily exceed standards at some location downgradient of a pit; however, in many cases, this simply represents a limitation on the use of groundwater in this area. It is possible to define this zone and provide land use controls for this area.

Another regulatory concern relates to surface water quality of flooded pits. Most regulatory jurisdictions have two sets of surface water quality criteria for mines:

i) effluent quality limits; and
ii) receiving water quality objectives.

Two potential issues arise:

- Firstly, surface water quality in the pit may exceed discharge limits. This may be a totally acceptable condition if receiving water quality is not impacted. Most jurisdictions are struggling with accepting this condition. The original discharge limits were likely based upon effluent quality that can be achieved by operating effluent treatment systems. A major objective for closure is to implement passive systems without treatment plants. Pit disposal is a passive solution.

- A second issue arises when pit water quality is below effluent discharge criteria but exceeds surface water quality objectives. In at least one case, the flooded pit was considered to be a water body and therefore the regulators wanted surface water quality objectives to be met.

## 2.5 OPEN PIT PLANNING

Open pit mines are extensive operations, some mines move in excess of 100,000 tonnes of ore and waste daily. Waste rock is typically blasted and truck hauled from the open pit to waste rock disposal areas. Reactive waste rock and low grade mineralization may be segregated and stockpiled separately.

The physical layout of an open pit mine, and the locations of open pit mine waste disposal areas are planned in advance of ore mining and waste stripping operations.

The open pit planning process focuses on optimizing the profitable extraction of ore in a safe and environmentally responsible manner. In concept, the economic value of a tonne of ore must be greater than the cumulative costs associated with the mining and processing of that tonne of ore, plus any other costs associated with the stripping and disposal of perhaps several tonnes of mine waste per tonne of ore. Several tens of thousands of tonnes of ore may be mined per day at an open pit operation, essentially to take advantage of economy of scale and lower the unit cost (e.g. cost per tonne) of ore extraction.

Economic evaluations of open pits at the planning stage are typically used to develop a cut-off grade which is the minimum grade of ore that can be mined profitably or, in some cases, to break-even. The cut-off grade is different for each open pit mine and is a function of the anticipated revenues and costs. The cut-off grade and the physical limits of an open pit mine are, therefore, sensitive to changes in revenue (e.g. metal price fluctuations) and costs (i.e. mining, processing, taxes, mine decommissioning, etc.).

At most new open pit mines, the potential for acidic drainage is usually determined early in the planning process. A decision may be made at the planning stage to segregate reactive wastes and relocate the wastes to the open pit once it is mined out. In such a case, the economic evaluation of the open pit, and the pit design would take into consideration all anticipated costs to implement the in-pit disposal scenario.

The separate stockpiling of mine waste rock may be difficult to carry out in practice due to the mixing of wastes during the blasting and removal cycle, and the availability of suitable storage areas within a reasonable truck haul distance of the open pit. Reactive waste rock must be stored in an environmentally sound location; this waste rock pile drainage should be collected or directed for interception and treatment along with other contaminated drainages at the mine site. Mine waste disposal areas for non-reactive waste rock may be located elsewhere.

The economic evaluation and design for an operating open pit mine, where acidic drainage from mine waste was not anticipated, would likely have been based on the permanent disposal of mine wastes in engineered waste rock stockpiles and tailings disposal areas. At some sites mine wastes have later been found to have the potential to produce acid; and as a result, alternate mine waste management strategies had to be developed. In such a case, an alternate waste management strategy may be more costly and could have an unfavourable impact on the future profitability of the open pit operation.

# 3.0 PIT DISPOSAL CONCEPTS

There are four basic concepts for placement of wastes in pits:

| | |
|---|---|
| Option 1: | Underwater Disposal |
| Option 2: | Elevated Water Tables |
| Option 3: | Dry Disposal |
| Option 4: | Perched Water Tables |

The disposal options reviewed in each of the following sections relate to deposition of reactive wastes; but, these techniques can also be used for non-reactive wastes. The four options are described in terms of the theoretical concepts and practical aspects; selected examples of research and field applications are provided from the published literature.

## 3.1 OPTION 1 - UNDERWATER DISPOSAL

This option assumes that a lake or wetland will exist upon completion of backfilling. There are four sub-options that can be considered for underwater disposal in a pit:

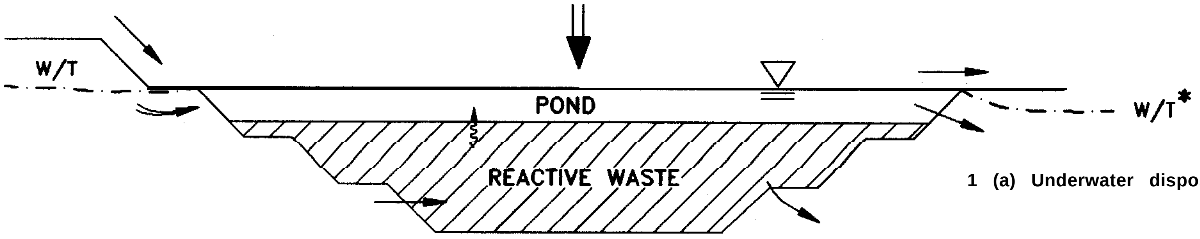
- Option 1a - Simple Underwater Disposal
- Option 1b - Underwater Disposal with a Surface Barrier
- Option 1c - Underwater Disposal with Groundwater Barriers
- Option 1d - Underwater Disposal with Surface and Groundwater Barriers.

The selection of the appropriate method will depend upon all the factors discussed in Chapter 2.0. A discussion of the use of underwater disposal options in pits is provided below. The underwater disposal concepts are illustrated in Figure 3.1.

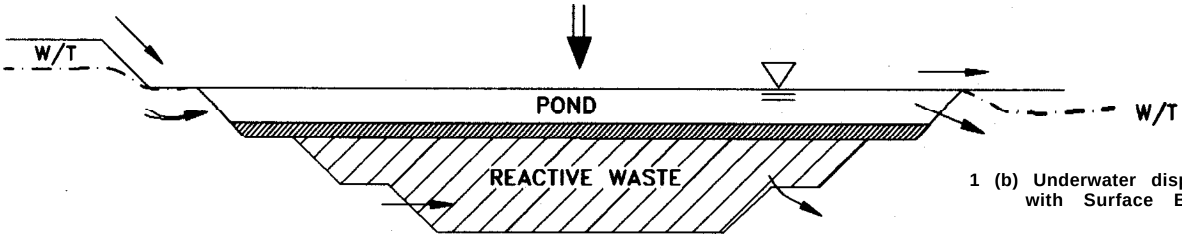
Several MEND studies have investigated subaqueous disposal of reactive mine wastes. Rescan (1989) prepared an overview of early investigations of subaqueous disposal of tailings. Subsequent studies looked at disposal of tailings in natural lakes; The Rawson Academy of Aquatic Science (1992) prepared a review of MEND studies

## FIGURE 3.1

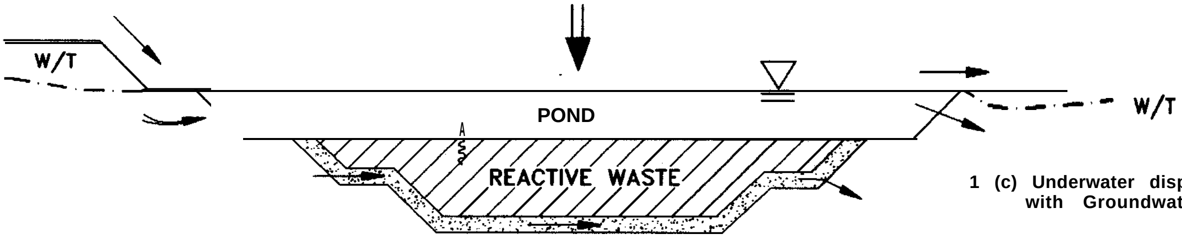
## Option 1
## PIT DISPOSAL CONCEPTS - Underwater Disposal



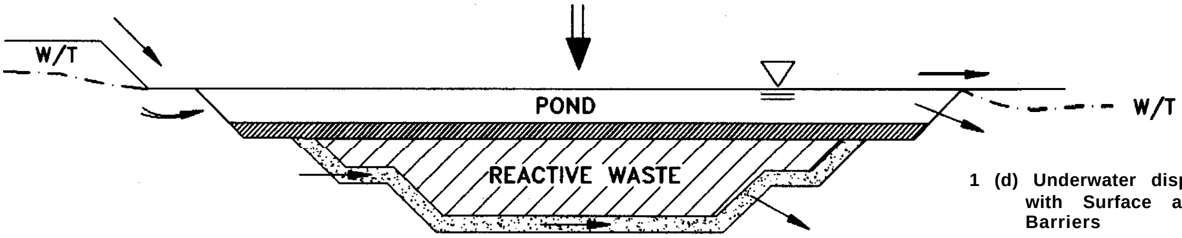
1 (a) Underwater disposal



1 (b) Underwater disposal with Surface Barriers



1 (c) Underwater disposal with Groundwater Barriers



1 (d) Underwater disposal with Surface and Groundwater Barriers

* W/T = Water Table

conducted to 1991. Macdonald (1992) and Stevens et al. (1994) provide a more recent review of mine pit lakes.

### 3.1.1 Option 1a - Simple Underwater Disposal

For simple underwater disposal, waste is placed at the bottom of the pit and flooded. In an ideal pit, convective groundwater transport would be minimal and the prime mechanism for release would be through mass transfer (diffusion) from the surface of the waste into the pit water. In simplistic terms, the mass transfer from the surface of the flooded waste can be described by the following equation:

$$Flux = K_{La} \quad (C^* - C)$$

where:

$K_{La}$ = effective mass transfer coefficient;
$C^*$ = concentration of a given contaminant in pore water within the waste;
$C$ = bulk concentration of contaminant in the pit water.

For deep water pits, the simple mass transfer equation is not adequate as many other factors may come into play. These can include development of:

- meromixis (chemical stratification);
- thermal stratification; or
- anaerobic conditions.

Stratification refers to a lack of mixing between the adjacent (stratified) layers. Some of these layers are very stable (e.g., meromixis), while others may break down (e.g. as during seasonal turn over events). A discussion of these phenomena is reviewed in the description of pit lakes provided in Chapter 4.0. When these phenomena occur, the pit models must be adapted to better describe the liminological conditions of the pit. The net result is that stratification forms an additional barrier to contaminant migration (see also Island Copper and Gunnar pit case studies).

The development of anaerobic or anoxic conditions may occur in deep pits as minimal to no oxygen can penetrate to the bottom, especially in pits where meromixis persists.

The chemical effects of anoxic conditions are not likely to be significant unless decomposable organics are present to support biological sulphate reduction and metal sulphide precipitation. Environmentally, meromixis and the anoxic conditions would make the bottom sediments in deep pits generally unsuitable for most aquatic species (fish, benthos, etc.).

Empirical and mechanistic models can be used to predict short-term and long-term concentration and examine how the pit will perform. Several publications describe the modelling of water quality in flooded pits:

- Kempton et al. (1994) describe the combined use of several models to predict source contributions and resulting water quality in future pit lakes at the Robinson Project in White Pine County, Nevada (see Robinson Project case study). A Monte Carlo technique was used to address uncertainty related to characterization of four parameters (chemical release from pit walls, net neutralization potential in wall rock, sulphide content of wall rock, and wall rock porosity).

- Morin (1990, 1994) developed a computer program (MINEWALL) which considers the relevant geochemical aspects of unit-rock-surface reaction rates (measured experimentally) and the total amount of reactive rock surface in a mine. The key factor in predicting mine water chemistry is the estimation of percentages of reactive surface that are flushed regularly, as these cannot be directly measured.

- Bird et al. (1994) examined the suitability of five popular hydrogeochemical computer modelling software packages (BALANCE, MINTEQA2, PHREEQE, WATEQF, and WATEQ4F) to predict the current pit water geochemistry at the Cortez Mine open pit. They concluded that each computer code could be utilized for a subset of the overall pit water modelling process (e.g. models should be used in combination).

- Stevens et al. (1994) describe the modelling of thermal stratification of water-filled mine pits.

Simple underwater disposal is the most common of the underwater disposal options. If the simple underwater deposition is inadequate, additional engineered controls can be considered. These controls are described below for Options 1b, c and d.

### 3.1.2 Option 1b - Underwater Disposal with a Surface Barrier

For this option, a barrier is placed over the surface of the submerged reactive wastes to reduce upward contaminant transport into the water. The most commonly used barrier would be a clean soil (sand, till, clay, etc.). By using 0.5 m or more of fine-grained material as a cover, the release of contaminants will be diffusion controlled. Models are available to determine a suitable barrier depth to ensure satisfactory concentrations in the pit water (see Collins "B" case study).

St-Arnaud (1994) reports that laboratory simulations of several wet tailings disposal scenarios demonstrate that:

- tailings oxidation in unsaturated conditions slows down with time;
- if the tailings are placed under water while still fresh (unoxidized), metal releases should be low compared to uncovered tailings;
- metal releases from water-covered oxidized tailings could be significant, depending on the level of oxidation, and could last for long time periods, but should however decrease with time; and
- upward metal release from water-covered oxidized tailings may be controlled by a layer of clean, granular material such as sand.

There are other potential barriers that could be considered. One possibility is a layer of organic material which would act as both a diffusion barrier as well as providing a geochemical environment where biological sulphate reduction and metal sulphide precipitation could occur. The experience with applied use of such systems in pits is not available, however, analogous situations do exist in lake environments. Pederson et al. (1994) clearly demonstrated that sulphide materials are stable in deep lake environments and further illustrated how natural organic substrates are effectively controlling contaminant release from submerged tailings. The development and effectiveness of such natural organic layers (i.e. benthos) in flooded pits would be difficult to quantify.

St. Arnaud (1994) examined an alternate situation where an organic substrate would be placed into a pit with the expectation that contaminant removal would occur from the pit water into the organic sediment. However, all the factors that make the pit bottoms good places to deposit reactive wastes proved to be detrimental to adding organic substrates to promote sulphate reduction and precipitation of metal sulphides. Conditions such as stratification and diffusion made the control of these processes inefficient and not likely applicable.

Kuyucak and St-Germain (1994) describe a study carried out at the Noranda Technology Centre to evaluate the feasibility of using sulphate reducing bacteria in a flooded pit or in an underground mine to treat acid mine drainage. They state the following requirements must be met for sulphate reducing bacteria to become established: pH > 6; reducing conditions; appropriate flowrate and composition of influent (i.e. load); easily degradable carbon sources; sufficient nutrients; good contact of acid mine drainage with substrate; and warm temperatures. Sulphate reduction, dissolution of carbonate minerals, and precipitation of metal sulphides are diffusion-controlled processes; therefore the physical flow and contact of nutrients, substrate, bacteria and water must be arranged to overcome mass transfer limitations (e.g. maximize surface area, optimize substrate thickness and permeability, gentle mixing). Therefore, the appropriate conditions may be difficult to establish and maintain.

### 3.1.3 Option 1c - Underwater Disposal with Groundwater Barriers

One of the concerns with some pits is that there may be a substantial convective flow of groundwater through the waste material. For these conditions, there are three different types of potential groundwater barriers:

(i) barriers which block groundwater flow such as liners, clay, dense till;
(ii) barriers which provide a low resistive flow path to groundwater; and
(iii) barriers which can remediate contamination entering the groundwater.

All of these controls are expensive and few applications exist. Options 1c (i) and (ii) require use of hydrogeological models to determine the effectiveness of the barriers. A substantial database is required for such assessments, including characterization of: permeability of all geological media; local flows; groundwater gradients; and, the piezometric surface. These data are necessary to calibrate the hydrogeological model.

A low permeability barrier, Option 1c(i), will serve two functions:

- reduce the flow through the tailings; and
- act as a barrier to contaminant diffusion.

There is no reported experience with use of low permeability barriers in actual pits but several modelling exercises have been completed to assess the potential benefits.

Creating a preferential flow path for groundwater, Option 1c(ii), was first proposed for the Rabbit Lake pit (Geocon, 1988). This concept involves creating a pervious envelope around the waste to create a preferential flow path for groundwater. Obviously if the waste is coarse rock, this type of barrier would not be effective, however, for low permeability tailings or sludges, the concept is quite attractive.

The envelope serves to equalize the gradient across the pit so that there is no driving force to cause groundwater to pass through the tailings. Groundwater entering the pervious envelope travels through the path of least resistance (i.e., the pervious shell). The best example of this application is the Rabbit Lake pit as described in Chapter 4.0.

The third possible barrier, Option 1c(iii), could be a layer that consumes contamination. This could be a redox barrier or an acid-consuming barrier.

Redox (organic) barriers have recently received considerable attention. Redox barriers are constructed within or downstream of impoundments and are currently being investigated as a method of containing acidity and soluble metals. Research in Canada is being pioneered by several universities. The success of this technology could significantly reduce the cost of leachate management, but the technology is still in the early stages of development. For a pit environment, it seems unlikely that an organic layer could be effectively placed into the groundwater pathway. The other concern is the functional life of such a layer.

Researchers at the Waterloo Centre for Groundwater Research at the University of Waterloo, and the National Water Research Institute at the Canada Center for Inland Waters, Burlington, Ontario are carrying out laboratory batch and column experiments to investigate the *in situ* treatment of mine drainage water using porous reactive walls (Blowes et al., 1994). Their research focuses on the use of organic carbon containing reactive walls to induce bacterially mediated sulphate reduction and subsequent metal-sulphide precipitation. The porous reactive walls could be installed by excavating a portion of the aquifer in the path of the groundwater plume and replacing the original aquifer material with a permeable reactive mixture. In field experiments, various forms of organic carbon were added to a small-scale test cell located in an anoxic aquifer downgradient from a mine-tailings impoundment at a mine site in Sudbury, Ontario. Bacterially catalyzed sulphate reduction and metal sulphide precipitation reactions decreased sulphate concentrations from 3,500 to 7 mg/L and iron concentrations from 1,000 to <5 mg/L, and increased pH and alkalinity. Monitoring and installation of additional test cells is proposed. Blowes et al. (1994) conclude that their preliminary results suggest that sulphate-reducing reactive walls may represent a potentially effective alternative for solution of acid mine drainage problems. However a substantial amount of organic carbon would be required. A draft report is to be submitted to MEND in 1995.

Another possibility for the bottom barrier in a backfilled pit is an acid-consuming layer such as an anoxic alkaline drain. This technology has not yet been proposed for pits, but technology developed for anoxic limestone drains could be adapted to a pit environment.

Skousen (1991) and other researchers at the University of West Virginia have investigated the use of anoxic limestone drains (e.g., buried trenches of limestone) as a way to neutralize acidic waters. They report that under low oxygen conditions, the buried limestone remains effective for long periods of time as it does not become coated with iron oxides but continues to dissolve and add alkalinity to acid waters (mostly in the form of bicarbonate $HCO_3^-$). Once the anoxic alkaline water reaches the surface, the water become oxygenated and metals readily precipitate; this typically occurs in a ditch, settling pond, or within an engineered wetland. Waters exiting an anoxic limestone drain cannot be immediately discharged into a receiving stream. Skousen (1991) reports that approximately 50 anoxic limestone drains have been built in the northeastern United States (as of fall of 1991). These were initially installed at sites where passive treatment using wetlands was not satisfactory; however, the anoxic limestone drains are also installed as stand-alone systems. Results from these installations indicate that anoxic limestone drains can add up to 300 mg/L alkalinity to water; however, if the acidic water has greater than 300 mg/L acidity, then treatment will be incomplete.

Some important factors for use of this technology are listed (Skousen, 1991):

- limestone with calcium carbonate content greater than 90% is recommended;
- particle sizes of limestone should range between 4 to 10 cm for wider ranges of dissolution rates and good flow properties;
- width and length of drain should correspond to volume required for 20 year supply of alkalinity, typical sizes are 0.6 to 1.5 m deep, 0.6 to 2.7 m wide, 30 to 600 m long, (calculation procedure is outlined in Skousen, 1991);
- shallow limestone drains have been covered with plastic liners (and layers of hay bales) to exclude oxygen;
- flow limit for passive systems is around 6 L/s, some systems have been designed at 30 L/s, but influent water quality was not very severe;
- dissolved oxygen concentration should be 2 mg/L or less and ferric iron concentrations should be low to prevent formation of iron hydroxide coatings (dissolved oxygen concentration in oxygenated water at 15 to 20°C is about 10 mg/L);
- aluminum concentrations in acidic waters should be less than 25 mg/L as aluminum precipitates can form above pH 5 (usually as gelatinous flocs which may clog the limestone drain);
- oxidation-reduction potential of the water (Eh) should be zero or less;

- monitoring should include flow, dissolved oxygen, ferrous/ferric iron levels, acidity and alkalinity; and,
- in order to function properly, limestone drains must be installed and saturated quickly to prevent formation of coatings.

A review by Kilborn Inc. (1994) explains that anoxic limestone drains have potential for application to low ferric iron, low aluminum systems with sulphate concentrations less than 2,000 mg/L. Hyman (1995) reports that aluminum concentrations over 20 mg/L resulted in coating of limestone with aluminum hydroxide within three months.

### 3.1.4 Option 1d - Underwater Disposal with Surface and Groundwater Barriers

This option is a combination of Options 1b and 1c. For this application, a complete envelope is required around the wastes. This is the proposal for the Rabbit Lake pit closure discussed in Chapter 4.0.

## 3.2 OPTION 2 - PIT BACKFILLING - ELEVATED WATER TABLE

For Option 2, the pit would be backfilled to near the original ground surface. The primary concept is to control oxidation by raising the water level above the reactive waste into a layer of clean fill/waste. The major difference between this concept and simple underwater disposal is that the water table is likely to be sloped, therefore, infiltration will likely pass through the waste as would groundwater, unless controls were put in place. The options for elevated water tables are illustrated in Figure 3.2.

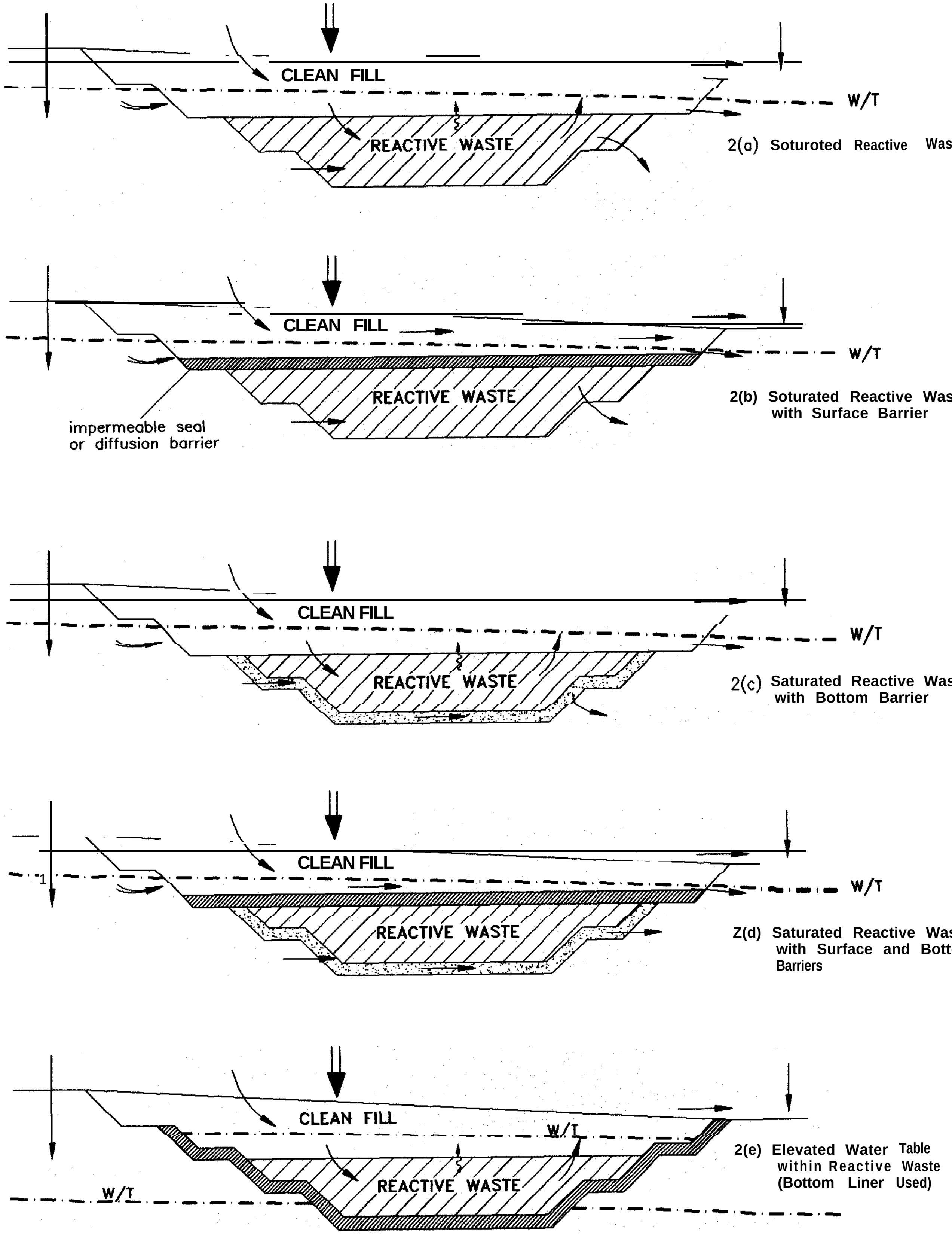
These options are as follows:

- Option 2a - Saturated Reactive Waste
- Option 2b - Saturated Reactive Waste with Surface Barrier
- Option 2c - Saturated Reactive Waste with Bottom Barrier
- Option 2d - Saturated Reactive Waste with Surface and Bottom Barriers
- Option 2e - Elevated Water Table within Reactive Wastes using a Bottom Liner

## FIGURE 3.2

## Option 2

## PIT DISPOSAL CONCEPTS - Elevated Water Table



2(a) Soturoted Reactive Waste

2(b) Soturated Reactive Waste with Surface Barrier

2(c) Saturated Reactive Waste with Bottom Barrier

Z(d) Saturated Reactive Waste with Surface and Bottom Barriers

2(e) Elevated Water Table within Reactive Waste (Bottom Liner Used)

Options 2a, b, c and d, are analogous to the underwater deposition options (see Figure 3.1). The surface barrier used in underwater disposal typically serves as a diffusion barrier. For elevated water tables, an infiltration barrier could also be considered (Option 2b); this layer would prevent convective groundwater flow by preventing infiltration of precipitation. The barrier could either be a low permeability layer to prevent infiltration into the waste or a pervious layer to preferentially transport infiltrating water. The latter would only be applicable if the waste had a low permeability. Similarly, Options 2c and d, use of pervious surround, apply in cases where wastes have low permeability.

The bottom barrier (Option 2e) could also be an impermeable liner used to trap infiltration water in a region where the natural groundwater table is depressed. In this case, the liner would create a basin where the water level would rise to the top and submerge the reactive waste.

It is also possible that waste itself may have a low enough permeability to cause an elevated water table without the need for a bottom barrier.

## 3.3 OPTION 3 - DRY DISPOSAL

It is not always possible to create a pond or an elevated water table. For these cases, alternative management systems must be developed. Four options were selected, as illustrated on Figure 3.3, to review the range of dry disposal options available:

- Option 3a - Engineered Cap/Cover
- Option 3b - Acid Buffering Barriers
- Option 3c - Alkali Blending
- Option 3d - Engineered Cover with Water Table Drawdown

### 3.3.1 Option 3a - Engineered Cap/Covers

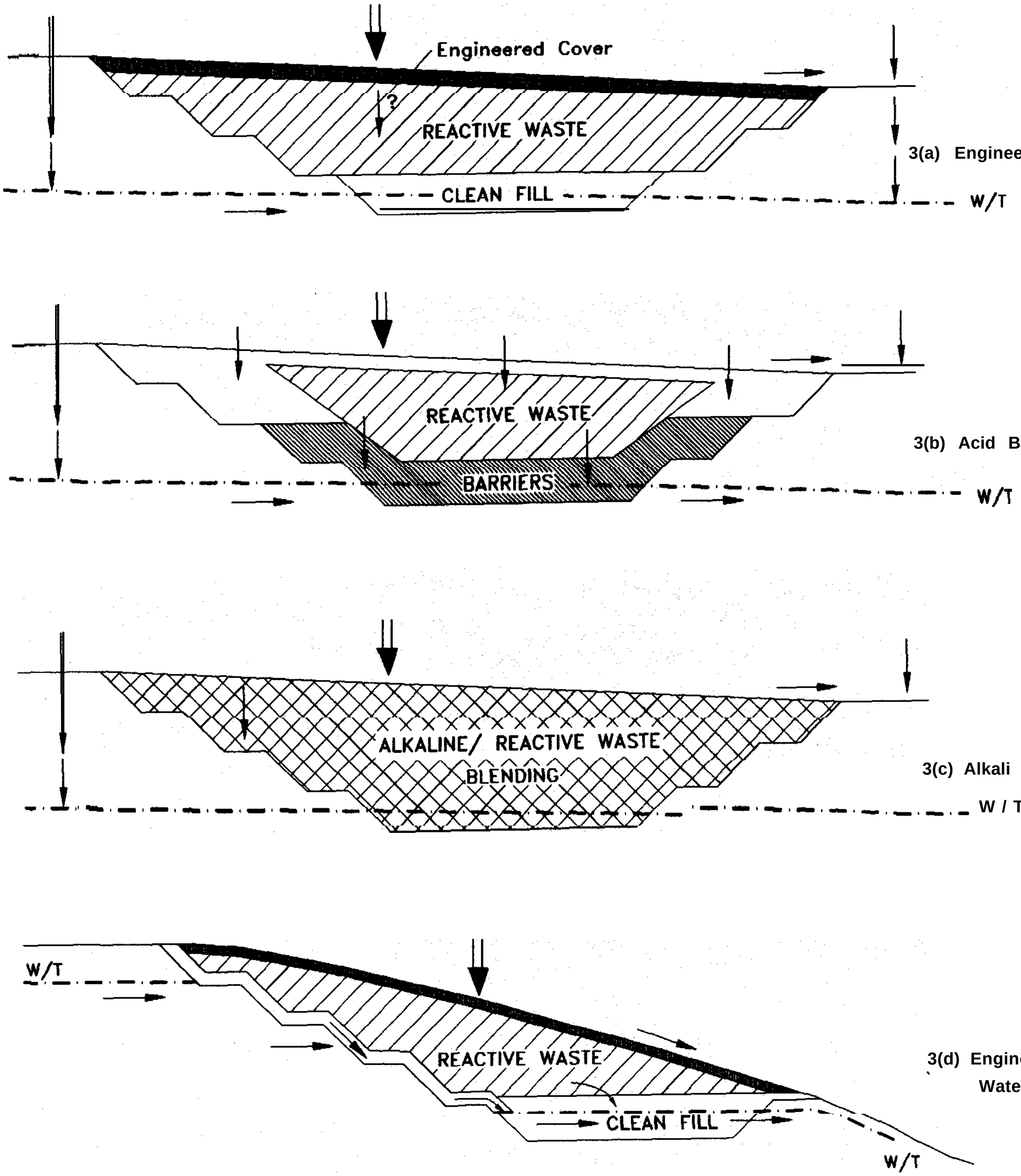
Dry covers have been the focus of extensive study in Canada. A recent report for MEND by SENES (1994a) reviews the status of the research and cover applications.

Dry covers can act as: barrier to water; barrier to oxygen; and/or barrier to both water and oxygen.

## FIGURE 3.3

## Option 3

## PIT DISPOSAL CONCEPTS - Dry Disposal



3(a) Engineered Cap/ Cover

3(b) Acid Buffering Barriers

3(c) Alkali Blending

3(d) Engineered Cover with Water Table Drowdown

The engineering design requirements for certain types of covers are well known (e.g., liners), but other dry cover applications (e.g., organics) are not well understood. The reader is directed to SENES (1994a) for additional discussion of dry covers.

### 3.3.2 Option 3b - Acid Buffering Barriers

The installation of barriers below a reactive waste to consume contaminants is possible but has many potential problems as discussed in Chapter 2.0. Two types of barriers are possible, alkaline barriers and organic barriers. Both types of barriers are described in previous options (see Options 1b and 1c). The primary difference could be the presence of aerobic conditions in the unsaturated backfill which may or may not affect the availability of alkali (refer to alkaline drains in Option 1c).

### 3.3.3 Option 3c - Alkali Blending

There is a considerable database on the effectiveness of use of alkaline materials for the control of acid generated by reactive tailings and waste rock. There are two basic approaches to alkali addition:

- addition of sufficient alkali to consume acid produced by reactive waste, or
- blending of waste materials with alkali to produce net acid-consuming materials (i.e. blended materials with NP:AP > 3:1 where NP = Neutralization Potential and AP = Acid Producing Potential expressed in terms of Kg calcium carbonate per tonne).

A summary of data collected from our review of laboratory and field studies is provided.

An extensive study on incorporation of limestone into waste material was reported by Day (1994) for the Cinola Gold Project. This was a 5-year program of column studies that investigated the effect on lime addition rates on acid production from reactive waste rock. The major finding was that limestone was very effective in controlling acidity but did not fully control the release of metals such as zinc, which are mobile under alkaline conditions. The major conclusions were (Day, 1994):

- *"the actual quantity of limestone required to prevent acid drainage in perpetuity would probably be at least twice that determined by conventional acid-base accounting;*
- *limestone availability was not reduced by ferric hydroxide coatings;*
- *the time required for marginally acid generating rock to release acidity increased exponentially as the quantity of limestone increased; and*
- *the time required for zinc release to begin increasing was linearly proportional to the neutralization potential."*

Sheremata et al. (1991) carried out a laboratory program to determine the rate of acid generation in waste rock and to compare the degree of control provided by different dosages of lime with that from control obtained by placing waste rock under water cover. Their column leaching tests were carried out under accelerated weathering conditions (27°C, 80% humidity). Acid production from sulphide rock underwater was generally found to be lower than acid production from lime-treated (unsaturated) rock. The dosage of lime or limestone necessary to prevent acid generation was greater for a given volume of smaller sized rocks than for the same volume of larger rocks. Added lime was rapidly consumed. From their extrapolation of acid production quantities for grain sizes large than the ones used in the laboratory (average diameter 37.5 mm), the authors estimated the addition of limestone at 10 kg/t of this particular waste rock (with average diameter of 300 mm) would only be effective for 170 weeks (or 3⅓ years).

Ziemkiewicz and Skousen (1992) investigated the use of lime kiln dust, fluidized bed combustion ash, and rock phosphate to prevent acid generation in pyritic coal wastes. From accelerated weathering tests with each amendment, the authors concluded that each amendment controlled acid generation; however, lime kiln dust was more effective (i.e., more consistent control at a lower application rate). Fluidized bed combustion ash only contains about 20% CaO within an otherwise inert aluminosilicate coal ash matrix. Phosphate rock was found to be inefficient, requiring twice the application rate as kiln dust.

Phosphate materials appear to be less effective than lime, therefore, use of phosphate would depend on the availability/proximity of a suitable source.

Brady et al. (1990) prepared a compilation of acid base accounting data and alkali addition rates for eight surface coal mines in Pennsylvania. Alkaline materials (limestone $CaCO_3$, hydrated lime $Ca(OH)_2$) were applied at rates ranging from 42 to greater than 1,000 tons (as $CaCO_3$) per acre. These sites represent backfilling of surface mines. On the basis of their study of the addition of alkaline materials to selected surface coal mines in western Pennsylvania, the following conclusions could be made (Brady et al, 1990):

- *"Previous methods for determining alkaline addition rates, especially the concept that only one-third the calculated deficiency was necessary, have failed to prevent or abate AMD. Most alkaline addition rates are negligible relative to calculated deficiencies (NNP < 0) and insufficient to prevent or neutralize AMD.*

- *The addition of alkaline materials to prevent AMD from surface coal mines may be effective providing that the alkaline-addition rates are sufficient (to offset negative NNP) and the overburden has relatively low-sulphur content. Alkaline materials added to high-sulphur mine spoil, even if sufficient to neutralize acid water, may not reduce concentrations of dissolved iron, manganese, and sulphate.*

- *Certain mining practices, such as addition of more alkaline material than required by permit conditions, selective handling of pit cleanings, removal of pyritic material from the mine site, and concurrent reclamation appeared to enhance the effect of alkaline addition on reducing acidity...*

- *Additional studies are needed to determine the most beneficial rates of application and placement of the alkaline materials. Calculations of deficiencies (NNP) and application rates should be conservative and consider the theoretical arguments given by Cravotta et al. (1990) and the empirical results of this study."*

In their Interim Policy for Acid Rock Drainage at Mine Sites, the Province of British Columbia states that blending of acid generating and acid consuming materials may be an acceptable acid rock drainage prevention strategy (BC RAC, 1993):

> *"While it is reasonable to assume that materials generating acid drainage can be mixed with acid consuming material in a waste rock dump to produce alkaline drainage, neither the proportion or the amount of acid generating material, nor the degree of mixing required is known with any certainty. In general, blending will not be considered unless the volume or mass weighted average neutralization potential to potential acidity ratio (NP:AP) is at least 3 to 1, and the acid generating material is not highly reactive. Blending becomes a more acceptable alternative as the NP:AP ratio increases. For each site, evidence will be required to demonstrate the long term effectiveness of the blending plan...*
>
> *Segregating of acid generating material within a disposal site and encapsulation within materials which will generate alkalinity may be acceptable, although this is also unproven technology. Segregation or layering commonly refers to the placement of potentially acid generating material between layers of acid consuming material.*
>
> *As with blending, segregation will not be considered for waste rock unless the ratio of neutralization potential to acid generation potential acidity ratio (NP:AP) is at least 3 to 1, and the potentially acidic material is not highly reactive. Segregation becomes a more acceptable alternative as the NP:AP ratio increases ... Methods to minimize oxygen and water infiltration into segregated potentially acidic materials or the placement of segregated materials beneath the final water table should also be incorporated into the waste management plan."*

The only reported application of alkali blending in Canada was at Owl Creek mine where lime was added to reactive waste before placement and flooding in the open pit (this is discussed in Chapter 4).

### 3.3.4 Option 3d - Engineered Cover with Water Table Drawdown

Several pits are located on hillsides and are therefore not suited for reactive waste disposal without engineered controls. The example shown in Figure 3.3d is a sidehill pit where the water table emerges in the head wall. An example of this pit configuration for waste disposal was recently adapted at Barrick Golds' Richmond Hill mine. The engineered cap minimizes infiltration and the bottom barrier drain prevents groundwater from entering the waste. In some cases, interim treatment of drain water may be required.

## 3.4 OPTION 4 - PIT DISPOSAL - PERCHED SATURATED LAYER IN COVER

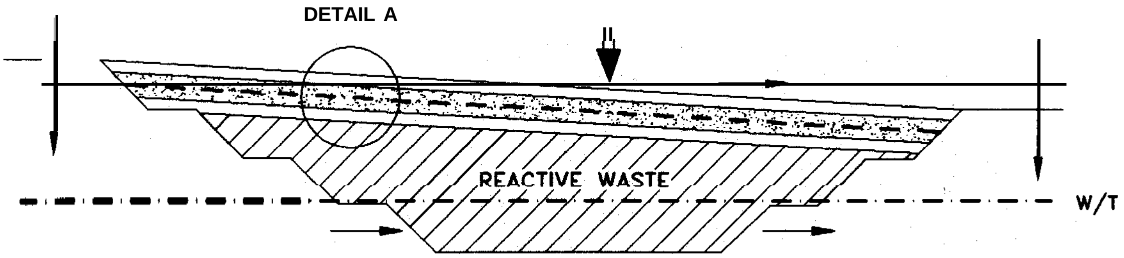
Option 4 is a dry disposal technique which includes a saturated oxygen barrier in the cover above the dry wastes. A typical example is shown in Figure 3.4. A substantial amount of research is being conducted on this concept. The challenge in the design is the development of the saturated layer. This layer could be thickened tailings, tills, or any well-graded material that has a naturally high degree of saturation. Most areas of Canada have local tills that could function well as this saturated layer. Examples of where this concept have been used are new, and include the Equity Silver South Tail pit.

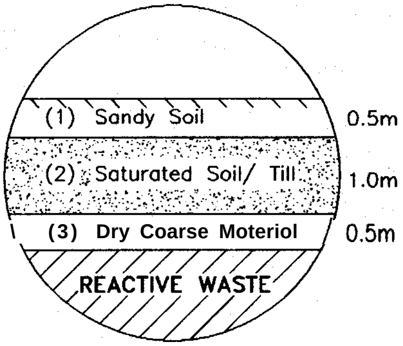
In summary, the concept is to provide:

- a surface layer which allows infiltration and provides erosion protection for the saturated layer;
- a saturated layer which remains near saturation and thus inhibits oxygen entering the reactive wastes; and
- a capillary break to prevent dewatering of the saturated layer.

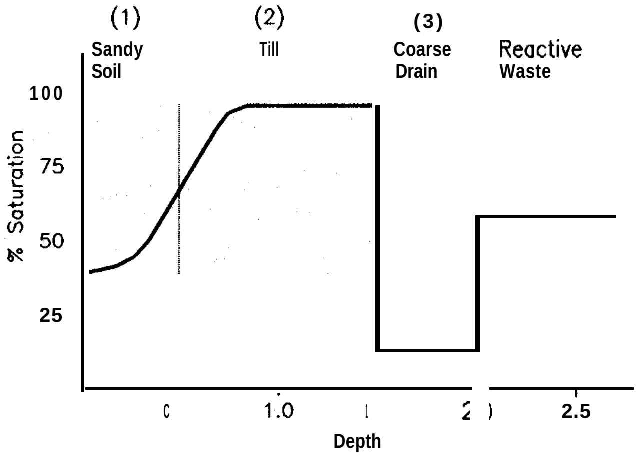
FIGURE 3.4

## Option 4
## PIT DISPOSAL CONCEPTS - Perched Saturated Layer In Cover





DETAIL A – Typical Design
Perched Water Table



Moisture Profile in Cover

| Zone | | |
|---|---|---|
| | (1) | Permeable zone of sandy soil to allow infiltration to maintain till near saturation and to protect till from evapotranspiration and dessication. |
| | (2) | Well graded glacial till with naturally high level of saturation. |
| | (3) | Coarse drain to act as a capilliary break and possibly low hydraulic conductivity barrier to infiltration. |

## 4.0 CASE STUDIES

Our study provided information describing over 60 sites in Canada, the United States and internationally. Sites in Canada and the United States are listed in Tables 4.1 and 4.2 respectively. The listings include additional information such as status (e.g. historic/active/proposed), types of wastes either in the pit or to be placed in pit (e.g. reactive waste rock or tailings, or non reactive waste), the type of cover that was placed or will be placed on the pit (e.g. wet/dry/combined wet-dry), and the type of monitoring data available for that site (e.g. surface water (SW), groundwater (GW)).

The information and reports received from the organizations contacted were reviewed and site-specific information was summarized according to the following categories:

- Status (Historic/Active/Proposed)
- Location (Canada/United States/Other)
- Type of Mine (Pit)
- Closure Concerns (slope stability/AMD/other)
- Plans for Pit
- Quantity of Wastes (currently in pit, and or to be placed, in pit)
- Size/Dimensions Capacity of Pit
- Hydrogeologic Setting (current)
- Dry/Wet Cover (future location of water table in relation to pit/wastes)
- Characteristics of Wastes/Backfill (AMD, contaminants of concern)
- Monitoring Data (surface water, groundwater, regulatory requirements)
- Method(s) of Placement (associated costs)
- Placement Strategy (classification/segregation/zoning/barrier/encapsulation/amendments
- Closure Plan (treatment/sludge disposal, reclamation, vegetation, biota)
- Documentation (reports/papers/Environmental Assessment).

Twelve sites were selected for case studies (Table 4.3). The selection of sites for detailed case studies was based on the quantity of information available (studies, reports, monitoring data etc.), and the suitability of the site for representing a typical

Table 4.1

## LIST OF SITES IN CANADA

| Name of Site | Location | Status | Types of Wastes | Cover | Monitoring Data |
|---|---|---|---|---|---|
| Cluff "D" | Cluff Lake, Saskatchewan. | Active | Reactive pit walls | Wet | SW & GW |
| Collins "B" | Rabbit Lake, Harrison Peninsula, Saskatchewan. | Active | Reactive waste rock | Wet | SW & GW |
| Owl Creek | Timmins, Ontario. | Historic | Reactive waste rock | Wet | SW |
| Solbec | Aylmer Lake, Eastern Townships, Stratford, Québec. | Historic | Reactive waste rock, tailings, and contaminated soil | Wet | SW & GW |
| Gunnar | Lake Athabasca , Crackingstone Peninsula, Saskatchewan. | Historic | Reactive waste rock & uranium tailings | Wet | SW & GW |
| Pits #1 & #2 (Gloryholes) | Buchans, Newfoundland. | Historic | Reactive mine tailings | Wet | SW |
| East Kemptville | Nova Scotia. | Historic | Sludge | Wet | - |
| Rabbit Lake | Rabbit Lake, Saskatchewan. | Active | Reactive tailings | Wet | SW & GW |
| Island Copper | Vancouver Island, British Columbia. | Proposed | Reactive waste rock | Wet | - |
| Brenda Mine | Peachland, British Columbia. | Historic | None | Wet | SW & GW |
| Brunswick No. 6 | Bathurst Area, New Brunswick. | Historic | Reactive waste rock & tailings | Wet | SW & GW |
| Heath Steele "A" | Bathurst Area, New Brunswick. | Proposed | Waste rock | Wet | SW & GW |
| Mattabi and "F" Group | Ignace, Ontario. | Historic | Waste rock & sludges | Wet | SW & GW |
| War Eagle | Whitehorse, Yukon. | Historic | Municipal waste | Wet | SW |
| Gibraltar | McLease Lake, British Columbia. | Inactive | No waste disposed in flooded pit | Wet | - |

Table 4.1 (Cont'd)

## LIST OF SITES IN CANADA

| Name of Site | Location | Status | Types of Wastes | Cover | Monitoring Data |
|---|---|---|---|---|---|
| Highland Valley Copper | Highland Valley Area, British Columbia. | Historic | No waste disposed in flooded pit | Wet | - |
| Similco Ingerbelle | Similkameen Area, British Columbia | Historic | No waste disposed in flooded pit | Wet | - |
| East Sullivan Mines | Val d'Or, Québec. | Historic | Flooded crown pillar | Wet | SW & GW |
| Crown Pillar | Ignace, Ontario. | Historic | Reactive mine tailings (AMD) | Combined | GW |
| Deilmann | Key Lake, Saskatchewan. | Active | Reactive waste rock & tailings | Combined | GW |
| Bell Mine | Babine Lake,<br>Newman Peninsula,<br>Saskatchewan. | Historic | Reactive waste rock & tailings | Combined | SW |
| Stratabound | Bathurst Area,<br>New Brunswick. | Historic | Reactive waste rock | Combined | SW & GW |
| Equity Silver | Houston,<br>British Columbia. | Historic | Waste rock | Combined | SW & GW |
| Nickel Plate South | Penticton Area,<br>British Columbia. | Historic | Waste rock | Combined | SW |
| Mount Washington | Vancouver Island,<br>British Columbia. | Historic | Waste rock | Dry | SW & GW |
| Faro Mine | Vangorda Creek-Anvil Area, Yukon. | Historic | Planned-tailings | Wet | SW & GW |
| Sturgeon Lake | Ignace, Ontario. | Historic | Waste rock | Wet | SW |

Table 4.2

## LIST OF SITES IN UNITED STATES

| Name of site | Location | Status | Types of Waste | Cover | Monitoring Data |
|---|---|---|---|---|---|
| Midnite Mine (pits 3 & 4) | Wellpinit, Washington. | Historic | Reactive waste rock & tailings | Wet | SW & GW |
| Nevada Precious Metal Mines | Nevada. | Historic | Reactive waste rock & tailings | Wet | GW |
| Robinson Mining (Veteran, Tripp, Liberty, Ruth & Kimbley pits) | White Pine, Nevada | Historic & proposed to reinitiate | Reactive waste rock & tailings | Wet | SW & GW |
| Berkeley | Butte, Montana. | Historic | Acid mine water from reactive waste rock, tailings & underground area | Combined | SW & GW |
| Iron Mountain Mine | Shasta, California | Historic | Acid mine water from reactive waste rock & tailings | Combined | SW & GW |
| Jackpile-Paguate | Albuquerque Area, New Mexico | Historic | Waste rock, overburden | Combined | SW |
| Placer Mining (Gold Mine) | Montana. | Active | Non-reactive waste rock and overburden | Dry | SW |
| Calaveras Asbestos Mine | Calaveras, California. | Historic | Asbestos fiber & tailings | Dry | SW & GW |
| Hecla Mining - Yellow Pine Gold Mine | McCall Area, Idaho | Historic | Non-reactive waste rock | Dry | None |
| Summitville Mine | Del Norte Area, Colorado | Historic/Active | Reactive waste rock & tailings | Dry | SW & GW |
| Coaltrain Corp. | Bakerstown & Pittsburgh, West Virginia | Active | Coal refuse | Dry | - |
| Bakerstown and Freeport | West Virginia | Active | Waste rock, overburden | Dry | SW & GW |
| Richmond Hill Mine | South Dakota | Active | Waste rock | Dry | GW |

Table 4.3

## CASE STUDY SITES[*]

| Case Study No. | Open Pit | Location | In-Pit Disposal Concept |
|---|---|---|---|
| 1 | OWL CREEK | Ontario | Underwater Disposal with Alkaline Blending |
| 2 | RABBIT LAKE | Saskatchewan | Underwater Disposal with Groundwater Barriers |
| 3 | COLLINS "B" | Saskatchewan | Underwater Disposal |
| 4 | ISLAND COPPER | British Columbia | Underwater Disposal |
| 5 | SOLBEC | Quebec | Underwater Disposal with a Top Barrier |
| 6 | UDDEN | Sweden | Underwater Disposal |
| 7 | STRATABOUND CNE | New Brunswick | Underwater Disposal with a Top Barrier |
| 8 | ROBINSON | Nevada, U.S.A. | No Waste Disposed - Flooded Pit Study |
| 9 | GUNNAR | Saskatchewan | No Waste Disposed - Flooded Pit Study |
| 10 | CLUFF "D" | Saskatchewan | No Waste Disposed - Flooded Pit Study |
| 11 | DEILMANN | Saskatchewan | Underwater Disposal with a Top Barrier |
| 12 | BERKELEY | Montana, U.S.A | No Waste Disposed - Flooded Pit Study |

[*] Detailed Case Studies of these sites are included in Volume 2 of this report.

situation within the Canadian context. Preference was given to historic sites where the flooded pit concept had been used. The selected sites are geographically distributed across Canada and represent several types of mines (ore) and reactive wastes. Two American sites were included as examples of a state-of-the-art approach to predicting pit water quality (Robinson Project), and an example of a serious AMD situation (Berkeley pit).

The detailed case studies are included in Volume 2 of this report. The geographic locations of the 12 case study sites are shown in Figure 4.1. It is recommended that the reader refer to the individual case studies after reading this chapter.

The project database includes information about the disposal of waste rock in a crown pillar lake (East Sullivan); flooded pits receiving drainage from adjacent waste rock piles (i.e. Midnite Mine, and Brunswick Nº. 6); and pit lakes (i.e. Cluff "D", Gunnar, Berkeley, Brenda, etc.). The discussion of key findings at each of these sites has been organized according to the main disposal concept (i.e. flooded pit, elevated water table, dry disposal) and is presented below.

## 4.1 UNDERWATER DISPOSAL (PIT LAKES)

Disposal of mine wastes in flooded pits is the most common pit disposal method.

Macdonald (1992) presents an in-depth review of the factors contributing to the water quality of pit lakes:

- **Groundwater Flow** - initial and final water table elevation, depth and flow rates of aquifers, direction of flow, groundwater recharge or discharge area.

- **Water - Wallrock Reactions** - area of wallrock exposed to water, permeability of wallrock, stability of submerged pit slopes, flow in fractures (provides additional mineral surface area for reaction), sloughing of pit walls.

- **Acid Versus Alkaline Pit Water** - geology of wallrocks, presence or absence of oxygen, bacteria-accelerated sulphide oxidation, sulphide

FIGURE 4.1

## GEOGRAPHICAL LOCATION OF CASE STUDY SITES

1 OWL CREEK
2 RABBIT LAKE
3 COLLINS "B"
4 ISLAND COPPER
5 SOLBEC
6 UDDEN
7 STRATABOUND
8 ROBINSON
9 GUNNAR
10 CLUFF 'D'
11 DEILMANN
12 BERKELEY

oxidation by ferric ion, acid-neutralizing minerals, inflowing alkaline groundwaters, bacterial sulphate reduction and precipitation of metal sulphides.

- **Trace Elements** - equilibrium with solid phase, potential complexes, complexing agents, adsorption substrates (clays, organic matter, iron/manganese/aluminum/silicon hydrous oxides), Eh/pH conditions, microbial uptake and bioprecipitation.

- **Metal Speciation** - mineral precipitation/dissolution, solution composition, adsorption/desorption, ion exchange, competing and complexing ions, chemical transformations, biologic activity, pH/Eh, aquifer mineralogy, reaction kinetics.

- **Evapoconcentration** - vapour pressure above water surface, temperature, wind speed, wind shear, atmospheric stability, geometry of drainage basins, local climate averages, water balance in pit, geochemistry of pit waters.

- **Hydrothermal Activity** - temperature and stratification affect mixing and water quality, geothermal gradients, groundwater temperature, hydrothermal springs and gas fumaroles, dissolved solids/salts/nutrients/metals, temperature of maximum density (4°C at 1 atm).

The characteristics of pit lakes discussed by Macdonald (1992) and others (e.g. Morin, 1990; Patterson, 1990; Stevens et al., 1994), are summarized in the following sections by type of mine.

### 4.1.1 Phosphate Mines

Phosphate mine pit lakes in the state of Florida are productive and support large populations of game fish. Studies in phosphate mine pit lakes have shown that the top benches of the mine should be left to provide appropriate (shallow) littoral areas in the future pit lake (Macdonald, 1992).

### 4.1.2 Uranium Mines

Uranium mine pit lakes in New Mexico (e.g. Jackpile-Paguate), Dakota, South Texas, Washington and Australia (e.g. Nabarlek in Northern Territory, Whites Pit at Rum Jungle Mine) are generally slightly contaminated with trace metals, radionuclides and suspended solids. Concerns about radiation promote covering of wastes and backfilling of pits. Three uranium mine pit lakes in Canada (Gunnar, Cluff "D", Collins "B") show development of stratification expected in colder climates.

#### Rum Jungle Mine, Australia

The three pits at Rum Jungle Mine (Dysons', Whites', Intermediate) originally contained acidic waters, and have been reclaimed using different methods. Tailings disposed in the bottom of the Dysons' pit were sloped and covered with a geotextile fabric and 1 m thick rock blanket to divert groundwater and seepage; heap leach materials and contaminated soils were placed above the rock blanket and above the water level in the pit. These wastes were covered with a geotextile sealing layer, a moisture retention layer and another sealing layer (Macdonald, 1992). This pit illustrates a combined (wet/dry) approach to disposal of wastes in open pits.

The waters in the Whites' and Intermediate pit lakes were treated (neutralized) *in situ* to raise the pH and precipitate metals. The water in the Whites' pit was also pumped through the treatment plant and returned to the pit; stratification occurred due to separation of the treated and untreated waters in the pit. The Intermediate pit was treated *in situ* by lime addition and aerated to promote mixing; metal hydroxide precipitates were allowed to settle and were pumped from the bottom of the pit to the treatment plant for disposal with the treatment plant sludges in a landfill (Macdonald, 1992).

### Jackpile - Paguate, New Mexico

The Jackpile-Paguate uranium mine is located on the Laguna Indian Reservation, 64 km west of Albuquerque, New Mexico. The mine was operated by the Anaconda Minerals Company continuously from 1953 through early 1982. Mining operations were conducted from three open pits and nine underground mines. Following shutdown of operations, a reclamation plan was developed for the mine site facilities (U.S. Department of the Interior, 1986). Reclamation activities are currently underway (Lucero, 1994).

The Jackpile, North Paguate and South Paguate open pits make up about 40 percent of the 1,075 ha of natural ground disturbed at the site. The depth of the pits vary due to irregular topography from 190 m at Jackpile to 61 m at North Paguate to 99 m at South Paguate. Approximately 92 million tonnes of backfill, composed principally of associated waste with some overburden, was returned to the pits at shutdown.

The Jackpile deposit was in a major sandstone bedrock aquifer; significant ground water seepage into the pits was encountered during excavation, and once mining ceased major ponds formed in each of the pits.

Several decommissioning alternatives were proposed which involved backfilling the pits with waste materials. The options differed mainly in the extent to which the pits would be backfilled and as to whether the pits would be left as closed basins or opened to restore natural overland flow.

For the alternatives involving backfilling above the ground water recovery level, it was assessed that the increased contact time of ground water with the oxidized and broken waste material to be used as backfill would initially increase the total dissolved solids, heavy metal, and radionuclide concentrations. In the long term, it was anticipated that the reclaimed pits would revert to a chemically reducing condition and that the contaminant levels would significantly decrease (U.S. Department of the Interior, 1986).

Water samples collected from the pits in 1982 and again in 1986 indicate that the quality is poor. The samples collected in 1982 showed TDS values from 900 to 3,300 mg/L, sulphate values from 540 to 2,270 mg/L, and a pH range of 6.9 to 8.4. The samples taken in 1986 were found to contain TDS levels of 1,800 to 5,920 mg/L, sulphate levels of 924 to 3,888 mg/L and radium-226 levels of 16.1 to 36 pCi/L. The increase noted in the TDS and sulphate levels in the ponds between 1982 and 1986 was attributed to evaporative concentration of pond waters.

<u>Midnite Mine, Washington State</u>

The Midnite uranium mine is located in northeastern Washington State; mining occurred at this site between 1955 and 1965 and then again in 1969 to 1981. During the mining period six pits or subpits were opened. Four of these have subsequently been backfilled with overburden while two pits (pits 3 and 4) were left open. Pit 3 contains approximately 1.6 million $m^3$ of water and there is approximately 0.72 million $m^3$ of water in pit 4. Oxidation of sulphide-containing minerals, primarily pyrite, in the ore body produces large quantities of acidic water. The water in pit 3 is from precipitation, groundwater flow, overland flow and pumpback of water from the pollution control pond. The water quality in this pit exceeds water quality standards. It has been suggested to dewater pit 4 and use it as a permanent disposal site for reactive rock. To help investigate the feasibility of this alternative a study was undertaken to characterize the waste. Grab samples were taken from various ore piles and waste rock piles; the preliminary tests revealed that the low-grade ore is reactive and requires isolation from ground and surface waters (Altringer and Froisland, 1993).

Different methods have been used to determine the hydrogeology of the pits. A site model was developed to describe the flow path (Marcy et al., 1994). The model was developed using the WATEQ4F model (Ball and Nordstorm, 1991) to identify aqueous species distribution and to calculate potential solid phase controls of solubility. Another model, BALANCE (Parkhurst et al., 1982), was used to assist in the interpretation of the changes in the water quality between the sampling locations. This geochemical modelling shows that the concentrations in pit 3 have increased significantly, and will affect any subsequent water entering the pit. The hydraulic connection between pits 3 and 4 was also investigated; the flow path model indicates that this situation is probable although would only contribute a small amount. Williams and Riley (1993) used data from monitoring wells at various locations and suggested that there is an interaction between pit 4 and the groundwater and that it would refill after dewatering. It was also proposed that pit 3 would recharge with a mixture of poor and good quality water and would again be above the set standards.

Environment Canada personnel sampled the Lower or Southern pit at Midnite Mine in 1992. Stevens et al. (1994) report that *"seepage from this pit is collected downslope and pumped back. This recycling of waters and high evaporation in this drybelt area concentrates pit waters, which in turn precipitate a gelatinous aluminum hydroxide. Note that mixing seems independent of high salt concentrations".* (See Appendix 1, Table 5A-5C for pit water quality data).

### Gunnar, Cluff "D", Collins "B", Saskatchewan

Three case studies of flooded uranium mine open pits are provided in Volume 2 of this report. All are located in northern Saskatchewan, one on the north shore of Lake Athabasca (Gunnar pit), one south of Lake Athabasca, (Cluff "D" pit), and one beside Collins Bay of Wollaston Lake (Collins "B" pit). In each case the pits were filled rapidly as a result of the diversion of surface waters. The Gunnar pit was filled to a depth of 110 m in 1964/65 with Lake Athabasca water while the Cluff "D" pit was flooded to a depth of 21.5 m with flow from Boulder Creek in 1983. The Collins "B" pit was flooded in 1992 by pumping water from Collins Bay.

Water quality surveys in the two older flooded pits (Cluff "D" and Gunnar) show that the pit water columns have become chemically stratified in both cases. The bottom waters contained the highest concentrations of most elements, particularly the major cations and anions of the trace elements. Uranium and radium-226 levels in particular were found to be elevated above background levels in both pits. Most of the non-radioactive trace elements measured were not found to be present in high concentrations with the exception of arsenic. When compared to the quality of seepage from waste rock, the flooded pit surface water at Gunnar was found to contain lower levels of most elements (radioactive and non-radioactive). Neither flooded pit was found to have an impact on adjacent surface water bodies, principally because there was no identifiable source of discharge from either pit.

The Collins "B" pit receives contaminated seepages from nearby surface waste rock piles, and contains waste rock, special waste placed under a till cover and mineralized zones exposed on the pit walls. Water quality analyses show metals, radionuclides and solids concentrate near the bottom of the pit. Levels of arsenic, nickel, uranium and radium-226 do not meet provincial objectives for protection of aquatic life. The effect of breaching the dyke between the pit and Collins Bay was investigated by modelling (SENES, 1995); this would result in lower contaminant levels but some provincial guidelines would not be met. A 5-year monitoring period was proposed to review conditions and develop new target levels (Cameco, 1990).

Deilmann Pit, Saskatchewan

The Deilmann orebody at Key Lake Mine is being mined by open-pit methods. Cameco Corporation (1994) evaluated the use of the Deilmann pit for future disposal of tailings. The proposed concept is described in Case Study 11, and is similar to that currently employed at Rabbit Lake (Case Study 2) which involves deposition of tailings within a pervious surround.

### 4.1.3 Surface Coal Mines

Coal mine pit lakes in Montana and Missouri showed both thermally stratified and non-stratified conditions. Turbidity caused by precipitation of ferric oxides was found to affect the heat budget in a pit lake (i.e. absorbs heat leading to thermal stratification). Acidified coal strip mine lakes were reported to progress through a series of stages in which the levels of AMD related contaminants are gradually reduced by sulphate reducing bacteria. Added organic matter (e.g. sewage sludge) greatly accelerated the recovery process. Weathering of clay minerals, feldspars and carbonates provided pH buffering required to sustain this process (Macdonald 1992).

### 4.1.4 Copper Mines

Copper mine pit lakes are located in:

- Montana, e.g. Berkeley pit;
- Nevada, e.g. three pits at the Ruth Mine (Liberty, Ruth, and Kimberly pits), and Yerington pit;
- British Columbia, e.g. Brenda Mine pit, Bell Mine pit, and Island Copper, and;
- Yukon Territory, e.g. War Eagle pit.

These pits show a range of water quality and illustrate the importance of geology and wallrock geochemistry. The Berkeley pit is highly acidic and shows chemical stratification with depth (see Case Study 12). The three pit lakes in the Robinson District, show different behaviour (see Case Study 8): Liberty pit is acidic (pH 2.96); Ruth pit was originally acidic (pH 3.23) but has become neutral (pH 8) due to addition of cyanide tailings; and Kimberly pit is not acidic (pH 7.59). The Yerington pit is neutral (pH 8) and the copper is present as a copper silicate rather than a copper sulphide. The Brenda pit lake is also neutral (pH 7.3), however molybdenum concentrations are elevated.

#### Brenda Mine, British Columbia

The Brenda Mine produced 109 million tonnes of waste rock containing approximately 0.10% copper as chalcopyrite and 0.015% molybdenum as molybdenite, stored in four rock piles around the pit. Acid drainage is not a problem with the low grade waste rock; however, the alkaline nature of the rock results in dissolution and release of low concentrations of molybdenum.

The pit was filled by pumping 12 million $m^3$ of process water from the tailings basin, when the mine closed. The pit receives approximately 2.5 million $m^3$ per year of rock pile water which is collected in the tailings area and pumped to the pit. Natural runoff is estimated as 0.3 million $m^3$ per year. The pit currently contains 21 million $m^3$ of water at a maximum depth of 150 m. The current level of molybdenum in the pit water is 2.0 mg/L (Bradburn and Perkins, 1995).

The mine has diverted as much fresh water as possible from the site using a system of ditches. The pit is expected to fill within 10 years and overflow via two watersheds to Okanagan Lake. The closure plan for the site addresses three options for long-term water management. It will be very difficult for the mine to meet water quality objectives for molybdenum (irrigation objectives <0.010 ppm). They are investigating several treatment technologies to reduce molybdenum levels and managing water releases with seasonal creek flows to provide adequate dilution (Bradburn and Perkins, 1995).

Safety and stability are major concerns for decommissioning as a modified land use proposal identifies this site as a possible location for a limited industrial park development. Bradburn and Perkins (1995) report that the pit slopes will be left in their existing condition as they are composed of granodiorite rock that is geotechnically competent and does not exhibit slaking characteristics. Perimeter and access restriction at the pit will consist of a 2 m berm supplemented by a ditch. The berms will not be revegetated so that it will be obvious that they are part of an engineered barrier. Warning signs will be posted at 50 m intervals.

The Brenda pit has similar dimensions to the Berkeley pit (Case Study 12); however the stratification observed at Berkeley pit results from dissolved salts whereas the stratification in Brenda pit appears to be related to temperature (Stevens et al., 1994). The Brenda Mine has been collecting monthly data since mid-1992 which includes chemical analyses and temperature and dissolved oxygen measurements at 5 to 15 m intervals. This water quality data is summarized by Stevens et al. (1994) who carried out thermal modelling for this site. (See Appendix 1, Tables 1A-1G for data).

### <u>Bell Mine, British Columbia</u>

The Bell Mine open pit copper mine commenced operations in 1970. The pit development rock was used to construct tailings pond dams or placed in four rock dumps. The mine closed temporarily from 1982 to 1985, was reopened, and operated until 1992. At that time, elevated copper levels were noted in effluents from areas where development rock had been placed. The Bell Mine Closure Team was assembled to address the potential for acid generation and develop a closure plan that would address the following key issues:

- understanding rock and tailings mineralogy and geochemistry;
- prediction of interim and long-term water chemistry;
- assessment of historical and existing environmental conditions;
- public safety, long-term stability of structures and land rehabilitation;
- management after closure; and
- impact of post closure discharges on local environment.

Studies determined that net acidic conditions in mine rock, that was not presently acid generating, may not occur for up to 30 years. Their water management plan is to redirect runoff flows containing elevated metal levels which are unacceptable for safe release into Babine Lake, into the open pit. The maximum water storage capacity is 48 million $m^3$, and the pit is expected to fill to capacity by the year 2050. A lime neutralization treatment plant would be constructed 3 years prior to attaining maximum storage capacity of the pit. Pit waters would be treated and discharged annually. The pit water is predicted to reach a steady-state pH value of 2.7 and an acidity of 2,200 mg $CaCO_3$/L by the year 2060, and to recover slowly over the long term (several centuries) (McArthur and Gallinger, 1994).

<u>Other Copper Mines</u>

The Island Copper pit is described in Case Study 4. The report by Stevens et al. (1994) also contains an appendix summarizing water quality data and other measurements (dissolved oxygen, temperature conductivity, redox potential) taken in 1982, 1992 and 1993 by Environment Canada personnel for six other water filled pits in British Columbia, Yukon Territory and Washington State. (The data are provided in Appendix 1 of this report). Four of these six pits are copper mines and are described below:

- *"Gibraltar West pit: The large Gibraltar copper mine, 38,000 tpd at full capacity, first opened in 1972 and mined several pits on the property before closing temporarily in the fall of 1993. Water in the small west pit shows no evidence of the oxidation and increased metals content shown by waste rock and waters elsewhere on the property, from which the company obtains anode copper by leaching and solvent extraction (SX/EW)."* (Stevens et al., 1994) (see Appendix 1, Table 3A-3C).

- *"War Eagle pit: New Imperial Mines (Whitehorse Copper Mines Ltd.) mined the small War Eagle pit near Whitehorse, Yukon, between 1969 and 1971. Until the early 1980's the city then used the pit area and ramp for disposal of municipal waste. Pit water reflect this runoff contamination in elevated chloride and ammonia. The limited data shows the absence of oxygen, the decrease in nitrate, and the increase in ammonia at depth, which suggests meromixis conditions."* (Stevens et al., 1994), (see Appendix 1, Table 4A-4D).

- *Highland Valley Copper: This is Canada's largest metal mine. It has assembled three adjacent mining properties which have produced copper-molybdenum ore since 1963. The largest pit, Highmont West, was mined between 1980 and 1983 and has filled from runoff since that date. Water quality resembles that at Brenda and Similco, except for elevated molybdenum."* (Stevens et al. 1994), (see Appendix 1, Table 6A-6C).

- *"Similco-Ingerbelle: Similco Mines Ltd. mined the Ingerbelle pit beginning in 1972, and has allowed it to fill from runoff since 1984. Pit size and water quality resemble those found at Brenda and Highland Valley Copper."* (Stevens et al., 1994), (see Appendix 1, Table 7A-7C).

### 4.1.5 Silver Mines

Open pits at the Equity Silver Mine in British Columbia (Southern Tail pit and Main pit) provide an example of backfilling with buffering material to ameliorate acidic conditions in a flooded pit. The Southern Tail Pit lake was initially neutral, then pH started to decrease to 3 by mid-1985. In October 1985, the Southern Tail pit was backfilled with material from the Main Zone pit. The pit was backfilled to a level that was 1 m below the projected flood level. Then 2 m of inert non-acid producing waste was placed as a buffer zone. This was followed by additional backfill material (Patterson, 1990). During the backfilling, the pH of the pit water increased from pH 3 to 6 within a few months, then dropped again to below pH 3.4, but increased to pH 7 by the end of backfilling in 1987. The initial pH increase is attributed to neutralizing minerals in the backfill. The pH decrease to 3.4 is attributed to a combination of flushing of stored acid products and decreasing flow of alkaline groundwater into the pit (Morin, 1990). The pH has varied from 7 to >8 from 1987 to 1990. Iron concentrations have decreased due to precipitation of iron hydroxide; copper and zinc concentrations have decreased presumably due to adsorption on the iron hydroxide precipitates. The mined-out Main Zone pit will also be backfilled and flooded and a dam will be constructed at the pit entrance to raise the water level above a section of wallrock that has been identified as being acid generating (Macdonald, 1992).

### 4.1.6 Gold Mines

Open pit lakes in British Columbia (e.g. Nickel Plate) and Nevada (e.g. Cortez Gold) contain neutral waters. Both pits are 20 to 30 m deep. The Cortez pit supports a full food chain that sustains fish (bass) introduced in the early 1980's. (Macdonald, 1992).

Environment Canada personnel sampled the pit water at Nickel Plate South pit in 1991. (Appendix 1, Table 2A-2C). Since that time, the pit has been backfilled with waste rock (Stevens et al., 1994).

### 4.1.7 Base Metal Mines

Base metal mine pit lakes are located in Ontario (e.g. Mattabi), Québec (e.g. Solbec, and a flooded crown pillar at East Sullivan), New Brunswick (e.g. Heath Steele, Stratabound CNE, Brunswick №. 6) and Newfoundland (e.g. Lucky Strike Glory Hole, Oriental West Pit and Oriental East Pit - all at Buchans Mine).

## Mattabi F-Group Open Pit, Mattabi Mine, Ignace, Ontario

The copper/lead/zinc F-Group open pit mine at Mattabi Mine was operated intermittently between 1980 and 1984. The pit has a total volume of 910,000 m$^3$, a maximum depth of 50 m, and an area of approximately 3.5 ha. About 600,000 tonnes of ore and 800,000 tonnes of waste rock were removed during production. The waste rock is stored adjacent to the pit and is acid generating. The seepage drains into the pit, along with surface drainage from the area. At intervals, the pit water is pumped approximately 5 km to the Mattabi pit for storage and subsequent treatment.

In 1991/93, a laboratory investigation was conducted at Noranda Technology Centre to determine if in-pit passive treatment by sulphate-reducing bacteria (SRB) was feasible (NTC, 1993). The concept examined was the utilization of SRB to generate hydrogen sulphide which would precipitate heavy metals as insoluble sulphides. Test work conducted in 5-L continuous reactors, 280-L drum and a 160-L column reactor established the appropriate conditions and organic feed to favour the SRB reactions. It was concluded that the system was not suitable for the high metal concentrations in the F-Group pit (e.g. 350 mg/L Zn, 160 mg/L Fe), due both to high costs and the engineering difficulties of ensuring uniform flow through the massive organic substrate required. However, the passive SRB system investigated by NTC might be suitable for in-pit treatment of low load situations (St. Arnaud, 1995).

## Mattabi Crown Pillar Pit, Ignace, Ontario

The Crown Pillar pit is 300 m long, 180 m wide and 25 m deep. The pit is surrounded by bentonite dykes to prevent infiltration of acidic drainage from tailings stored on adjacent land. The pit is currently filled with water, is meromictic (i.e. stratified), and has been investigated as a site for subaqueous disposal of acid-generating metal mine tailings. The water column is separated into distinct layers: the first two metres of surface water are well-mixed; the second layer (thermocline) from 2 to 8 m shows sharp temperature decline from 9°C to 4°C; and the bottom layer (hypolimnion) is characterized by relatively constant temperature, higher conductivity (i.e. higher level of dissolved chemical species), and a decrease in oxygen levels. The upper region, mixed surface layer and thermocline, contain an essentially constant concentration of oxygen with a maximum at the start of the thermocline; this behaviour is called "positive heterograde" and results from oxygen saturation due to intense productivity of blue-green algae. The main assumption of sub-aqueous disposal of tailings is that the hypolimnion layer remains stable. Infiltration of oxygen is a concern at this site, although the oxygen levels would be expected to be lower during the winter (i.e. when algae inactive). (Brassard and Mudroch, n.d.).

### Nº. 6 Open Pit Mine, Bathurst, New Brunswick

Between 1966 and 1983, Brunswick Mining and Smelting Corporation extracted a total of 12,125,000 tonnes of lead/zinc/copper ore from the Nº. 6 open pit. Following cessation of mining, the pit was used as a storage pond for both lime-treated and untreated seepage from the adjacent waste rock dumps, as well as surface runoff and precipitation. Also, a limited volume of high pyrite waste rock was dumped into the pit. The total volume of the pit is about 8,500,000 $m^3$, and it was estimated that it would be filled by 1999.

Monitoring programs were established in 1988 to continuously evaluate the effect of the gradual flooding of the pit on local surface and groundwater. By 1991, some elevations in heavy metal levels and acidity were detected in adjacent groundwater. It was decided to continue to use the pit to collect local contaminated surface drainage, and to pump the pit water at intervals to the nearby Nº. 12 Mine for treatment (St. Arnaud, 1995).

### Heath Steele Mines, New Brunswick

The Heath Steele Mine, owned by Noranda, continues to operate at intervals. As part of the closure strategy, the feasibility of in-place treatment of acidic water in A-pit and Nº. 4 Shaft (450,000 $m^3$ of acidic water containing Cu, Pb and Zn) was investigated. A laboratory-scale simulation (Payant, 1990a,b) investigated the feasibility of using a continuous in-line circulating lime treatment system to treat the pit water and utilize the bottom of the shaft as a sludge settling area. The pit was dewatered and the concept has not been implemented (St. Arnaud, 1995).

### Buchans Mine, Buchans, Newfoundland

At the Buchans Mine, the effectiveness of biological treatment of metal-rich acidic leachate has been evaluated in two small open pits containing 208,000 $m^3$ and 66,200 $m^3$ of contaminated leachate. In an on-going study initiated in 1989 (Kalin, 1992), different organic amendments were tested as suitable carbon and nutrient sources. The initial studies which treated a total of 43 $m^3$ showed significant improvements in water quality. The second phase utilized leachate volumes of 759 $m^3$ and 390 $m^3$ (Kalin, 1992). Although no direct evidence was presented, the results suggested that biological processes were responsible for metal removal.

### East Sullivan Crown Pillar Pit

A comprehensive plan was developed by the Québec, Ministère des ressources naturelles, Service du développement minier, to relocate approximately 200,000 $m^3$ of reactive wastes into a 280 m deep crown pillar pit located at the historic East Sullivan mine site near Val d'Or, Québec. Advantages predicted included: the inhibition of acid production; ease of controlling water quality (acidity) in the water-filled crown pillar pit; and a relatively low cost, in the range of $350,000. Available information includes waste characterization and relocation studies. The work was completed in 1994, and information is available from Ministère des ressources naturelles.

## 4.2 ELEVATED WATER TABLE

A few selected examples where pit lakes had been backfilled with wastes (i.e. Dysons' pit at Rum Jungle, and Southern Tail pit at Equity Silver) were provided in the previous section. Some other examples of an elevated water table within backfilled wastes are discussed in this section.

### Iron Mountain Mine, Shasta County, California

The Iron Mountain Mine consists of two massive sulphide deposits, the Richmond and

Hornet, which were mined for gold/silver/copper/zinc by underground methods, and the pyrite-rich Brick Flat deposit which was mined for pyrite by open-pit methods from 1950 to 1962. The AMD at Iron Mountain Mine is among the most acidic ever reported because the massive sulphide deposits have remained unsaturated. Analyses of underground seepage samples collected in 1990 show pH values less than minus 1.5, dissolved sulphate concentrations as high as 760 g/L, dissolved iron concentrations of 141 g/L, zinc at 24 g/L (Nordstrom and Alpers, 1990). As part of a remedial action mandated by the U.S. EPA in 1985/86, the Brick Flat pit was equipped with a liner and used for disposal of pyritic tailings. The Richmond Adit and the Lawson Tunnel at elevations of 2,600 and 2,200 feet above sea level, act as drains for the AMD produced within the Richmond and Hornet deposits, respectively. Future plans for remediation of this site include preparation of the Brick Flat pit for disposal of high-density sludge from the Richmond and Lawson portals (Alpers et al., 1994).

### Lichtenberg Pit Thurigia, Germany

*"The Ronneburg Mining region in east Thüringia (former East Germany) produced over 170 million m$^3$ of waste rock, all of which is potentially acid generating. At present, over 100 million m$^3$ of waste rock are stored on surface in numerous waste piles. One pile was subjected to in situ uranium leaching using mine water supplemented with sulphuric acid... As with most of the waste piles in south eastern Germany, the waste piles are located close to villages and individual homes (within several hundred metres). In addition to the understandable concerns about environmental radioactivity, particularly radon emissions, there are concerns about contamination of surface waters and groundwater, and physical access to the materials... Mining ceased at Ronneburg in December 1991, and the lower levels of the underground mines are now being allowed to flood."* (Feasby et al., 1994).

One of the Ronneburg mines, the Lichtenberg pit has a surface area of 160 ha and had a depth of 240 m at the southern end. Some mining wastes have already been backfilled into the bottom and onto the side (balcony) of the pit, the remaining volume is approximately 84 million m$^3$ (BMWi, 1993).

*"Current plans (Wismut, 1992) are to fill the open pit with as much waste rock as possible. The most severe acid producing materials would be placed on the pit bottom; but about 30 million* $m^3$ *will remain above the water table. The final contouring and cover applied to these materials will be important factors in determining long-term acid production. Excess alkalinity, for example lime and/or limestone is being considered to help control acid generation, and studies were recently completed to determine the effect of submerging most of the waste rock under the water table in the open pit.*

*Until the mine workings are completely flooded, acidic seepages will continue to be produced from oxidation of sulphide minerals in open spaces and fractured zones underground. In addition, in the long term after flooding, acid will continue to be produced in the fractured ground above the water table."* (Feasby et al., 1994).

## 4.3 DRY DISPOSAL

This section describes sites where dry disposal of wastes in pits has been used or proposed. There is only one case study for dry disposal, at the Stratabound CNE pit in New Brunswick (Case Study 7).

### Bakerstown/Upper Freeport Coal Seams, Taylor and Preston Counties, West Virginia

Since mining of the upper Freeport coal seam ceased in the 1950's acidic seepage from the abandoned underground workings has been responsible for degrading the water quality of the Mountain Run stream (Skousen and Larew, 1994). In order to remediate the site Coaltrain Corp. commenced an operation of remining the near-surface coal remnants followed by the placement of acid consuming local material into the now-open pits. Alkaline shale overburden excavated from the Bakerstown operation, located within a distance of 1 km, was considered a cost efficient source of acid consuming material.

Removal of the coal from the slopes and placement of the acid consuming material onto the floor of the open pits occurred simultaneously. Several layers of alkaline shale were interlayered with acid generating overburden removed during mining. After completion of the backfilling operation, each pit was capped with a mixed layer of topsoil and alkaline shale. The alkaline shale was applied at a rate of 15,000 tonnes per hectare. Although the seepage from this site currently maintains a pH of 7.0, the Mountain Run stream continues to receive acidic leachate from other abandoned mining operations located in the area.

### Calaveras Asbestos Mine, Calaveras County, California, USA

Prior to mine closure in 1987, the Calaveras Mine was the largest open pit asbestos mine in the United States producing 35,000 tons of asbestos per year (Calaveras County Planning Department, 1989a, b, c). Calaveras Asbestos Ltd. proposed that the open pit be converted into a landfill for asbestos waste generated primarily by demolition and asbestos removal projects. With a landfill capacity of 12.2 million cubic metres, the projected life of the operation was estimated at more than 100 years. The proposal was accepted and the facility is now operated as an asbestos landfill.

Water is applied over the asbestos wastes by sprinklers to minimize airborne emissions. Once the pit is filled, a cover consisting of a 0.6 m lower layer of natural material will be overlain by 0.3 m of clay with a saturated hydraulic conductivity of less than $1 \times 10^{-6}$ cm/sec, topped by 0.3 m of topsoil. Measures will be taken to minimize the release of asbestos fibres into surface water and ground water.

### A-8 Open Pit Uranium Mine, Gas Hills, Wyoming

The A-8 open pit uranium mine was abandoned in the early 1970's. The pit measured approximately 600 m by 140 m by 50 m deep. After considering three possible options, partial backfilling allowing for exterior drainage out of the pit was selected by AML (Abandoned Mine Lands Program) as the most appropriate approach. Approximately 2.6 million cubic metres of backfill was required.

Richmond Hill Mine, South Dakota

Open pit disposal is being considered by the South Dakota Department of Environment and Natural Resources for the safe disposal of approximately 2,500,000 tonnes of acid producing waste rock (Durkin, 1995). The pit will be filled by waste rock up to within 2 m of the pit surface. The wastes will be capped by a 2 m thick cover consisting of a 15 cm layer of crushed limestone placed immediately over the waste which will be overlain by 0.6 m of compacted manufactured soil, followed by a root zone of 1.2 m to provide a thermal protection and drainage layer, and a 15 cm surface layer of top soil.

In addition to continuous long-term monitoring, periodic remedial maintenance such as cap reconstruction, erosion damage repair, etc. will likely be required.

Uranium Mines in Western North Dakota

*"Between 1955 and 1967, approximately 590,000 lb of uranium oxide were recovered from 95,000 tons of lignite in at least 16 pits in western North Dakota. The overburden was stripped, and the lignite was burned in pit bottoms or nearby kilns to concentrate the uranium in its ash by a factor of about 10. Because uranium salts in the overburden generally were not recovered during mining, spoils piles at abandoned mine sites have surface gamma-ray exposure levels as high as 500 microroentgens/hr, approximately 30 times local background levels. Infiltrating water leaches piles and residual ash and introduces U and associated elements such as Ra, As, Mo, and Se to water in the lignite aquifers or exposed in the pits. Aquifer and pit water have U concentrations ranging from 12 to 19,000 mg/L and accompanying 226-Ra concentrations ranging from 1 to 360 picoCuries/L. Groundwater in mine areas also commonly contains concentrations of As, Cd, Mn, and Hg in excess of Federal drinking water standards. A pilot reclamation project was implemented at one abandoned pit 6 miles* (10 km) *northwest of Belfield, ND, during the summer of 1985. Basically, the reclamation involved the selective placement of spoils into the pit from which they had been removed. Replaced spoils of high radioactivity and specific conductance also were capped with clay from the base of the pit, and the surface topography was mounded to minimize infiltration that might introduce radioactive and other soluble salts into the aquifer. A minimum of 4*

*ft* (1.2 m) *or less contaminated spoils and topsoil were spread above the clay cap to minimize post-reclamation surface-radiation levels. Similarly, spoils with specific conductances >5,000 microSiemens/cm were replaced at least 8 ft* (2.4 m) *below the post-reclamation land surface but above the water table to prevent the movement of dissolved solids to the aquifer."* (Houghton et al., 1988).

Mt. Washington, British Columbia

Mt. Washington is a copper mine, located on Vancouver Island. Mining occurred at this site from 1964 to 1967, during which time, two pits were mined. Approximately 392 000 tons of 1.16% Cu ore was milled and rock and tailings were generally placed in two main dumps. In the 1970's, a decline in the fish population in the Tsolum River was attributed to the production of acid and subsequent leaching of copper and other heavy metals from mine wastes at this site. A reclamation program was put in place. In 1987, piles of mine waste were collected, and placed over the dumps and a glacial till blanket was placed over the pile. A diversion ditch between the pit and the dumps was also constructed (Galbraith, 1990). It was later confirmed that the major contribution of copper to the river system was originating from the pit.

Further reclamation efforts were conducted to reduce the contribution of contaminants from the pit to the downstream waters. In 1991 a study was undertaken to investigate the encapsulation of excavated waste and neutralization of wastes using calcium hydroxide and limestone. Bedrock cleaning and experimental capping activities were completed and preliminary results looked promising. Geotextile, and asphalt emulsion covers had been found to be an effective, and relatively inexpensive waterproof sheet. In 1992, it was proposed to implement a geotextile cover on the pit floor, and to continue monitoring and biologically treat the seepage from under the cover (Galbraith and Chaudry, 1992). Another alternative suggested was neutralization in place or downstream (Rennie, 1992); this required contacting a calcium hydroxide slurry with all acid producing materials, a downstream lime treatment plant, or direct addition of a lime slurry to neutralize acidic waters collecting in Pyrrhotite Lake. The final solution for Mount Washington remains unsolved.

# 5.0 DISCUSSION OF FINDINGS

## 5.1 KEY FINDINGS

The key findings from this study are summarized below.

- Pit disposal of reactive waste is becoming a common practice. Examples of recent disposal or proposed disposal of reactive wastes were identified at numerous minesites.

- Not all pits are suited for waste disposal. Site-specific condition will dictate the suitability of pit disposal and the need for engineered controls.

- There are several examples of where pit disposal has resulted in environmental improvements. Two recently completed projects (Owl Creek pit, Collins "B" pit) are examples of how acid generation and/or contaminant leaching problems (from surface waste rock piles) can be controlled through underwater deposition in a pit.

- The technology for pit disposal is reasonably well-developed. The geochemistry, hydrogeology etc. can be determined, and models to assess contaminant release and transport are well developed. The design of engineering controls for pit disposal can be reasonably assessed.

- The major deficiency in the database is monitoring data. Although there are many examples of pit disposal, few sites (other than pit lakes) have been monitored in detail.

- The geology, hydrogeology and climate of the site (i.e. elevation of water table) dictate which, cover (wet or dry) will likely be used; wet cover (i.e. pit lakes) are most common in Canada and Sweden while dry disposal is more common in the United States.

- It is expected that pit disposal will increasingly be considered as a means of preventing or controlling acidic drainage from reactive wastes. Persons considering pit disposal of mine wastes should be aware that the development of a pit disposal program requires thorough consideration of related issues including, but certainly not limited to: environmental benefits and risks; the concerns of other stakeholders; regulatory requirements; criteria (and monitoring data) that would later be used to measure the performance of the pit disposal program over the short term and the long term; and contingency measures.

  The preparation of a pit disposal program would as a matter of course include the development of a closure strategy for the pit, and related closure objectives. As with any scientifically based closure strategy, a pit disposal plan must be supported by technical data and studies (i.e. waste characterization studies, hydrogeological and hydrological studies, predictive modelling, biological studies, etc.) and be defensible. Uncertainties and risks need to be considered in the comparison of closure options. The nature and extent of technical studies required will vary from pit to pit. As a guide, the following subsection indicates basic technical data requirements.

## 5.2 DATA REQUIREMENTS

Persons considering pit disposal of mine wastes should ask the following questions:

***Is the potential waste well-defined (quantity, mineralogy, acid generating characteristics, state of oxidation, size)?***

> If the answer is No then field studies and testwork programs should be planned to adequately characterize the wastes, prior to any decommissioning work.

***Is there mineralization within or under the pit? Is future mining a possibility?***

If the answer is Yes, then backfilling with waste could restrict future access to this ore. The mine may want to consider simple flooding as an interim plan, and collect and treat seepages from surface waste piles or reclaim these on surface.

***Where would the water table be? Would it be above the added material? Is the pit sufficiently "water-tight" so that water could be maintained "artificially" high to provide flooding?***

If containment is desired but not naturally present then some conceptual designs should be evaluated (e.g. pervious surround, barrier layers, etc.).

***How long would it take to flood the pit? A few years or many decades?***

This can be determined from hydrogeological modelling, and/or experience with flooding at nearby sites.

***What are local groundwater flows? Would potentially contaminated pit water provide a significant contribution to the contaminant loadings in the groundwater, and what would be the advance rate of the "plume"?***

Again, hydrogeological modelling would be required to assess time frame for flooding and direction(s) of flow. However, the possible extent of the plume (i.e. impacted areas) can be easily estimated; for example using simple dilution techniques.

***What are the possible environmental and health impacts of groundwater? Are there adjacent wells, sensitive waterbodies etc?***

Sensitive receivers (wells, waterbodies) should be identified. Possible impacts could be addressed by carrying out a screening level ecotoxicity assessment consisting of a biological survey and preliminary calculations of possible contaminant concentrations and exposure levels. For example, using the simple dilution technique mentioned above, it may be demonstrated that the risk of impact is low and therefore no further work may be required. However, should these receivers be at risk to contamination at an unacceptable level of impact (i.e. exceedances of a water quality objective or guideline) then further study may be warranted.

***Is the pit interconnected to underground workings? Are the workings potential sources of contaminated water, or quick routes for outflow?***

The contribution of workings to contaminant loadings can be assessed by examining water quality data for flows intercepted/collected underground. The workings may be a source, or possibly a sink for contaminants, depending on the mineralogy, pH/redox conditions and use of backfill or sealants in the underground mine. The connected workings can also be used to intercept and collect (pump) waters to surface for treatment. The future flow situation must be thoroughly investigated to develop conceptual plans to support decisions for either sealing the pit from the workings, or using the connected workings as part of the disposal concept.

***What is the effective capacity of the pit for waste material? Can material be trucked and dumped safely and adequately?***

The simplest method for backfilling a pit is to use pit ramp access and roads to replace material at specific locations. If this is not possible then material can be end-dumped over the edge. It is important to identify the most potentially acid generating or contaminated materials and to place these at the appropriate location, i.e. below the water table, or layered or mixed in with alkaline (acid-consuming) materials.

Depending upon the pit ramp length, grade etc. and type of haulage trucks used, additional measures may be required to suit regular downgrade fully loaded hauling.

***How accurate is the reactive waste volume estimate? Experiences at several pits have demonstrated that volumes of waste can be significantly underestimated.***

Volume estimates would involve several approaches including surveying, test drilling of non-reactive waste piles, roads, yards, etc.

***Is there a possibility of planning the mining so that material can be segregated and stored in mined-out sections of the pit? Or, is it practical to segregate acid producing wastes and relocate them to the pit at the end of the mine production phase?***

Ideally, the waste management program should commence with the start of mining; however, operating or inactive mines may currently be re-evaluating their waste management practices. A segregated waste dump should be near the pit (to reduce haul distance) and on relatively flat ground (to facilitate reclamation of the waste).

***Would the walls contribute alkalinity or acidity?***

The exposed surface area of the pit walls should be quantified in terms of acid-generating or acid-neutralizing ability.

***Would the configuration of the pit offer the prospect of establishing a stratified water column and maintaining a meromictic layer (e.g. mixing is more likely if shallow and wind-swept)?***

Stratification may or may not develop and depends on the presence of several factors that will determine the required density difference for stratification to occur and remain stable. The site should be compared to a similar site to determine if physical dimensions and predicted chemistry and temperature regime will result in stratification. Several practices that encourage stratification could be considered. If the pit waters are not likely to stratify, then the future contaminant levels should be determined to decide if a top barrier layer would be required to isolate the wastes from the water column.

***Are there any regulations or preferences regarding the final aesthetic, usage and safety aspects of the pit (accessibility, slope stability), pit water quality?***

These considerations are site-specific.

***How does pit disposal compare with other disposal options (re: timing, cost, effectiveness permanence, etc.)?***

Any environmental assessment of pit decommissioning and disposal of mine water will require evaluation of several options and selection of the preferred alternative.

Pit disposal should be evaluated (screened) against other options for waste disposal/pit decommissioning, based on several criteria, for example: economics (cost per ton of material); strategical considerations (significant quantity); efficiency (avoid moving material twice); effectiveness (before acid generation begins); and, safety (minimal risk of groundwater contamination, etc.).

***What are the monitoring requirements (e.g. number of stations, location, depth of water sampling wells)?***

Depending on the level of containment expected to be provided by the disposal strategy, the monitoring should be designed to fully characterize the decommissioned system and to demonstrate that the expected performance can be achieved and maintained.

***What safeguards may be required (e.g. pump-back wells downstream)?***

> One safeguard that could be built into the disposal concept is a system to batch treat acidic pit lake overflow.

## 5.3 FURTHER TECHNOLOGY DEVELOPMENT/FUTURE STUDIES

We believe that the existing state of the technology is adequate (e.g. pervious surround, engineered covers and barriers, etc.). However, the major weakness identified was the status of the monitoring database. Few sites other than pit lakes have been thoroughly monitored. Monitoring is generally used to demonstrate (often rather superficially) that pit disposal is effective.

A large scale monitoring program at a backfilled pit should be funded. A candidate site would be Owl Creek.

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# APPENDIX 1

# WATER QUALITY DATA
# FOR SELECTED PITS

**Note:** Tables Reproduced from Stevens et al., (1994) Appendix III

# TABLE 1A

## SUBSURFACE WATER QUALITY, BRENDA MINES LTD, SEPT 24,1991

| Time | Diss. Depth m | O2 (mg/l) | Temp (°C) | pH | Cond (mmhos/cm) | Redox (mv) |
|---|---|---|---|---|---|---|
| | 1 | 7.40 | 13.67 | 7.74 | 1.59 | 0.207 |
| | 5 | 7.65 | 12.84 | 7.73 | 1.62 | 0.205 |
| | 10 | 7.55 | 12.79 | 7.73 | 1.61 | 0.203 |
| | 15 | 7.47 | 12.76 | 7.73 | 1.60 | 0.202 |
| | 20 | 3.89 | 8.87 | 7.36 | 1.70 | 0.218 |
| | 25 | 4.12 | 4.89 | 7.29 | 1.86 | 0.217 |
| | 30 | 4.11 | 4.24 | 7.28 | 1.87 | 0.216 |
| | 35 | 4.08 | 4.11 | 7.27 | 1.87 | 0.215 |
| | 40 | 4.04 | 4.11 | 7.26 | 1.89 | 0.214 |
| | 45 | 4:00 | 4.01 | 7.26 | 1.85 | 0.214 |
| | 50 | 3.90 | 4.01 | 7.25 | 1.88 | 0.212 |
| | 55 | 3.85 | 3.99 | 7.25 | 1.85 | 0.212 |
| | 60 | 3.81 | 3.96 | 7.25 | 1.85 | 0.212 |
| | 65 | 3.71 | 3.96 | 7.25 | 1.86 | 0.211 |
| | 70 | 3.61 | 3.94 | 7.25 | 1.83 | 0.210 |
| | 75 | 3.56 | 3.92 | 7.25 | 1.85 | 0.209 |
| | 80 | 3.36 | 3.91 | 7.25 | 1.85 | 0.208 |
| | 85 | 3.16 | 3.88 | 7.25 | 1.85 | 0.208 |
| | 89.7 | 2.85 | 3.85 | 7.25 | 1.85 | 0.202 |

# TABLE 1B

## SUBSURFACE WATER QUALITY, BRENDA MINES LTD, Sept 24,1991

| Depth* (m) | Diss O2** (mg/L) | Temp** (°C) | Lab pH | Lab Cond. (umhos/cm) | Alkalinity (mg/L) | Total Hardness (mg/L) | Hardness [as CaCO3] (mg/L) | Sulphate (mg/L) | Nitrate & Nitrate (mg/L) | Ammonia (mg/L) | Total P (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 7.40 | 13.67 | 8.0 | 1550 | -- | 375 | 371 | 330 | 3.33 | 0.075 | 0.009 |
| 15 | 7.47 | 12.76 | 8.0 | 1550 | -- | 403 | 399 | 370 | 3.14 | 0.063 | 0.024 |
| 30 | 4.11 | 4.24 | 7.8 | 1790 | -- | 492 | 487 | 420 | 5.79 | 0.014 | 0.007 |
| 45 | 4.00 | 4.01 | 7.8 | 1790 | -- | 509 | 503 | 450 | 6.04 | 0.006 | 0.014 |

*=By calibrated pulley. ** From Table 1A. --= note performed. <=equal to, or less than concentration detection limit
Analyses for sulphide gave concentrations equal to or below detection limits.

# TABLE 1C

## SUB-SURFACE WATER QUALITY, BRENDA MINES LTD, Sept 24,1991

| Depth* m | B (mg/ml) | Ba (mg/ml) | Ca (mg/ml) | Co (mg/ml) | Cr (mg/ml) | Cu (mg/ml) | Fe (mg/ml) | K (mg/ml) | Mg (mg/ml) | Mn (mg/ml) | Mo (mg/ml) | Na (mg/ml) | Si (mg/ml) | Ti (mg/ml) | V (mg/ml) | Zn (mg/ml) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | .11 | .052 | 134 | < | < | .012 | .016 | 25 | 24.1 | .006 | 1.46 | 140 | 3.21 | .005 | .02 | .007 |
| 15 | .1 | .052 | 134 | < | < | .009 | .024 | 24 | 24 | .005 | 1.45 | 141 | 3.21 | .004 | < | .005 |
| 30 | .13 | .058 | 172 | .006 | .007 | .01 | .048 | 23 | 29.8 | .263 | 1.7 | 162 | 4.38 | .007 | .02 | .1 |
| 45 | .1 | .057 | 167 | .008 | .01 | .109 | .044 | 23 | 29.3 | .258 | 1.65 | 161 | 4.32 | .006 | .02 | .094 |

* = By calibrated pulley. < = equal to, or less than concentration detection limit. Concentrations are for total metals. Analyses for Al, Ag, As, Be, Cd, Ni, P, Pb, Sb, Se, Sn showed concentrations equal to or below detection limits.

# TABLE 1D
# SUB-SURFACE WATER QUALITY, BRENDA MINES LTD, June 23,1992

| Time | Diss. Depth m | O2 (mg/l) | Temp (°C) | pH | Cond (mmhos/cm) | Redox (mv) |
|---|---|---|---|---|---|---|
| 1330 | 1 | 10.57 | 19.56 | 8.74 | 1.72 | 0.337 |
| 1340 | 10 | 7.88 | 8.28 | 8.05 | 1.79 | 0.360 |
| 1344 | 20 | 5.57 | 4.19 | 7.75 | 2.00 | 0.371 |
| 1347 | 30 | 3.83 | 4.26 | 7.66 | 2.09 | 0.373 |
| 1349 | 40 | 2.71 | 4.33 | 7.64 | 2.12 | 0.373 |
| 1350 | 50 | 2.55 | 4.28 | 7.64 | 2.10 | 0.373 |
| 1352 | 60 | 2.46 | 4.24 | 7.63 | 2.14 | 0.372 |
| 1354 | 70 | 2.39 | 4.20 | 7.63 | 2.12 | 0.372 |
| 1357 | 80 | 2.33 | 4.13 | 7.65 | 2.18 | 0.371 |

## TABLE 1E

## SUB-SURFACE WATER QUALITY, BRENDA MINES LTD, June 23, 1992

| Depth* (m) | Diss O2** (mg/L) | Temp** (°C) | Lab pH | Lab Cond. (umhos/cm) | Alkalinity (mg/L) | Total Hardness (mg/L) | Hardness [as CaCO3] (mg/L) | Sulphate (mg/L) | Nitrate & Nitrate (mg/L) | Ammonia (mg/L) | Filterable Residue (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 10.57 | 19.56 | 8.4 | 1390 | 47 | 363 | 366 | 340 | 1.6 | 0.097 | 990 |
| 22 | 5.43 | 4.21 | 7.9 | 1660 | 76 | 484 | 489 | 410 | 4.43 | 0.012 | 1230 |
| 44 | 2.65 | 4.30 | 7.9 | 1720 | 83 | 513 | 519 | 410 | 4.28 | 0.012 | 1270 |
| 66 | 2.42 | 4.22 | 7.8 | 1720 | 83 | 510 | 516 | 410 | 4.65 | 0.018 | 1270 |
| 88 | 2.33 | 4.13 | 7.8 | 1740 | 85 | 518 | 524 | 360 | 4.81 | 0.05 | 1280 |

* = By calibrated pulley.
** From Table 1D. All analyses for sulphide and total phosphorous gave concentrations equal to or below detection limits.

## TABLE 1F

## SUB-SURFACE WATER QUALITY, BRENDA MINES LTD, June 23, 1992

| Depth* m | Al (mg/ml) | B (mg/ml) | Ba (mg/ml) | Ca (mg/ml) | Cu (mg/ml) | Fe (mg/ml) | K (mg/ml) | Mg (mg/ml) | Mn (mg/ml) | Mo (mg/ml) | Na (mg/ml) | Si (mg/ml) | Sr (mg/ml) | Zn (mg/ml) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | < | .09 | .045 | 108 | < | .029 | 21 | 22.7 | .041 | 1.93 | 123 | 1.73 | 2.72 | .003 |
| 22 | .05 | .11 | .063 | 148 | .013 | .044 | 22 | 27.6 | .14 | 2.03 | 144 | 1.66 | 3.92 | .05 |
| 44 | .07 | .1 | .063 | 157 | .015 | .065 | 21 | 29.5 | .241 | 1.95 | 152 | 1.93 | 4.3 | .07 |
| 66 | .06 | .11 | .058 | 156 | .018 | .045 | 21 | 29.5 | .239 | 1.98 | 151 | 12.93 | 4.29 | .081 |
| 88 | .08 | .11 | .058 | 158 | .021 | .087 | 21 | 30.1 | .258 | 1.97 | 154 | 2.02 | 4.44 | .081 |

* = By calibrated pulley. Concentrations are for extractable metals.
< = equal to, or less than concentration detection limit. All analyses for Ag, As, Be, Cd, Co, Ni, P, Pb, Sb, Se, Sn, Ti, V showed concentrations equal to or below detection limits.

# TABLE 1G
## SUB-SURFACE WATER QUALITY, BRENDA PIT, MARCH 10, 1994

| Diss. Depth m | O2 (mg/l) | Temp (°C) | pH | Cond (mmhos/cm) | Redox (mv) |
|---|---|---|---|---|---|
| 0.5 | 10.68 | 1.02 | 1.218 | 8.23 | 0.309 |
| 10.0 | 10.82 | 2.70 | 1.215 | 8.05 | 0.318 |
| 15.0* | 9.64 | 3.43 | 1.240 | 8.00 | 0.314 |
| 17.5* | 8.90 | 3.81 | 1.290 | 7.91 | 0.317 |
| 18.0* | 7.87 | 4.08 | 1.400 | 7.79 | 0.321 |
| 20.0 | 6.24 | 4.28 | 1.490 | 7.64 | 0.327 |
| 20.0* | 5.20 | 4.41 | 1.510 | 7.56 | 0.325 |
| 30.0 | 3.06 | 4.25 | 1.580 | 7.49 | 0.331 |
| 30.0* | 2.59 | 4.28 | 1.540 | 7.48 | 0.327 |
| 40.0 | 2.42 | 4.26 | 1.580 | 7.49 | 0.330 |
| 50.0 | 2.22 | 4.26 | 1.600 | 7.47 | 0.330 |
| 60.0 | 2.01 | 4.26 | 1.600 | 7.49 | 0.328 |
| 70.0 | 1.46 | 4.28 | 1.600 | 7.47 | 0.329 |
| 80.7 | 0.96 | 4.32 | 1.600 | 7.47 | 0.328 |
| 91.0 | 0.67 | 4.35 | 1.620 | 7.46 | 0.329 |
| 99.0 | 0.35 | 4.42 | 1.600 | 7.45 | 0.328 |

*Readings on return of sensor to surface

# TABLE 2A

## SUB-SURFACE WATER QUALITY, NICKEL PLATE SOUTH PIT, SEPT. 23, 1991

| Depth m. | Diss. 02 (mg/l) | Temp. (°C) | pH | Cond (mmhos/cm) | Redox (mv) |
|---|---|---|---|---|---|
| 1 | 8.50 | 10.91 | 7.60 | 1.205 | 0.206 |
| 2 | 8.48 | 10.63 | 7.67 | 1.223 | 0.202 |
| 5 | 8.62 | 10.64 | 7.69 | 1.236 | 0.202 |
| 6 | 5.50 | 9.91 | 7.39 | 1.361 | 0.208 |
| 7 | 2.87 | 7.89 | 7.39 | 1.49 | 0.218 |
| 10 | 1.83 | 6.25 | 7.48 | 1.52 | 0.220 |
| 15 | 0.99 | 5.29 | 7.42 | 1.54 | 0.220 |
| 18.5 | 0.62 | 5.11 | 7.41 | 1.54 | 0.218 |

# TABLE 2B

## SUB-SURFACE WATER QUALITY, NICKEL PLATE SOUTH PIT, SEPT. 23. 1991

| Depth* (m) | Diss O2** (mg/L) | Temp** (°C) | Lab pH | Lab Cond. (umhos/cm) | Total Phosphorous (mg/L) | Total Hardness (mg/L) | Hardness [as CaCO3] (mg/L) | Sulphate (mg/L) | Nitrate & Nitrate (mg/L) | Ammonia (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 8.50 | 10.91 | 8.0 | 1160 | 0.009 | 573 | 575 | 370 | 42.4 | .499 |
| 10 | 1.63 | 6.25 | 7.8 | 1460 | 0.011 | 701 | 704 | 500 | 58.1 | 2.42 |
| 19 | 0.62 | 5.11 | 7.8 | 1490 | 0.01 | 704 | 70B | 524 | 60.5 | 2.82 |

* By calibrated pulley. ** From Table 2A.

# TABLE 2C

## SUB-SURFACE WATER QUALITY, NICKEL PLATE SOUTH PIT, SEPT. 23, 1991

| Depth* m | As (mg/ml) | B (mg/ml) | Ba (mg/ml) | Ca (mg/ml) | Cu (mg/ml) | Fe (mg/ml) | Mg (mg/ml) | Mn (mg/ml) | Na (mg/ml) | Se (mg/ml) | Sr (mg/ml) | Ti (mg/ml) | Zn (mg/ml) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | .07 | ,13 | .009 | 223 | .015 | .031 | 19.4 | .11 | 6.5 | 0.1 | 1.7 | .007 | .015 |
| 10 | .07 | ,15 | .009 | 289 | < | .023 | 20.5 | .492 | 11 | .18 | 2.65 | .009 | .006 |
| 19 | .06 | .15 | .008 | 294 | < | .024 | 21.4 | .537 | 11 | .15 | 2.72 | .008 | .003 |

* = By calibrated pulley. Concentrations are for total metals. < = equal to, or less than concentration detection limit. All analyses for Ag, AI, Be, Cd, Co, Cr, K, Mo, Ni, P, Pb, Sb, Si, Sn, Ti, and V showed concentrations equal to or below detection limits.

# TABLE 3A

# SUB-SURFACE WATER QUALITY, GIBRALTAR WEST PIT, JUNE 25, 1992

| Time | Depth m. | Diss. 02 (mg/l) | Temp. (°C) | pH | Cond (mmhos/cm) | Redox (mv) |
|---|---|---|---|---|---|---|
| 1015 | 1 | 7.13 | 20.65 | 8.16 | 1.56 | .328 |
| 1029 | 5 | 9.58 | 10.81 | 8.06 | 1.51 | .343 |
| 1040 | 10 | 8.86 | 5.52 | 7.91 | 1.52 | .355 |
| 1044 | 15 | 8.60 | 4.35 | 7.91 | 1.51 | .357 |
| 1048 | 20 | 7.60 | 4.01 | 7.78 | 1.57 | .362 |
| 1053 | 25 | 5.37 | 4.19 | 7.62 | 1.55 | .367 |
| 1056 | 30 | 2.53 | 4.44 | 7.48 | 1.57 | .371 |
| 1100 | 1 | 7.28 | 20.20 | 8.22 | 1.57 | .332 |

## TABLE 3B

## SUB-SURFACE WATER QUALITY, GIBRALTAR WEST PIT, JUNE 25, 1992

| Depth* (m) | Diss O2** (mg/L) | Temp** (°C) | Lab pH | Lab Cond. (umhos/cm) | Alkalinity (mg/L) | Total Hardness (mg/L) | Hardness [as CaCO3] (mg/L) | Sulphate (mg/L) | Nitrate & Nitrate (mg/L) | Ammonia (mg/L) | Filterable Residue (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 7.13 | 20.65 | 8.2 | 1220 | 106 | 730 | 729 | 536 | 3.56 | < | 1050 |
| 8 | 9 | 7 | 8.2 | 1200 | 112 | 687 | 685 | 539 | 3.53 | .013 | 1060 |
| 16 | 8.60 | 4.35 | 8.0 | 1230 | 113 | 690 | 688 | 500 | 3.81 | .007 | 1080 |
| 24 | 5.37 | 4.19 | 7.9 | 1240 | 114 | 702 | 701 | 550 | 3.82 | < | 1090 |
| 32 | 2.53 | 4.44 | 7.7 | 1260 | 116 | 716 | 714 | 559 | 3.64 | .003 | 1120 |

* = By calibrated pulley.
** From Tabla 3A. All analyses for sulphide gave concentrations equal to or below detection limits.

## TABLE 3C

## SUB-SURFACE WATER QUALITY, GIBRALTAR WEST PIT, JUNE 25, 1992

| Depth* m | Ba (mg/ml) | Ca (mg/ml) | Cu (mg/ml) | Fe (mg/ml) | K (mg/ml) | Mg (mg/ml) | Mn (mg/ml) | Mo (mg/ml) | Na (mg/ml) | Si (mg/ml) | Sr (mg/ml) | Ti (mg/ml) | Zn (mg/ml) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | .012 | 241 | .007 | < | 3 | 30.7 | .022 | .16 | 22 | 6.48 | *.707* | .003 | .051 |
| 8 | .012 | 227 | .052 | .025 | 3 | 28.6 | .132 | .15 | *20.5* | 6.29 | .672 | .004 | .275 |
| 16 | .012 | 228 | .072 | .039 | 4 | 28.6 | .156 | .14 | 20.5 | 6.32 | .681 | .004 | .275 |
| 24 | .011 | 233 | ,079 | .037 | 3 | 28.9 | .13 | .15 | 20.5 | 6.41 | ,695 | .004 | .305 |
| 32 | .009 | 238 | .091 | .023 | 2 | 29.3 | .078 | .15 | 20.6 | 6.27 | .729 | .004 | .349 |

* = By calibrated pulley. Concentrations are for extractable metals.
< = equal to, or lass than concentration detection limit.
All analyses for Ag, Al, As, B, Be, Ca, Cd, Co, Cr, Ni, P, Pb, Sb, Se, Sn, and V showed concentrations equal to or below detection limits.

# TABLE 4A

## SURFACE WATER QUALITY, WAR EAGLE PIT, YUKON TERRITORY: 1982 TO 1992

| YEAR | Temp (C) | pH lab | Lab Cond. (umhos/cm) | Hardness (asCaCO3) (mg/L) | Total Hardness (mg/L) | Sulfate (mg/L) | Chloride (mg/L) | Inorg Carbon (mg/L) | Organic Carbon (mg/L) | Total P (mg/L) | Nitrite (mg/L) | Nitrite & Nitrate (mg/L) | Ammonia (mg/L) | FR (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1981 | 6.5 | 7.8 | 825 | --- | --- | 265 | 8.38 | --- | --- | < | 0.128 | 19.5 | 0.02 | 610 |
| 1982* | 3.9 | 7.7 | 900 | 418 | 420 | 300 | 9.77 | --- | --- | 0.017 | 0.15 | 22.8 | 0.33 | --- |
| | 3.9 | 7.7 | 910 | 418 | 419 | 200 | 9.49 | --- | --- | 0.015 | 0.14 | 23.8 | 0.323 | --- |
| | 3.9 | 7.8 | 900 | 416 | 417 | 310 | 9.72 | --- | --- | 0.014 | 0.13 | 6.52 | 0.419 | --- |
| | --- | 7.8 | 900 | 419 | 421 | 300 | 9.6 | --- | --- | 0.012 | 0.12 | 23.1 | 0.401 | --- |
| | --- | 7.8 | 900 | 422 | 424 | 300 | 9.4 | --- | --- | 0.012 | 0.12 | 23.1 | 0.412 | --- |
| 1983 | 13.2 | 8.2 | 796 | 405 | 407 | 283 | --- | 22 | 4 | 0.014 | 0.068 | 16.6 | 0.027 | 700 |
| 1984 | 9 | 7.9 | 738 | 364 | 365 | 210 | --- | 22 | 7 | 0.015 | 0.042 | 15.8 | 0.02 | 610 |
| 1985 | 11 | 8.2 | --- | 419 | 421 | 220 | 8.5 | 23.3 | 7.5 | 0.055 | 0.5 | 15 | 0.136 | 592 |
| 1986 | 10.5 | 8.2 | 750 | 393 | 394 | 210 | < | 21 | 6 | 0.044 | 0.033 | 13 | 0.024 | 628 |
| 1991 | 11.3 | 8.2 | --- | 391 | 393 | 252 | 31 | --- | --- | 0.007 | 0.036 | 9.73 | 0.016 | 760 |
| 1992 | 1.8 | 7.9 | 1020 | 515 | 517 | 300 | 44.4 | --- | --- | 0.013 | 0.033 | 10.6 | 0.314 | 920 |

* Surface waters sampled through the ice at five different stations.
--- = not sampled     < = equal to, or less than concentration detection limit.

# TABLE 4B

## SUB-SURFACE WATER QUALITY, WAR EAGLE PIT, YUKON TERRITORY: 1982 TO 1992

| YEAR | Depth (m) | Diss. $O_2$ (mg/L) | Temp (C) | pH | Cond. (umhos/cm) | Hardness (asCaCO3) (mg/L) | Total Hardness (mg/L) | Sulfate (mg/L) | Chloride (mg/L) | Inorg Carbon (mg/L) | Organic Carbon (mg/L) | Total P (mg/L) | Nitrite (mg/L) | Nitrite & Nitrate (mg/L) | Ammonia (mg/L) | FR (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1982* | 1 | 6.0 | 1.7 | 7.8 | 900 | 418 | 420 | 300 | 9.7 | --- | --- | 0.015 | 0.13 | 23.1 | 0.40 | --- |
| | 25 | nil | 3.9 | 7.9 | 1200 | 468 | 470 | 300 | 9.4 | --- | --- | 0.012 | 0.12 | 23.1 | 4.64 | --- |
| 1991 | 1 | 10.0 | 11.3 | 8.2 | --- | 391 | 393 | 252 | 31 | --- | --- | 0.007 | 0.036 | 9.73 | 0.026 | 760 |
| | 6 | 10.9 | 5.7 | 8.1 | --- | 412 | 414 | 280 | 30 | --- | --- | 0.006 | 0.029 | 9.86 | 0.002 | 750 |
| | 12 | 0.9 | 4.3 | 7.9 | --- | 507 | 509 | 300 | 61 | --- | --- | 0.01 | 0.111 | 7.4 | 1.93 | 970 |
| | 18 | nil | 3.8 | 7.8 | --- | 572 | 575 | 250 | 123 | --- | --- | 0.049 | 0.058 | 3.28 | 7.59 | 1210 |
| | 22 | nil | 3.6 | 7.8 | --- | 579 | 581 | 300 | 140 | --- | --- | 0.055 | 0.069 | 1.8 | 7.99 | 1230 |
| 1992 | 1 | --- | 1.8 | 7.8 | 1020 | 515 | 517 | 300 | 44.4 | --- | --- | 0.013 | 0.033 | 10.6 | 0.314 | 920 |
| | 12 | --- | 3.0 | 7.8 | 1010 | 521 | 522 | 310 | 45 | --- | --- | 0.008 | 0.034 | 10.5 | 0.051 | 910 |
| | 23 | --- | 3.8 | 7.4 | 1490 | 709 | 711 | 320 | 147 | --- | --- | 0.046 | 0.04 | 1.84 | 7.86 | 1260 |

* Average of five surface samples collected through ice. The 25 m. sample is a composite of five samples taken at that depth.
--- = not sampled     < = equal to, or less than concentration detection limit.

# TABLE 4C

## SURFACE WATER QUALITY, WAR EAGLE PIT, YUKON TERRITORY: 1982 TO 1992

| YEAR | B (mg/L) | Ba (mg/L) | Ca (mg/L) | Cd (mg/L) | Cu (mg/L) | Fe (mg/L) | K (mg/L) | Mg (mg/L) | Mn (mg/L) | Mo (mg/L) | Na (mg/L) | Si (mg/L) | Sr (mg/L) | Zn (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1981 | < | 0.0289 | 136 | < | 0.091 | 0.107 | --- | 9.86 | 0.029 | 0.27 | 11.8 | 17 | 1.18 | 0.0354 |
| 1982* | < | 0.035 | 149 | < | 0.119 | 0.015 | --- | 11.2 | 0.034 | 0.322 | 13.4 | 18.7 | 1.31 | 0.046 |
|  | < | 0.035 | 149 | < | 0.119 | 0.009 | --- | 11.4 | 0.032 | 0.328 | 13.4 | 18.7 | 1.31 | 0.038 |
|  | < | 0.035 | 148 | < | 0.117 | 0.008 | --- | 11.3 | 0.032 | --- | 13.4 | 18.5 | 1.31 | 0.038 |
|  | < | 0.035 | 149 | < | 0.121 | 0.009 | --- | 11.4 | 0.033 | 0.319 | 13.4 | 18.7 | 1.31 | 0.037 |
|  | --- | 0.04 | 150 | < | 0.122 | 0.009 | --- | 11.5 | 0.033 | 0.319 | 13.4 | 18.8 | 1.31 | 0.04 |
| 1983 | 0.01 | 0.032 | 145 | < | 0.099 | 0.068 | --- | 10.4 | 0.022 | 0.262 | 12 | 17.1 | 1.16 | 0.026 |
| 1984 | 0.046 | 0.028 | 130 | < | 0.097 | 0.019 | --- | 9.3 | 0.018 | 0.249 | 11.2 | 16.3 | 1.05 | 0.024 |
| 1985 | 0.017 | 0.032 | 151 | 0.002 | 0.113 | 0.083 | --- | 10.3 | 0.019 | 0.263 | 11.9 | 11.6 | 1.14 | 0.071 |
| 1986 | 0.002 | 0.03 | 140 | < | 0.107 | 0.015 | --- | 10.3 | 0.019 | 0.278 | 11.9 | 17.8 | 1.15 | 0.024 |
| 1991 | 0.03 | 0.025 | 155 | < | 0.065 | 0.041 | 4 | 11 | 0.019 | 0.26 | 14.3 | 18.5 | 1.12 | 0.016 |
| 1992 | 0.03 | 0.026 | 194 | < | 0.061 | 0.088 | 6 | 13.8 | 0.027 | 0.28 | 20 | 20.5 | 1.32 | 0.031 |

* Surface waters sampled through the ice at five different stations
Analyses are extractable or total metal concentrations
Analyses for Ag, Al, As, Be, Cd, Co, Cr, Ni, P, Pb, Sb, Se, Sn, Ti, V gave results equal to or below detection limits.
--- = not sampled    < = equal to, or less than concentration detection limit.

# TABLE 4D

## SUB-SURFACE WATER QUALITY, WAR EAGLE PIT, YUKON TERRITORY: 1982 TO 1992

| YEAR | (mg/L) | B (mg/L) | Ba (mg/L) | Ca (mg/L) | Cd (mg/L) | Cu (mg/L) | Fe (mg/L) | K (mg/L) | Mg (mg/L) | Mn (mg/L) | Mo (mg/L) | Na (mg/L) | Si (mg/L) | Sr (mg/L) | Zn (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1982* | 1 | < | 0.03 | 149 | < | 0.119 | 0.009 | --- | 11.4 | 0.033 | 0.322 | 13.4 | 18.7 | 1.31 | 0.04 |
|  | 25 | < | < | 167 | < | 0.118 | 0.034 | --- | 12.4 | 0.117 | 0.371 | 16.8 | 22.6 | 1.6 | 0.044 |
| 1991 | 1 | 0.03 | 0.025 | 155 | < | 0.065 | 0.041 | 4 | 11 | 0.019 | 0.26 | 14.3 | 18.5 | 1.12 | 0.016 |
|  | 6 | 0.03 | 0.025 | 156 | < | 0.063 | 0.047 | 4 | 11 | 0.019 | 0.27 | 14.5 | 18.5 | 1.13 | 0.014 |
|  | 12 | 0.05 | 0.033 | 196 | < | 0.069 | 0.056 | 5 | 14.1 | 0.115 | 0.29 | 23.8 | 23.6 | 1.48 | 0.018 |
|  | 18 | 0.12 | 0.04 | 228 | < | 0.11 | 0.132 | 7 | 16.8 | 0.205 | 0.3 | 36.7 | 26.4 | 1.81 | 0.035 |
|  | 22 | 0.14 | 0.041 | 236 | < | 0.164 | 0.13 | 8 | 17.8 | 0.223 | 0.28 | 40 | 27.4 | 1.88 | 0.043 |
| 1992 | 1 | 0.03 | 0.026 | 194 | < | 0.061 | 0.088 | 6 | 13.8 | 0.027 | 0.28 | 20 | 20.5 | 1.32 | 0.031 |
|  | 12 | 0.04 | 0.025 | 194 | 0.006 | 0.055 | 0.031 | 4 | 13.2 | 0.027 | 0.26 | 19.8 | 20 | 1.32 | 0.025 |
|  | 23 | 0.14 | 0.041 | 265 | 0.008 | 0.11 | 0.226 | 9 | 19.7 | 0.25 | 0.27 | 48.4 | 25 | 2.01 | 0.046 |

* Average of five surface samples collected through ice; the 25 m. sample was a composite of five samples taken at that depth.
Analyses are extractable or total metal concentrations
Metals Ag, Al, As, Be, Cd, Co, Cr, Ni, P, Pb, Sb, Se, Sn, Ti, V not reported: all concentrations were equal to or below detection limits.
--- = not sampled    < = equal to, or less than concentration detection limit.

## TABLE 5A

## SUB-SURFACE WATER QUALITY, WELLPINIT, WA, 1992

| Depth* m. | Diss O2 (mg/l) | Temp (oC) | pH | Cond (mmhos/cm) | Redox (mv) |
|---|---|---|---|---|---|
| 1 | 8.96 | 16.55 | 3.92 | 3.52 | 0.411 |
| 5 | 10.71 | 11.02 | 3.89 | 3.59 | 0.431 |
| 10 | 11.07 | 7.50 | 3.91 | 3.55 | 0.438 |
| 15 | 11.31 | 6.06 | 3.91 | 3.55 | 0.443 |
| 20 | 11.36 | 5.48 | 3.92 | 3.54 | 0.447 |
| 25 | 11.33 | 5.26 | 3.93 | 3.56 | 0.454 |
| 30 | 11.33 | 5.17 | 3.94 | 3.57 | 0.457 |
| 35 | 11.38 | 5.08 | 3.95 | 3.55 | 0.460 |
| 1 | 9.20 | 16.28 | 3.85 | 3.59 | 0.431 |

*Depths by calibrated pulley: sonde sensor inoperative.

## TABLE 5B

## SUB-SURFACE WATER QUALITY, WELLPINIT, WA, MAY 6, 1992

| Depth (m) | Diss. O2* (mg/L) | Temp* (C) | Lab pH (mg/L) | T. Org Carbon (mg/L) | Hardness as CACO3 (mg/L) | Total Hardness (mg/L) | Sulfate (mg/L) | Total P (mg/L) | Nitrite & Nitrate (mg/L) | Chloride (mg/L) | Filterable Residue (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 8.96 | 16.55 | 4.3 | 5.1 | 2080 | 2490 | 2570 | < | 4.86 | 2.8 | 4410 |
| 10 | 11.07 | 7.50 | 4.2 | 1.5 | 2080 | 2490 | 2580 | < | 4.82 | 3 | 4350 |
| 20 | 11.36 | 5.48 | 4.2 | 4.2 | 2130 | 2570 | 2570 | .002 | 4.85 | 2.8 | 4520 |
| 30 | 11.33 | 5.17 | 4.2 | 2.0 | 2120 | 2550 | 2520 | .003 | 4.8 | 2.8 | 4610 |
| 37 | 11.38 | 5.08 | 4.2 | 2.1 | 2170 | 2610 | 2300 | .002 | 4.82 | 2.8 | 4600 |

*Field readings < = equal to, or less than detection limit

Analyses for **Alkalinity, Total Inorganic Carbon, Nitrite, Total Phosporous, Non-filterable Residue**, and **Sulphide** gave concentrations less than or equal to detection limits.

## TABLE 5C

## SUB-SURFACE WATER QUALITY, WELLPINIT, WA, MAY 5, 1992

| Depth m | Al (mg/l) | As (mg/l) | Be (mg/l) | Ca (mg/l) | Cd (mg/l) | Co (mg/l) | Cu (mg/l) | Fe (mg/l) | Mg (mg/l) | Mn (mg/l) | Na (mg/l) | Ni (mg/l) | SI (mg/l) | SR (mg/l) | ZN (mg/l) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 47.7 | .31 | .031 | 426 | .064 | .94 | .244 | .201 | 246 | 122 | 57.7 | 1.48 | 10.1 | 1.5 | 3.53 |
| 10 | 55.1 | .34 | .035 | 463 | .069 | 1.04 | .267 | .204 | 224 | 113 | 65.4 | 1.65 | 10.5 | 1.67 | 3.93 |
| 20 | 54 | .3 | .034 | 449 | .066 | 1.02 | .269 | .178 | 246 | 124 | 63.2 | 1.62 | 10.4 | 1.62 | 3.85 |
| 30 | 56.4 | .34 | .036 | 472 | .073 | 1.07 | .281 | .333 | 229 | 115 | 65.2 | 1.72 | 10.7 | 1.68 | 4.04 |
| 37 | 58.6 | .34 | .037 | 484 | .071 | 1.09 | .284 | .269 | 234 | 117 | 68.3 | 1.73 | 10.7 | 1.76 | 4.11 |

Concentrations are for **extractable** metals. Analyses for **Ag, B, Ba, Cr, K, Mo, P, Pb, Sb, Se, Sn,** Tl, **V** gave concentrations equal to or below detection limits.

I.C.P. Metal analyses of a light-coloured, gelatinous precipitate at the pit bottom totalled 0.11/g/g, with A1-67%, Fe-20%, Mg-3.6%, Ca-3% K-1.6%, with other constituents 1% or less.

## TABLE 6A

## SUB-SURFACE WATER QUALITY, HIGHLAND VALLEY COPPER, SEPT. 23 1992

| Time | Diss Depth m. | O2 (mg/l) | Temp (oC) | pH | CondRedox (mmhos/cm)(mv) |
|---|---|---|---|---|---|
| 1425 | 1 | 9.52 | 10.55 | 8.24 | 0.476336 |
| 1430 | 5 | 8.68 | 10.27 | 8.29 | 0.478335 |
| 1432 | 10 | 8.74 | 6.53 | 8.14 | 0.509342 |
| 1434 | 15 | 7.55 | 5.52 | 8.00 | 0.530356 |
| 1445 | 54 | 5.63 | 4.83 | 7.82 | 0.544356 |
| 1455 | 1 | 8.39 | 10.37 | 8.27 | 0.481341 |

*Depths by calibrated pulley: sonde sensor inoperative.

## TABLE 6B

## SUB-SURFACE WATER QUALITY, HIGHLAND VALLEY COPPER, SEPT. 23, 1992

| Depth* (m) | Diss. O2** (mg/L) | Temp** (C) | Lab pH | Lab Cond. (umhos/cm) | Alkal. (mg/L) | Hardness as CaCO3 (mg/L) | Total Hardness (mg/L) | Sulfate (mg/L) | Total P (mg/L) | Nitrite & Nitrate |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 9.52 | 10.5 | 8.33 | 433 | 100 | 171 | 176 | 102 | < | 3.06 |
| 14 | 7.55 | 5.52 | 8.23 | 466 | 103 | 180 | 186 | 93 | < | 3.88 |
| 27 | --- | --- | 8.07 | 492 | 109 | 189 | 196 | 111 | < | 4.92 |
| 38 | --- | --- | 8.03 | 497 | 110 | 190 | 196 | 101 | < | 4.61 |
| 46 | --- | --- | 7.96 | 508 | 114 | 191 | 198 | 100 | < | 4.7 |
| 54 | 5.63 | 4.83 | 7.99 | 507 | 114 | 191 | 198 | 103 | 0.02 | 4.6 |

* From Table 6A. --- = not sampled < = equal to, or less than concentration detection limit.

## TABLE 6C

## SUB-SURFACE WATER QUALITY, HIGHLAND VALLEY COPPER, SEPT. 23, 1992

| Depth m | Al (mg/l) | B (mg/l) | Ba (mg/l) | Ca (mg/l) | Cu (mg/l) | Mg (mg/l) | Mn (mg/l) | Mo (mg/l) | Na (mg/l) | Si (mg/l) | Sr (mg/l) | Zn (mg/l) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | < | < | 0.049 | 40.4 | 0.045 | 12.2 | 0.009 | 5.87 | 21.8 | 3.21 | 4.51 | < |
| 14 | < | 0.02 | 0.048 | 51.2 | 0.054 | 12.8 | 0.012 | 6.3 | 24.9 | 3.21 | 4.95 | < |
| 27 | < | 0.02 | 0.046 | 53.6 | 0.074 | 13.4 | 0.013 | 6.99 | 28 | 3.12 | 5.48 | < |
| 38 | 0.06 | 0.02 | 0.045 | 53.8 | 0.086 | 13.4 | 0.016 | 7.04 | 27.4 | 3.09 | 5.49 | 0.004 |
| 46 | < | < | 0.044 | 54.3 | 0.098 | 13.5 | 0.017 | 7.2 | 27.9 | 3.04 | 5.71 | 0.004 |
| 54 | 0.06 | 0.02 | 0.044 | 54.2 | 0.098 | 13.5 | 0.019 | 7.15 | 27.6 | 3.04 | 5.68 | 0.005 |

Concentrations are for **extractable** metals. < equal to, or less than concentration detection limit. Analyses for **Ag, As, Be, Cd, Co, Cr, Fe, K, Ni, P, Pb, Sb, Se, Sn, Tl, V** gave concentrations equal to or below detection limits.

## TABLE 7A

## SUB-SURFACE WATER QUALITY, SIMILCO-INGERBELLE, MAY 5, 1992

| Depth m. | Diss O2 (mg/l) | Temp (oC) | pH | Cond (mmhos/cm) | Redox (mv) |
|---|---|---|---|---|---|
| 1.0 | 9.94 | 11.96 | 7.76 | 1.83 | 0.164 |
| 10 | 8.63 | 7.39 | 7.54 | 2.22 | 0.172 |
| 20 | 5.97 | 6.16 | 7.40 | 2.26 | 0.181 |
| 30 | 4.59 | 5.61 | 7.32 | 2.24 | 0.183 |
| 40 | 3.88 | 5.37 | 7.27 | 2.27 | 0.185 |
| 50 | 2.85 | 5.28 | 7.24 | 2.18 | 0.186 |
| 60 | 2.32 | 5.21 | 7.22 | 2.27 | 0.186 |
| 69 | 2.14 | 5.17 | 7.21 | 2.20 | - |
| | | | | | |
| 1 | 10.30 | 11.21 | 7.79 | 1.83 | 0.156 |

## TABLE 7B

## SUB-SURFACE QUALITY, SIMILCO-INGERBELLE, MAY 5, 1992

| Depth (m) | Diss. O$_2$* (mg/L) | Temp (°C) | Lab pH (mg/L) | Alkalinity (mg/L) | Sulphate P (mg/L) | Total Nitrite (mg/L) | Nitrite & Chloride (mg/L) | Inorg (mg/L) | Total org (mg/L) | Carbon Filt. (mg/L) | Residue |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 9.94 | 11.96 | 8.2 | 121 | 804 | .004 | 3.03 | 16.7 | 29.8 | 6.5 | 1560 |
| 15 | - | - | 8.0 | 99 | 1020 | .004 | 6.67 | 17.9 | 25.0 | 3.2 | 1900 |
| 30 | 4.59 | 5.61 | 7.9 | 99 | 1060 | .004 | 6.82 | 18.1 | 25.6 | 3.1 | 1970 |
| 45 | - | - | 7.9 | 98 | 1030 | .007 | 6.84 | 18. | 25.3 | 2.9 | 1950 |
| 60 | 2.32 | 5.21 | 7.8 | 102 | 1060 | .036 | 6.52 | 18.1 | 25.3 | 3.4 | 1960 |

*From Hydrolab readings Analyses for **Sulphide** gave results less than detection limit.

## TABLE 7C

## SUB-SURFACE QUALITY, SIMILCO-INGERBELLE, MAY 5, 1992

| Depth m | Al (mg/l) | B (mg/l) | Ba (mg/l) | Ca (mg/l) | Cu* (mg/l) | Fe (mg/l) | Mg (mg/l) | Mn (mg/l) | Mo (mg/l) | Na (mg/l) | Si (mg/l) | Sr (mg/l) | Zn (mg/l) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | .15 | .08 | .017 | 201 | .0235* | .244 | 64.3 | .006 | .21 | 89.5 | 6.26 | 3.79 | .026 |
| 15 | < | .14 | .016 | 220 | .0183* | .029 | 72.5 | < | .43 | 151 | 6.04 | 4.84 | .024 |
| 30 | < | .14 | .015 | 234 | .0156* | .049 | 76.7 | .008 | .45 | 159 | 6.09 | 5.17 | .005 |
| 45 | .09 | .15 | .017 | 237 | .0158* | .054 | 78 | .006 | .47 | 162 | 6.35 | 5.27 | .013 |
| 60 | 1.21 | .16 | .019 | 233 | .036 | .782 | 76.7 | .017 | .45 | 160 | 8.92 | 5.24 | .018 |

*By graphite furnace; all other analyses by I CP. < = less than detection limit. Analyses for **Ag, As, Be, Cd, Co, Cr, K, Ni, P, Pb, Sb, Se, Sn, Ti, V** gave results at or below detection limits.

# FINAL REPORT

# REVIEW OF IN-PIT DISPOSAL PRACTICES FOR THE PREVENTION OF ACID DRAINAGE · CASE STUDIES

## VOLUME 2 OF 2

Prepared for:

The Mine Environment Neutral Drainage (MEND) Program
Canadian Centre for Mineral and Energy Technology (CANMET)
(Work Funded Under the Canada - Ontario Mineral Development Agreement)
SSC# 028SQ.23440-4-1135A
Contract# 23440-4-1135/01-SQ
CANMET Scientific Authority: Gie Tan
MEND Representative: Gilles A. Tremblay
September 1995

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# CASE STUDY 1: OWL CREEK

## 1.0 Background Information

*Production History:*

The historic Owl Creek gold mine was an open pit mining operation located about 18 km northeast of Timmins, Ontario. The open pit was mined from 1981 to 1989, and while in production produced approximately 1.7 million tonnes of ore and 7.8 million tonnes of pit waste material.

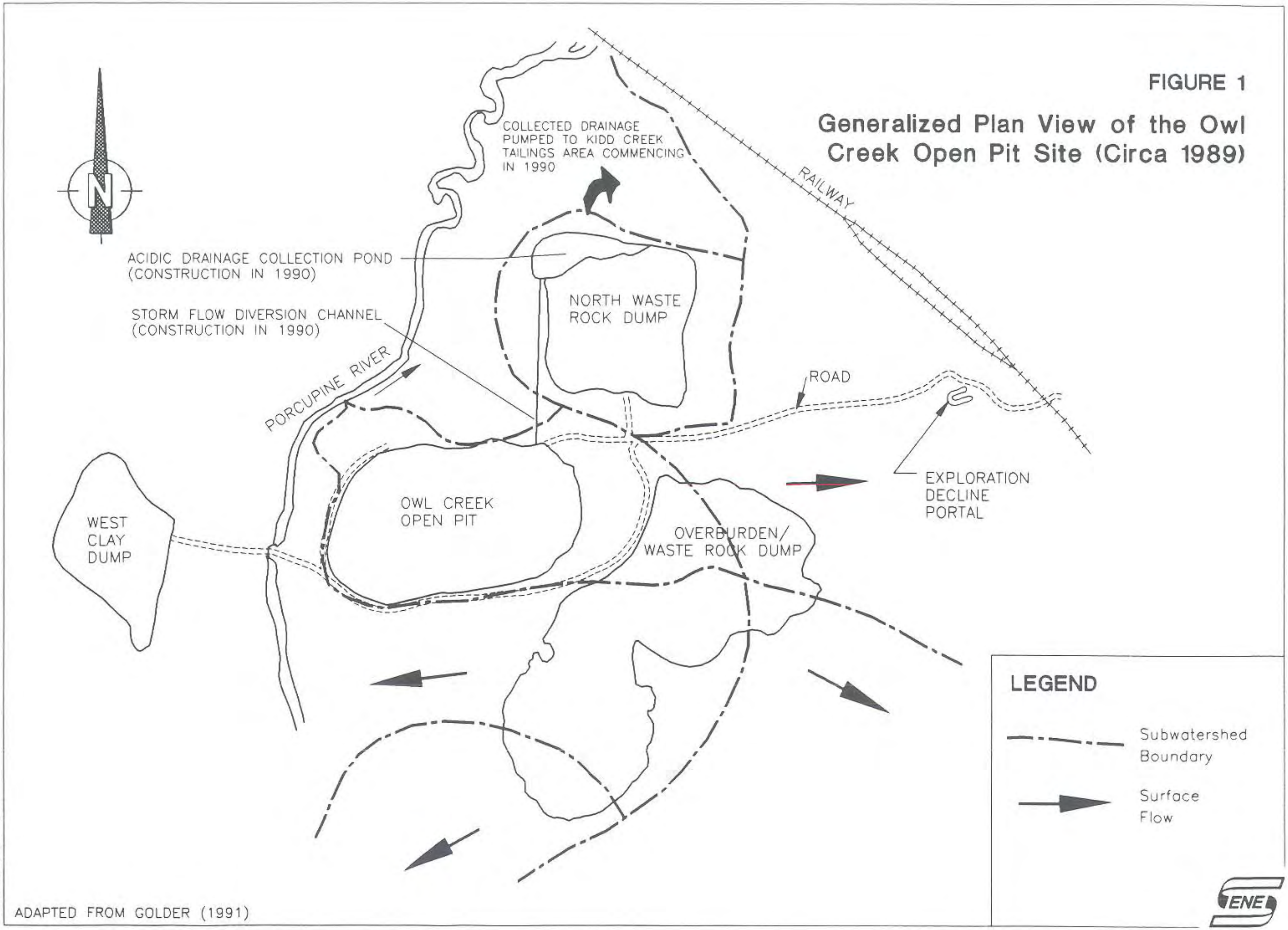
A simplified plan view of the Owl Creek open pit site as it appeared at the completion of mining activities in 1989 is provided in Figure 1. The Porcupine River, located west of the open pit, flows northward. The three principal waste disposal areas were located adjacent to the open pit.

The open pit was mined conventionally. Blasted material was loaded into 45 tonne capacity haul trucks using front end loaders. The waste material was hauled out of the pit to the three principal waste disposal areas and a small special waste (graphitic argillite) stockpile. Some waste was diverted for use elsewhere on site (e.g. road construction). With the exception of the last few benches, nominal 16 cm diameter blastholes were used which typically resulted in a maximum waste rock size of one metre. Air track drills and hydraulic excavators were used during the excavation of the last three benches. The ore was milled offsite; initially at the Kidd Creek mill which had a small flotation circuit, and later at the Bell Creek mill.

Record keeping and monitoring practices used were consistent with those in wide use at that time in the industry. This included maintaining detailed records related to geology, blast layouts, pit waste dump records, etc. This historic information was to later become quite useful. During the operating life of the pit, the pit wall stability monitoring program was effective in predicting a slope failure which resulted in the relocation of the access ramp within the pit.

FIGURE 1

Generalized Plan View of the Owl Creek Open Pit Site (Circa 1989)



ADAPTED FROM GOLDER (1991)

31607/27MAR95/FIG1.DWG/PJK

An exploration decline was driven adjacent to and below the open pit. The decline was driven in stages starting in 1979. By 1989, the decline had been driven to its lowest level, about 180 m below surface. In contrast, the open pit bottom was about 45 m lower in elevation than the surface. An underground exploration heading driven off the decline eventually connected to the open pit near the second pit bench. To facilitate the dewatering of the exploration decline, the pit was kept dewatered by pumping from the pit bottom sump.

Open pit operations ceased in 1989 after the pit had been excavated to its ultimate depth. Mineralization below the open pit (approximately 750,000 tonnes) would require underground access. The mined-out pit measured approximately 350 m by 500 m and was 45 m deep.

### *Bedrock Geology:*

The Owl Creek gold deposit occurs within a sequence of metasedimentary and mafic to ultramafic metavolcanic rocks. The rocks are Archean in age have been subjected to greenschist facies metamorphism.

The open pit geology consists of a core of massive to pillowed basalt surrounded to the north, east, and south by metasedimentary rocks - predominantly greywacke and argillite. Thin graphitic horizons occur at the north and south contacts of the central basalt (the main ore zone).

The dominant alteration is carbonization which is most prevalent in the basalt which characteristically contained abundant plagioclase (calcium rich). Carbon and chlorite alteration, although present to some degree in all three rock types, are much less significant.

### *Ore Mineralogy:*

The gold mineralization occurred as free gold and gold included in sulphide associated with quartz veins and disseminated sulphide mineralization in strongly sheared basalt and carbonaceous shale. The majority of the gold was present as inclusions in pyrite. The highest grade of ore, however, was characterized by free gold quartz veins.

The dominant sulphide minerals were pyrite ($FeS_2$), marcasite ($FeS_2$), pyrrhotite ($Fe_7S_8$), arsenopyrite (FeAsS), and chalcopyrite ($CuFeS_2$). The sulphide content was generally less than 5% however contents in excess of 10% were noted in graphitic argillite and brecciated metasedimentary rocks (Kingston, 1987).

*Glacial Geology:*

Locally the bedrock is overlain by a complex sequence of glacial and glacio-fluvial sediments. Within the open pit, the stratigraphy consists of a sequence of alternating till and glacial fluvial beds varying in thickness from 10 to 25 m in thickness. The sequence is overlain by a 5 m thick layer of glacio-lacustrine clay and capped by a 1 to 2 m layer of till. North of Timmins, in the James Bay/Hudson Bay area, relatively soft Palaeozoic limestone rocks have been successively eroded by ice advances. Consequently, the tills in the Timmins area, and throughout northeastern Ontario and northwestern Québec are carbonate rich.

*Inventory of Pit Waste Materials:*

It was estimated that a total of 7,820,000 tonnes of pit waste materials were excavated from the open pit. This included 4,770,000 tonnes of waste rock, and 3,050,000 tonnes of overburden (till and varved clay). Of the waste rock, approximately 515,000 tonnes were used for road construction and 170,000 tonnes for construction of the Porcupine River diversion channel. The remaining 4,085,000 tonnes of waste rock were principally deposited in three dump sites: the North Dump (waste rock), the Overburden/Waste Rock Dump, and the Clay Dumps (see Figure 1). A summary of pit waste tonnages is provided in Table 1.

Table 1

## SUMMARY OF PIT WASTE TONNAGE AT OWL CREEK(A)

| **Location** | **Pit Waste Material (tonnes)** | | | |
|---|---|---|---|---|
| | **Overburden** | **Greywacke/ Volcanies** | **Graphitic Argillite** | **Wet Tonnes Relocated Later** |
| North Dump | 150,000 | 1,500,000 | 300,000 | 2,289,000 |
| South East Dump | 1,000,000 | 1,500,000 | 200,000 | 970,000 |
| South Dump | 1,050,000 | 10,000 | 15,000 | 20,000 |
| West Dump | 850,000 | 0 | 0 | 0 |
| On-Site Roads | 0 | 500,000 | 15,000 | 369,000 |
| River Diversion | 0 | 170,000 | 0 | 0 |
| Diverse Sources | 0 | 555,000 | 5,000 | 0 |
| Total | 3,050,000 | 4,235,000 | 535,000 | 3,648,000 |

(A) Adapted from Table 1 (Blakey, 1991).

*Acidic Drainage Occurrence:*

In June 1990, it was reported that the drainage to the Porcupine River from the north end of the North Waste Dump had become acidic. Sampling of the surface drainage taken in June 1991 indicated: a pH in the order of 2.3; elevated concentrations of zinc, copper, nickel, iron and aluminum; lesser concentrations of cadmium, magnesium, and manganese; and high conductivities. Water quality data for the seepage from the North Dump for selected dates are shown in Table 2.

The mine operator responded quickly by constructing a drainage collection pond and pumping system. The acidic drainage which flowed into the pond at rates of 4 L/s was pumped approximately 3 km to the Kidd Creek tailings basin for treatment (ore had been trucked to the Kidd Creek mill). The initial pumping system involved the use of a nominal 10 cm diameter pipeline and stainless steel submersible pumps. Actions that were subsequently taken included:

Table 2

## SELECTED SURFACE WATER QUALITY DATA AT OWL CREEK(A)
## (JUNE/JULY 1990 SAMPLING)

Units are mg/L except for pH

| **Location** | **Sample Date** | **pH** | **Al** | **As** | **Ca** | **Cd** | **Co** | **Cu** | **Fe** | **765 Mg** | **Ni** | **Pb** | **S** | **Sb** | **Se** | **Zn** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Discharge at Toe of North Dump(B) | 11 June | 2.3 | 1325 | 16 | 395 | 1.2 | 22 | 68 | 7750 | 2680 | 48 | 0.15 | 13400 | 4 | <0.1 | 148 |
| | 18 June | 2.6 | - | - | - | - | - | - | 5800 | - | - | - | - | - | - | 107 |
| | 28 June | 2.3 | 1245 | 19 | 460 | 0.9 | 18 | 59 | 7000 | 2450 | 5 | - | 11450 | 2.8 | <0.1 | 120 |
| | 3 July | 2.2 | 1540 | 12 | 575 | 1.5 | 20 | 69 | 8400 | 3100 | 47 | <0.1 | 14200 | 4.3 | <0.1 | 190 |
| | 25 July | - | 1048 | 15 | 450 | 0.8 | 13 | 58 | 6678 | 2265 | 31 | <0.1 | 1069 | 2.7 | <0.1 | 105 |

(A) Source: SENES (1990).

(B) Actions were taken immediately to impound and treat the acidic flows.

- the application of lime slurry to the pit waste dumps;
- the contouring of the North Dump surface to increase runoff;
- the excavation of ditches around the North Dump to divert external run-off from the stockpile;
- increasing the containment capacity of the acidic drainage collection pond to approximately 27,000 $m^3$, and the excavation of an overflow channel from the spillway at the acidic drainage collection pond to the open pit so that storm events would not cause untreated, acidic runoff to be discharged to the off-site environment; and
- installing larger pumps and pipelines to provide a pumping capacity of approximately 30 L/s.

Investigations were simultaneously commenced regarding the abatement of the acidic drainage.

## 2.0 Investigative Procedures

Fifteen boreholes were drilled in the North Dump to allow for sampling of the waste rock and monitoring of the water within the stockpile.

Grab samples of pit waste were collected from various locations across the property. These additional samples included overburden samples, waste rock samples, and water samples. This work was complimented by reviews of the pit geology, site hydrogeology, hydrology, pit waste disposal records, field inspections of the pit waste materials, and field pH measurements of water.

The hydrogeological assessment of the North Dump showed that water was flowing through the base of the waste rock in a northerly direction, following the original ground surface.

Samples were submitted for the following testing:

- Overburden
    - determination of the acid consuming potential to pH 3.5 (Method - B.C. Research, Preliminary Acid Consuming/Production Potential)

- Waste Rock (waste rock and drill cuttings)
    - net acid generation potential;
    - ICP metal scan; and
    - the mineralogical investigation of samples of greywacke, buff mafic, and graphitic argillite.

- Water
    - laboratory pH;
    - alkalinity/acidity;
    - total dissolved solids;
    - sulphate concentration; and
    - ICP metal scan.

*Results of Analysis and Evaluations:*

The overburden was found to have a net acid consuming ability ranging from 91 to 178 Kg $H_2SO_4$/t.

Acid production potential test results for waste rock samples, excluding drill hole cuttings, are summarized in Table 3. The graphitic argillite was shown to be the main acid generating rock with a net acid production ranging from 55 to 334 Kg $H_2SO_4$/t. This was confirmed by the mineralogical investigation which showed that the sulphide minerals in the graphitic argillite occurred as anhedral crystals, amorphous nodules, which can oxidize more readily than euhedral crystals due to their increased surface area per unit mass of pyrite. The pyrite content (up to 20% in some grab samples) combined with the fissile nature of the argillite was seen to account, in part, for the rapid rate of oxidation.

The results of testing on waste rock grab samples indicated that the basalt was a strong acid consumer (net acid potential of -133 Kg $H_2SO_4$/t). Similar results were shown for the greywacke which had a net acid production potential of -105 Kg $H_2SO_4$/t. These data and other evaluations showed that the greywacke and basalt would not present an acid generating problem if stockpiled separately from the graphitic argillite.

The results of net acid production potential testing on drill hole cutting samples collected from the North Dump (each sample represented a 3 m length of hole) are summarized in Table 4. These results showed that a significant percentage of the northwestern section of the North Dump was acid generating. Net acid production potential ranged from -42.23 to 96.04 Kg $H_2SO_4$/t with an average for the North Dump of 33.2 Kg $H_2SO_4$/t.

Elemental analyses of the waste rock grab samples indicated that of the major elements, sulphur contents were less than 1%, calcium contents ranged from 1.46 to 2.48%, and sodium contents ranged from 1.30 to 1.91%. These results were consistent with visual inspections of hand samples which exhibited low sulphide mineral contents and relatively high carbonate mineral contents. The dominant metals, iron and magnesium, showed levels ranging from 5.6 to 6.3%, and 1.8 to 2.3% respectively, which is typical of predominantly mafic volcanic rock.

Elemental analyses of the drill cuttings collected from the North Dump showed higher sulphur and iron contents, and lower calcium contents - which were indicative of the higher increase in the percentage of sulphide minerals contained within the North Dump. The lower calcium contents were similarly indicative of the mineralogy of the dominant rock type (graphitic argillite) and the absence of carbonate alteration.

Table 3

## ACID PRODUCTION POTENTIAL TEST RESULTS WASTE ROCK(A)

| Sample Location | Description | Net Acid Producing Potential (Kg $H_2SO_4$/t)[B] |
|---|---|---|
| North Waste Rock Dump | Greywacke/Buff Mafic | Ranged from -8.46 to -95.71(A) |
| Separate Graphitic Dump (Approximately 35,000 t in Stockpile) | Predominantly Graphitic Argillite | Ranged from 55.85 to 201.91 |
| Overburden Waste Rock/Dump | Predominantly Graphitic Argillite | Ranged from 15.43 to 169.90 |
| Clay Dumps | -- | 41.62 |
| Roads and Ore Stockpile Area | Greywacke/Ore | Ranged from -105.12 to -142.33 |
| | Buff Mafic (Basalt) | -133.28 |
| | Graphitic /argillite | 334.62 |

(A) Source: SENES (1990).

(B) A negative result denotes net acid consumer.

Table 4

## ACID PRODUCTION POTENTIAL TEST RESULTS DRILL CUTTINGS - NORTH DUMP AT OWL CREEK(A)

| Hole No. | Depth in Dump | Net Acid Producing Potential (Kg $H_2SO_4$/t)(B) |
|---|---|---|
| 1 | 0 to 3 m<br>3 to 6 m<br>6 to 9 m<br>9 to 12 m | -30.30<br>96.04<br>78.80<br>68.78 |
| 13 | 0 to 3 m<br>3 to 6 m | 73.93<br>96.05 |
| 15 | 0 to 3 m<br>3 to 6 m | -32.50<br>-42.23 |
| | | Average(C) 33.2 |

(A) Source: SENES (1990).

(B) A negative result denotes net acid consumer.

(C) This table presents selected hole data. The average is based on all data including data not presented here.

Water samples collected from the drill holes in the North Dump had laboratory pH values averaging 2.2, sulphate levels of 25,000 to 47,400 mg/L, and total dissolved solids of 48,300 to 114,700 mg/L. As expected the metal concentrations in the acidic water within the North Dump were elevated (i.e. Al, 1,240 to 2,090 mg/L; As, 9.9 to 37 mg/L; Cu, 36 to 120 mg/L; Fe, 2,810 to 8,820 mg/L; Mn, 2,410 to 4,270 mg/L; Ni, 24 to 44 mg/L; and Zn, 11,100 to 18,800 mg/L).

The field and laboratory data showed that the North Dump was well mixed and therefore, the entire North Dump was considered to be an acidic drainage source. It was estimated that if the North Dump was left in place, and no actions were taken to inhibit the generation of acid, approximately 50,000 tonnes of acid would be produced within 50 years. Graphitic argillite waste rock contained in the Overburden/Waste Rock Dump and the South and South East Dump was shown to be a strong acid generator. However, relatively minor quantities of acidic drainage had been observed at these dumps, perhaps due to the physical characteristics of the overburden/waste rock mixture, and the significant acid consuming ability of the overburden. It was estimated that if no actions were taken, sulphide oxidation in these dumps would continue for at least a century.

## 3.0 Waste Management Options

A long list of potential options was developed. The short list of options included the following strategies for the decommissioning of the reactive waste rock.

| Option | Description |
|---|---|
| 1 | Continued collection and treatment |
| 2 | In-situ flooding |
| 3 | Disposal in a tailings management area |
| 4 | Geomembrane capping |
| 5 | Disposal in the Owl Creek open pit |

These options are briefly described below. Much of the data referenced was obtained from a report by Golder (1991).

*Option 1 - Continued collection and treatment:*

This option was based on the extension of the short term acidic run-off collection and treatment program that had already been put in place. In this option, acidic drainage from all reactive wastes would be collected and pumped to the Kidd Creek tailings area for treatment.

As indicated in Table 5, it was estimated that this option would result in the long-term commitment to dispose of 6,000,000 $m^3$ of treatment sludge to be produced over a century. The net present value of all capital and operating costs anticipated over 100 years was estimated to be $7,400,000.

In summary, the key drawbacks to Option 1 - continued collection and treatment were as follows:

- There would need to be a commitment to collect, pump, and treat acidic run-off for 100 years or more. It would also require ongoing monitoring, and maintenance of pumps, pipelines, dykes, etc.

- A replacement sludge disposal area would be needed after about 15 years of treatment when the Kidd Creek tailings area that was proposed to be used was then expected to be decommissioned. At that time a replacement site with sufficient capacity to store the anticipated large volume of treatment sludge would have to be available. The addition of large volumes of treatment sludge would have also represented a significant loss of valuable tailings storage capacity at the Kidd Creek tailings disposal area.

- The acid generating process would not be inhibited.

Table 5

## POTENTIAL ACID GENERATION FROM WASTE ROCK DUMPS AT OWL CREEK[(A)]

| Dump | Tonnage of Waste Rock (tonnes)[(B)] | Estimated Net Acid Generation Capacity (Kg $H_2SO_4$/tonne) | Total Mass of Acidity in Effluent (tonnes) | Estimated Volume of Neutralized Sludge ($m^3$) | Estimated Period for Depletion of Sulphides |
|---|---|---|---|---|---|
| North Dump | 1,500,000 | 33 | 50,000 | 1,800,000 | 75% in 20 years |
| Graphitic Argillite Stockpile | 35,000 | 129 | 4,640 | 200,000 | 100 years |
| Waste Rock/Overburden Plus Clay Dumps[(B)] | 1,720,000 | 61 | 105,000 | 4,000,000 | 100 years |
| Totals | 3,250,000 | - | - | 6,000,000 | - |

[(A)] Initial Estimate of Tonnage.

[(B)] South Dump and South East Dump.

*Option 2 - In-Situ flooding:*

In this option it was proposed that a low permeability dyke would be constructed around the existing North Dump. The top surface of the waste rock stockpile would be flattened and capped with a layer of permeable material. In concept, the waste rock mass would be kept saturated to inhibit acid production. To achieve the saturated conditions, the waste rock mass would initially be flooded using pumps. Precipitation would create a pond on the cap and water from the pond would percolate through the permeable cap to maintain an elevated water table within the North Dump. Lime slurry would initially be added to the waste rock mass to neutralize the acidity of the porewater.

In summary, the key drawbacks to Option 2 - *in-situ* flooding were as follows:

- There would be a perpetual requirement to monitor the level of water in the pond on the cap and whenever necessary to add water to the pond.

- It was estimated that at least 11,000 $m^3$ of porewater would be lost annually through seepage. This would have required a seepage monitoring program for both the dykes and the underlying natural overburden.

- This approach did not address the control or inhibition of acid drainage from other locations.

- A high cost, as the net present value of all costs was estimated to be in the order of $10,000,000.

*Option 3 - Disposal in a tailings management area:*

This option was based on relocating reactive waste rock (the North Dump and graphitic argillite reclaimed from other pit waste areas), to one of two active tailings disposal areas located nearby. In concept the reactive waste rock would be covered by the tailings and ultimately located beneath an elevated water table within a tailings mass.

The addition of lime to the waste rock was expected to be required to neutralize acidity until the reactive waste rock was covered by saturated tailings.

The key drawbacks to Option 3 - disposal in a tailings management area were as follows:

- The requirement to schedule transfer of waste rock to the tailings area to suit the tailings disposal plan. If appropriate space was not available, additional acidic runoff collection and treatment costs would be incurred.

- A high cost, as the net present value of all costs was estimated to be in the range of $9,200,000.

*Option 4 - Geomembrane capping:*

In this option, the North Dump would be covered with a synthetic geomembrane to inhibit the acid generation process (through the significant reduction in the diffusion of atmospheric oxygen to the reactive waste rock and the exclusion of gravitational water). The Overburden/Waste Rock Dump would be covered in a similar manner. Graphitic argillite from other locations on the mine property would be relocated to these waste dumps and subsequently covered by the geomembrane.

The top surfaces of the dumps would be flattened; however, slopes would be incorporated to ensure rapid runoff of precipitation. The composite cover would consist of topsoil, geotextile, a gravel drain layer, a geomembrane, a sand bedding layer, and geotextile overlaying a base layer. Drains would be provided to reduce erosion of the topsoil and drainage layer. The groundwater beneath the dumps would be monitored.

In brief, the key drawbacks to Option 4 - Geomembrane capping were as follows:

- The cost of the cover was high, and a high level of quality control would be required during construction.

- The effectiveness of the cover for inhibiting the acid generating process in perpetuity was uncertain.

The net present value of capital costs to prepare the two dumps and install the covers was estimated to be $7,600,000. That cost excluded long-term maintenance costs (i.e. cover repair or replacement).

*Option 5 - Disposal in the Owl Creek open pit:*

In this option reactive waste rock (the North Dump and graphitic argillite selectively excavated from other areas) would be disposed in the open pit. The pit would then be allowed to naturally flood to a elevation higher than the level of waste rock within the pit.

In concept, once the reactive waste rock was submerged, acid generation rates would be extremely low and no further environmental degradation would occur. The substantial acid inventory that could be released from the relocated waste rock could impact on the groundwater quality and delay the expected recovery of the quality of the surface water within the pit. Although extensive sampling and analyses had been completed there was uncertainty regarding the amount of acidity that could be released into the pit from the relocated waste rock.

An estimate of the acidity that would have to be neutralized indicated that 9 Kg of crushed limestone would be required for each tonne of waste rock relocated to the open pit. This estimate was based on using twice the theoretical neutralization requirement.

The plan view of the flooded open pit is shown in Figure 2. As a minimum, the North Dump and approximately 40,000 tonnes of graphitic argillite from the small special waste stockpile could be relocated to the open pit. Graphitic argillite selectively reclaimed from the other dumps and roads could also be relocated to the pit.

A water balance evaluation was carried out to determine the time required for the pit to flood naturally. It was predicted that based on average precipitation, the waste rock relocated to the pit would be flooded within 1 to 2 years. The pH of the pit water could be monitored during this time and adjusted, if required, through the addition of lime. The dewatering of the underground exploration workings below the pit was to be discontinued in order to minimize the hydraulic gradient and interchange of water between the open pit and the underground openings.

It was predicted that the open pit would ultimately flood to near elevation 922 feet (see Figure 2) and thereby submerge the reactive waste rock and inhibit further acid generation. The pit lake was expected to remain contained within the confines of the open pit. In the unlikely event that the water level in the pit rose excessively, the flow of water from the pit could be controlled and treated with lime, if required, prior to release.

The net present value of costs for this option was estimated to be $6,200,000 before allowances for surface grading and additional waste rock tonnage.

It was accepted that the flooding of the open pit would prohibit the underground mining of lower grade mineralization located below the open pit.

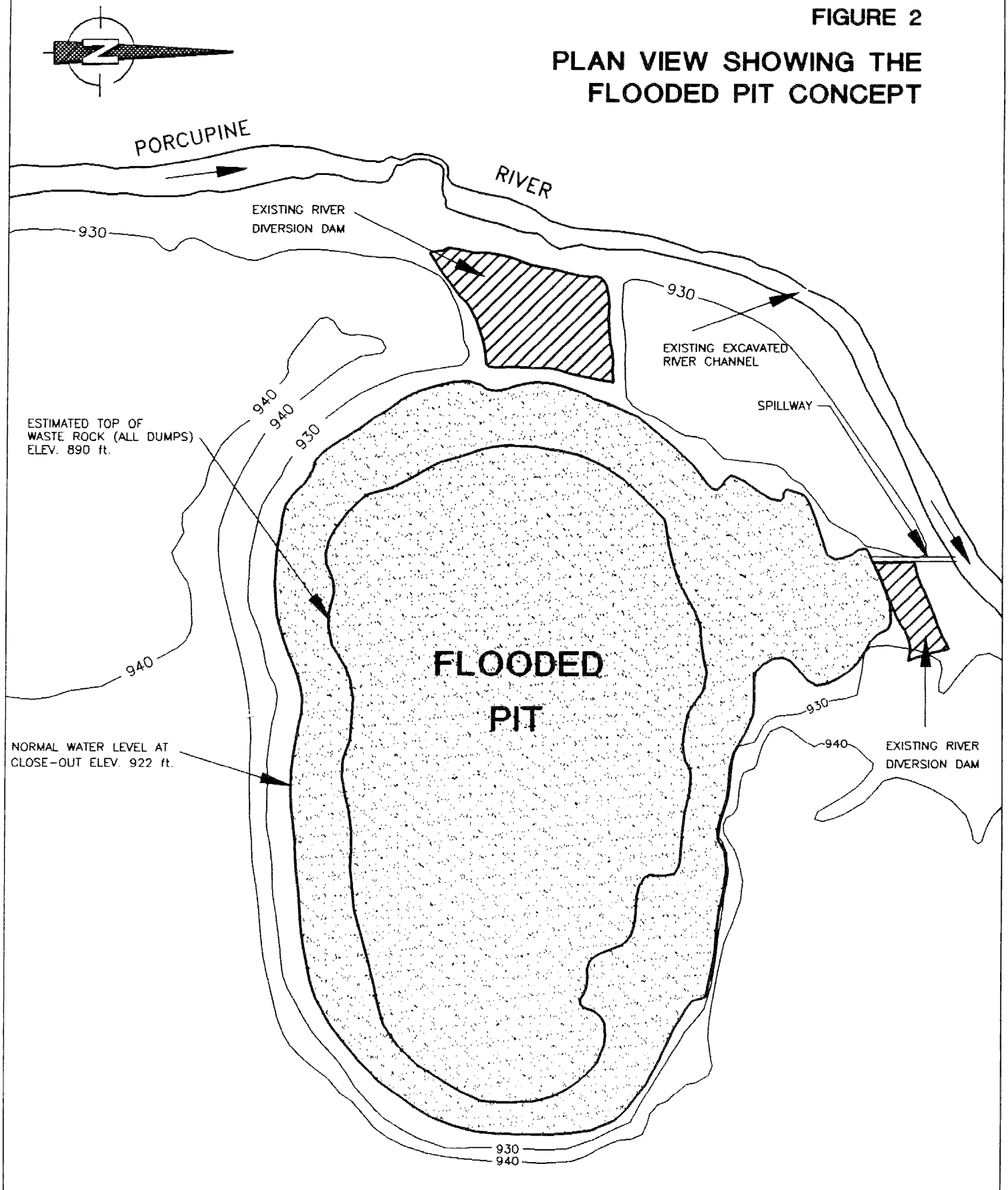
*Selection of the Preferred Option:*

Option 5 (disposal in the Owl Creek open pit) was selected as being the preferred option for the following key reasons:

- the option provided a walk-away type decommissioning plan for the reactive waste rock;
- the generation of additional acid would be inhibited and it was likely that the existing acidity released in the pit would be neutralized;
- the open pit had the capacity to contain the waste rock; and
- the plan could be implemented sooner and at a overall lower cost.

FIGURE 2

## PLAN VIEW SHOWING THE FLOODED PIT CONCEPT



ADAPTED FROM GOLDER (1991)

31607/27MAR.95/FIG2.DWG/PJK

## 4.0 Implementation of Preferred Option

The pumps for the underground exploration decline were shut off in early winter of 1991, and the workings began to flood naturally.

In December 1991, work commenced on the removal and relocation of the North Dump and graphitic argillite from other waste disposal locations to the open pit. Ultimately 3,648,000 wet tonnes of waste rock (see Table 1) was loaded into conventional rock haul trucks, transported, dumped, and spread across the floor of the Owl Creek open pit in 1.5 m lifts. Each layer of waste rock placed into the pit was mixed with minus 95 mm (3/8 inch) crushed limestone.

Visual inspections were used, along with the data collected earlier, to identify the graphitic argillite in various waste disposal locations. The reclamation was made easier by the fact that the dumps had been constructed on relatively flat land.

The remaining pit waste dumps were regraded and sloped towards the pit to direct surface water runoff or seepage into the pit. This was done to promote natural flooding of the pit, prevent further acid rock drainage (if any) into the Porcupine River, and to provide a greater watershed to the flooded pit.

The relocation of reactive waste rock to the open pit was completed in August 1992. By September 1992, the water level within the pit was about 6 m above the level of the waste in the pit - and about 15 m below the pit wall crest.

The relocation of the reactive waste rock to the open pit and the grading of the remaining waste dumps on surface was completed at a cost in the range of $7,500,000.

## 5.0 Monitoring

Monthly testing by the company of the water quality in the pit indicates that the pH is neutral and that water quality is continuing to recover.

PHOTOGRAPH OF THE OWL CREEK OPEN PIT
( LOOKING WESTWARD )
PRIOR TO THE RELOCATION OF WASTE TO THE PIT

Table 6

## OWL CREEK PIT - PIT LAKE WATER QUALITY MONITORING DATA[(A)]
## 10 JUNE 1994 SAMPLING

| Parameters | Units | 1 | 1B | 1C | 2 | 2B | 2C | 3 | 3B | 3C | 4 | 4B | 4C | 5 | 5B | 5C | 6 | 6B | 6C |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Depth** | **m** | **0.00** | **7.00** | **3.50** | **0.00** | **6.00** | **3.00** | **0.00** | **7.00** | **3.50** | **0.00** | **5.00** | **2.50** | **0.00** | **6.00** | **3.00** | **0.00** | **6.00** | **3.00** |
| D.O. | mg/L | 13.00 | 11.00 | 8.00 | 10.50 | 8.50 | 8.00 | 10.00 | 7.50 | 8.00 | 9.50 | 8.00 | 8.50 | 8.50 | 8.00 | 8.00 | 7.50 | 7.50 | 8.00 |
| pH | | 7.50 | 6.74 | 6.95 | 7.92 | 6.87 | 6.62 | 7.75 | 6.83 | 7.67 | 7.60 | 7.53 | 6.72 | 7.81 | 7.64 | 7.77 | 7.73 | 7.46 | 7.72 |
| Temp. | °C | 18.40 | 21.20 | 23.30 | 18.70 | | 19.00 | 19.00 | 22.60 | 20.30 | 19.00 | 18.00 | 18.30 | 19.50 | 18.90 | 18.10 | 18.80 | 20.50 | 19.10 |
| Sodium | mg/L | 6.20 | 6.50 | 6.70 | 6.20 | 6.70 | 7.20 | 6.20 | 6.20 | 6.50 | 6.32 | 6.20 | 7.80 | 6.40 | 6.30 | 6.20 | 6.20 | 6.20 | 6.30 |
| Choride | mg/L | 2.00 | 2.00 | 2.00 | 1.80 | 2.30 | 2.20 | 1.80 | 1.80 | 1.90 | 1.70 | 1.80 | 2.30 | 1.90 | 1.80 | 1.80 | 1.80 | 2.00 | 1.80 |
| Sulphate | mg/L | 630.00 | 670.00 | 730.00 | 660.00 | 730.00 | 770.00 | 660.00 | 660.00 | 710.00 | 660.00 | 680.00 | 890.00 | 670.00 | 660.00 | 670.00 | 860.00 | 670.00 | 670.00 |
| Phosphorus | mg/L | 0.01 | 0.01 | 0.01 | 0.01 | 0.06 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.45 | 0.01 | 0.0 | 0.01 | 0.01 | 0.01 |
| Ammonium | mg/L | 0.02 | 0.05 | 0.05 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.05 | 0.05 | 0.04 | 0.07 | 0.04 | 0.03 | 0.06 |
| Nitrate | mg/L | 0.01 | 0.01 | 0.00 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.0 | 0.01 | 0.01 | 0.01 |
| Nitrite | mg/L | 0.19 | 0.20 | 0.20 | 0.21 | 0.01 | 0.19 | 0.21 | 0.20 | 0.21 | 0.21 | 0.21 | 0.20 | 0.20 | 0.21 | 0.2 | 0.21 | 0.20 | 0.21 |
| Copper | mg/L | 0.01 | 0.04 | 0.03 | 0.03 | 0.02 | 0.01 | 0.03 | 0.02 | 0.02 | 0.06 | 0.01 | 0.01 | 0.01 | 0.02 | 0.0 | 0.01 | 0.01 | 0.02 |
| Nickel | mg/L | 0.09 | 0.13 | 0.10 | 0.10 | 0.13 | 0.10 | 0.10 | 0.09 | 0.12 | 0.11 | 0.10 | 0.3 | 0.09 | 0.09 | 0.09 | 0.09 | 0.10 | 0.10 |
| Lead | mg/L | 0.01 | 0.02 | 0.02 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.0 | 0.01 | 0.01 | 0.01 |
| Zinc | mg/L | 0.10 | 0.15 | 0.13 | 0.10 | 0.25 | 0.13 | 0.10 | 0.10 | 0.14 | 0.27 | 0.12 | 0.6 | 0.10 | 0.11 | 0.1 | 0.11 | 0.11 | 0.11 |
| Iron | mg/L | 0.17 | 2.10 | 0.31 | 0.15 | 5.90 | 0.24 | 0.18 | 0.20 | 2.70 | 0.19 | 0.31 | 0.4 | 0.19 | 0.21 | 0.20 | 0.19 | 0.49 | 0.19 |
| Silver | mg/L | 0.01 | 0.01 | 0.01 | 0.01 | 0.10 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.0 | 0.01 | 0.01 | 0.01 |
| Aluminum | mg/L | 0.14 | 0.15 | 0.19 | 0.12 | 1.50 | 0.16 | 0.13 | 0.16 | 0.32 | 0.12 | 0.14 | 0.1 | 0.17 | 0.16 | 0.15 | 0.15 | 0.15 | 0.12 |
| Barium | mg/L | 0.02 | 0.02 | 0.02 | 0.02 | 0.03 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| Cadmium | mg/L | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.0 | 0.01 | 0.01 | 0.01 |
| Cobalt | mg/L | 0.03 | 0.07 | 0.05 | 0.04 | 0.07 | 0.05 | 0.04 | 0.04 | 0.06 | 0.03 | 0.05 | 0.06 | 0.05 | 0.05 | 0.05 | 0.05 | 0.04 | 0.04 |
| Chromium | mg/L | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.10 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.0 | 0.01 | 0.01 | 0.01 |

(A) Source: MOEE (1995)

Station 1 - Surface
1B - Bottom
1C - Centre

Monitoring of the quality of the water in the open pit was also carried out by the regulatory agency, the Ontario Ministry of Environment and Energy (MOEE). In June 1994, the MOEE sampled the open pit water column in six locations. At each location, water was collected from surface, at the bottom (top of the submerged waste rock), and midway in the water column. The depth of water ranged from 5 to 7 m. The MOEE water quality data is provided in Table 6. The MOEE found that the water quality in the pit has improved and is typical of mine water quality in the region.

## 6.0 Principal Findings

Key factors in the success of this in-pit disposal program include:

- the neutralization of acidic pore water;
- the relatively fast flooding of the waste rock (within 1.25 years after the first report of acidic drainage);
- sufficient waste rock storage capacity below the water table;
- the natural water table elevation results in the pit lake remaining within the confines of the open pit with no surface discharge.

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# CASE STUDY 2: RABBIT LAKE

## 1.0 Background

Rabbit Lake Mine is situated on the western shores of Wollaston Lake in Northern Saskatchewan. The Rabbit Lake mine was developed in 1975 and operated until 1984. The orebody was a near surface low grade uranium deposit located in a crystalline bedrock with $U_3O_8$ content of about 0.4%. The former Rabbit Lake was drained to permit access to the orebody. The ore was extracted using conventional open pit mining techniques leaving a pit with surface dimensions of about 460 m by 365 m and a maximum depth of about 122 m. A generalized plan of the Rabbit Lake mine site is provided in Figure 1.

During the early 1980's, Gulf Minerals and subsequently Eldorado Resources proposed the use of the Rabbit Lake pit for disposal of uranium tailings, instead of an expansion to an existing surface tailings impoundment. The tailings that would be deposited in the pit were from milling of ore from nearby mines; these were much higher grade than the Rabbit Lake tailings and contained arsenic and other elements of concern.

In December of 1982, Ministerial Approval was issued for the Collins Bay B-Zone Mining project which included the use of the Rabbit Lake pit for tailing disposal. We believe this was the first application of an engineered pit disposal concept, which in broad terms, included the following features.

- A bottom rock drain was used to collect drainage/seepage and for tailings dewatering.

- An engineered pervious envelope served as a drainage conduit during operations and as a pervious envelope at closure (the intent was that groundwater would flow around the pit through the envelope and that containment release would be controlled by diffusion through the pervious barrier).

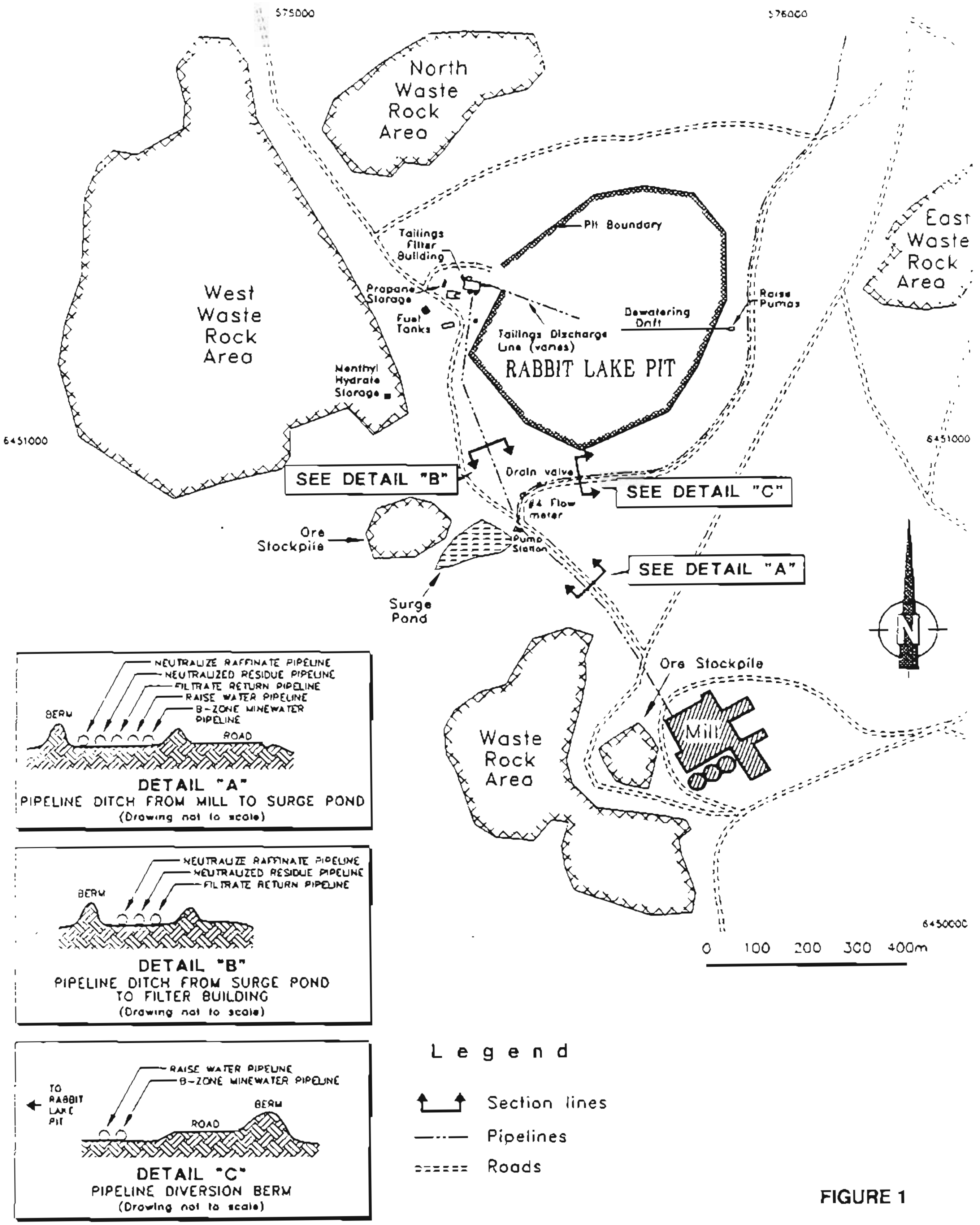

FIGURE 1

RABBIT LAKE OPEN PIT
IN-PIT TAILINGS DISPOSAL SYSTEM
AND PIPELINE ARRANGEMENT

SOURCE: CAMECO, 1994

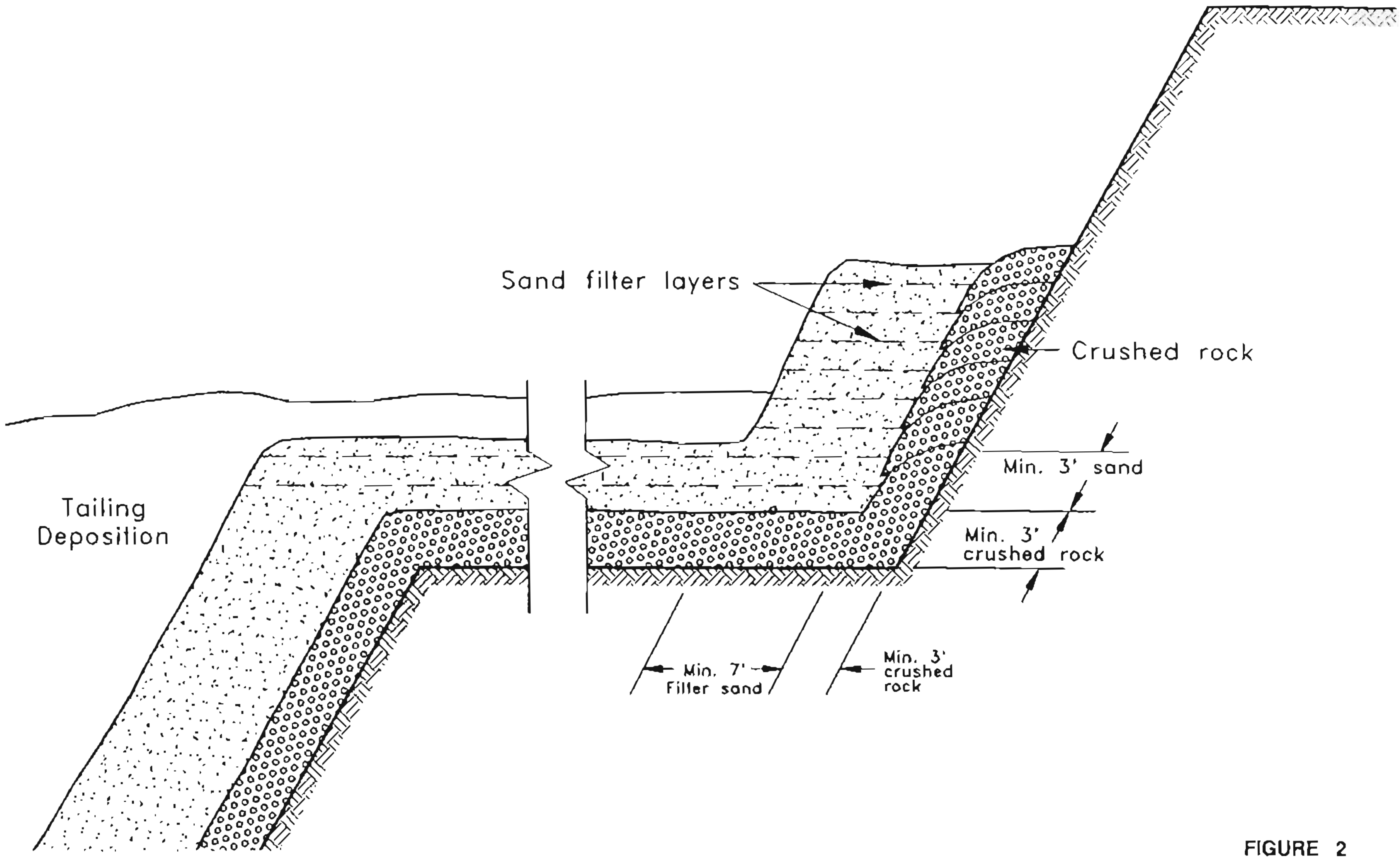

FIGURE 2

IN-PIT TAILINGS DISPOSAL
GENERAL SECTION
CONSTRUCTION PHASES - CRITERIA

Drawing not to scale

SOURCE: CAMECO, 1994

- Upon close-out, a soil/sand surface layer would be used to ensure contaminant release to the surface lake is controlled by diffusion.

- The final closure plan was a wet cover (surface lake).

The concept is illustrated in Figures 2 and 3.

A review of the history of events since start-up of the pit disposal concept is summarized from Cameco (1994):

- the initial dewatering drifts, drains and pervious envelope were completed by mid 1984;

- the first placement of tailings over a test section was completed in the fall of 1984. Filtered tailings were placed with earth moving scrapers;

- continuous deposition was initiated in November 1985; however, a thick layer of frozen tailings was produced. Thawing of the layer during 1986 made access to the tailings by mechanical equipment impractical;

- a test program using slurry deposition was proposed and accepted. Tailings would be thickened by blending CCD (counter-current decant) tailings thickener underflow with filter cake from filtered neutralized raffinate solutions;

- the slurry testwork results were encouraging and approval was given to extend operations to 1987 to evaluate the operation under winter conditions'

- a detailed assessment of the slurry placement option was completed by Geocon (1988) and formal approval was received following submission of an Environmental Impact Statement (EIS) by Cameco (1990); and

- the pit continues as the tailings basin for all ores milled at Rabbit Lake.

*Chemical Characteristics - Tailings Solids and Pore Water:*

The chemistry of the tailings solids is summarized from Cameco (1994) in Table 1. The results shown in Table 1 were from a series of boreholes drilled in September 1993. The tailings solids have a very high component of chemical precipitates. Gypsum content as $CaSO_4 \cdot 2H_2O$ averages more than 20% by weight. The arsenic content is elevated and averages 0.7% from milling ore from B-Zone pit.

The corresponding tailings pore water data from Cameco (1994) are provided in Table 2. The radium-226 levels average 51 Bq/L (ranging from 30 to 65 Bq/L) as compared with predicted levels of 69 to 121 Bq/L. The arsenic levels are elevated and average about 55 mg/L.

*Physical Characteristics - Tailings Solids:*

At the end of August 1994, approximately 3 x $10^6$ $m^3$ of tailings had been placed in the Rabbit Lake pit. The tailings solids have an average specific gravity of 2.74 and an overall average dry density for the entire tailings management facility. The dry tailings density is reported to vary horizontally from 0.97 $t/m^3$ at the centre to 0.80 $t/m^3$ at the periphery and vertically from 0.68 $t/m^3$ in the upper 40 m zone to 1.29 $t/m^3$ in the lower zone (Jarrell, 1995). Further consolidation will increase this density. The projected final configuration is shown in Figure 3.

Seasonal freezing requires ongoing revision to the original deposition plan. Field investigations and thermal modelling are being carried out. Several concepts are being investigated to minimize freezing and thus improve the overall consolidation rate of the tailings

## 2.0 Design Criterion

The Rabbit Lake pit was designed as an engineered containment basin. The existing pit was not ideally suited for simple underwater disposal for several reasons:

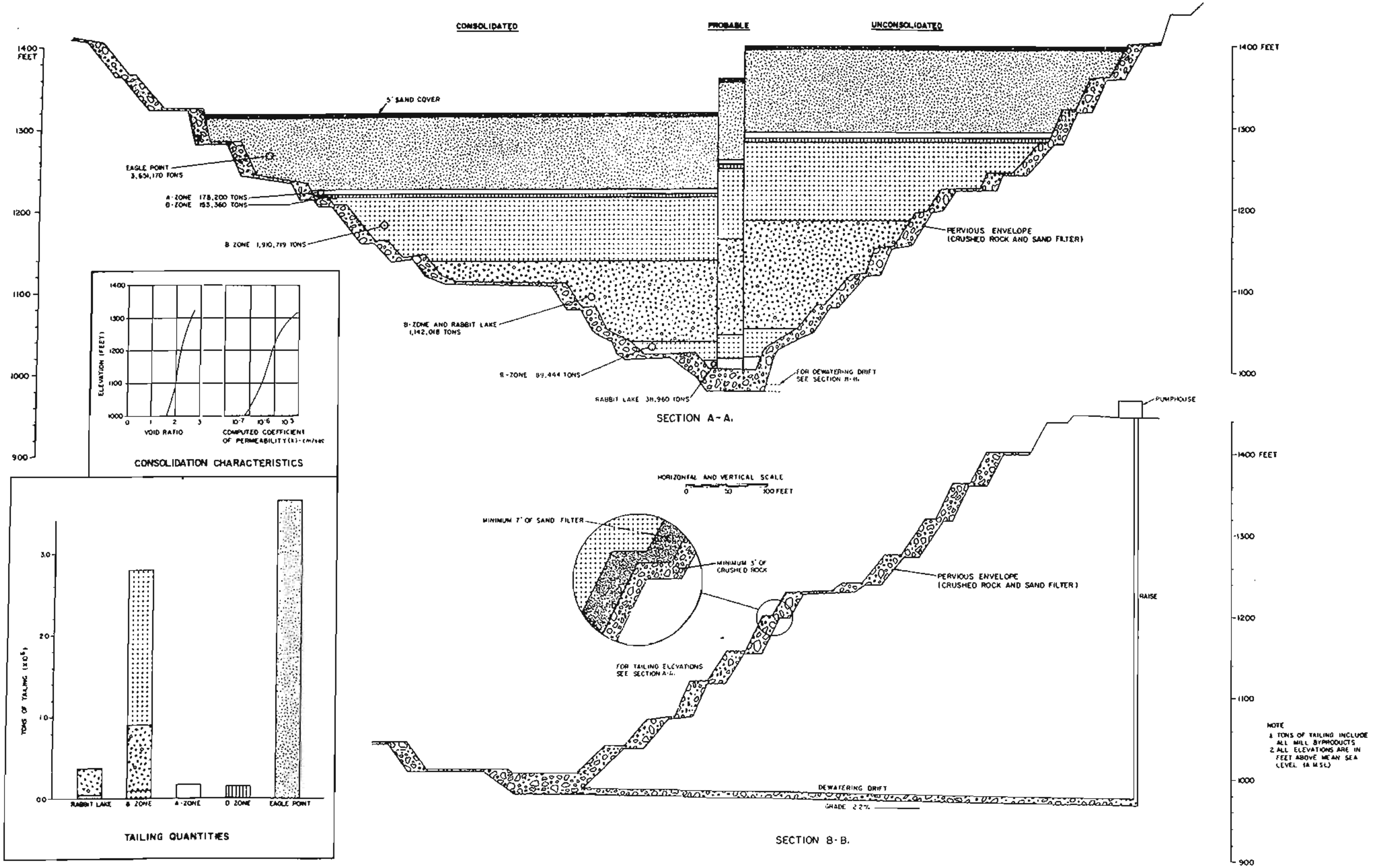

FIGURE 3

SCHEMATIC OF TAILINGS DEPOSITION
FOR THE DIFFERENT COLLINS BAY ORE DEPOSITS

SOURCE: CAMECO, 1994

Table 1

## RABBIT LAKE IN-PIT TAILINGS SOLIDS CHEMISTRY[*]

| Sample | Al mg/g | As mg/g | Ca mg/g | Fe mg/g | K mg/g | Mg mg/g | Mn mg/g | Ni mg/g | Pb mg/g | $SO_4$ mg/g | $^{226}$Ra Bq/g | U mg/g |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 18220 | 30 | 6.7 | 42 | 21 | 18 | 3 | 0.110 | 4 | 0.460 | 88 | 65 | 0.391 |
| 18221 | 28 | 10.0 | 47 | 15 | 16 | 2 | 0.160 | 6 | 0.510 | 265 | 70 | 0.305 |
| 18222 | 29 | 2.6 | 42 | 12 | 5 | 26 | 0.140 | 2 | 0.520 | 100 | 30 | 0.224 |
| 18223 | 23 | 7.8 | 55 | 14 | 5 | 12 | 0.140 | 5 | 0.490 | 109 | 45 | 0.485 |
| 18224 | 21 | 2.8 | 43 | 11 | 5 | 18 | 0.120 | 2 | 0.220 | 77 | 25 | 0.438 |
| 18225 | 34 | 4.2 | 45 | 25 | 12 | 5 | 0.180 | 4 | 0.110 | 87 | 55 | 1.010 |
| 18226 | 30 | 11.0 | 61 | 24 | 14 | 2 | 0.140 | 10 | 0.500 | 134 | 80 | 0.305 |
| 18227 | 38 | 11.0 | 57 | 14 | 12 | 3 | 0.120 | 8 | 0.580 | 1,150 | 90 | 0.378 |
| 18228 | 24 | 7.2 | 62 | 12 | 6 | 8 | 0.110 | 5 | 0.480 | 1,030 | 50 | 0.952 |
| n | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 |
| Min. | 21 | 2.8 | 42 | 11 | 5 | 2 | 0.110 | 2 | 0.110 | 77 | 25 | 0.224 |
| Max. | 38 | 11.0 | 62 | 25 | 18 | 26 | 0.180 | 10 | 0.580 | 1,150 | 90 | 1.010 |
| Mean | 29 | 7.0 | 50 | 16 | 10 | 9 | 0.136 | 5 | 0.430 | 120 | 57 | 0.499 |

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[*] From Cameco (1994), Table 6.2.4.

Table 2

## RABBIT LAKE IN-PIT TAILINGS PORE WATER CHEMISTRY[*]

| **Sample** | **Al mg/L** | **As mg/L** | **Ca mg/L** | **Fe mg/L** | **K mg/L** | **Mg mg/L** | **Mn mg/L** | **Ni mg/L** | **Pb mg/L** | **$SO_4$ mg/L** | **$^{226}Ra$ Bq/L** | **$U_T$ mg/L** | **pH** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| n | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| Min. | 0.74 | 12 | 580 | 0.016 | 8.5 | 2 | <0.005 | 0.03 | <0.02 | 1,650 | 30 | 0.040 | 8.08 |
| Max. | 0.99 | 132 | 698 | 0.024 | 32 | 13 | 0.008 | 0.17 | <0.02 | 2,330 | 65 | 0.383 | 8.77 |
| Mean | 0.88 | 55 | 650 | 0.019 | 17.5 | 7.2 | 0.006 | 0.08 | <0.02 | 1,886 | 51 | 0.200 | 8.40 |

---

[*] From Cameco (1994), Table 6.2.3.

- high source strength concentration of contaminants;
- hydrogeological conditions that created a relatively strong hydraulic gradient across to the pit;
- the poor settling nature of the tailings solids which required drainage to consolidate and provide adequate storage capacity; and
- the basin could not be adequately decommissioned with a surface barrier until consolidation of the surface had occurred.

As a result, engineering design and modifications were required to address these primary issues.

The pervious surround concept is described in the original Collins "B" Environmental Impact Statement (EIS) (GMCL 1981). The primary design concepts addressed:

- the consolidation characterization of the tailings;
- the pore water concentration of the tailings; and
- the engineering properties/performance of the pervious envelope.

The final envelope design is shown on Figure 2. In summary, the pervious envelope consists of a filter sand transition layer, against the tailings and a coarse clean crushed rock filter. Geocon (1988) specified the grain size and width for the filter. Clean waste rock from the original Rabbit Lake pit excavation was used for the crushed rock filter.

The criteria for permeability of the filter zone and width of the diffusion barrier to prohibit unacceptable contaminant releases were determined using conventional hydrogeological groundwater models.

*Predicted Performance:*

The objective of the pit disposal concept was to develop a tailings repository which provided secure long-term containment and did not impact on the environment. The pit meets these conditions; however the potential impacts can only be predicted as the facility is still operating. Cameco (1992) summarized the modelling that was completed to demonstrate the potential impacts from the facility. Some of the key assumption/data used for this assessment were as follows.

- The tailings permeability is $10^{-6}$ to $10^{-7}$ cm/s, thus under essentially a zero groundwater gradient, seepage from the facility (i.e. convective transport) can be ruled out as an important contaminant transport pathway.

- Molecular diffusion is the prime transport pathway through the sand filter. Estimates indicate that hydrodynamic dispersion is not important.

Based upon the above, simple diffusive transport equations were used to estimate the diffusive flux of contaminants from the tailings.

## 3.0 Implementation

The following description of the construction of the pervious envelope is taken from Cameco (1994).

> *"The pervious envelope consists of two different media, crushed waste rock and sand...The waste rock is crushed on an as-needed basis, close to the source and stockpiled near the crusher and/or on the ramp in the open pit. Transportation from the crusher site is by either end-dump trucks or by scrapers. Prior to use, the crushed waste rock must be checked for compliance with the screen-size criteria. The sand is hauled by scraper from the borrow area and put directly in place. After placement, any large rocks, tree parts or debris are removed to ensure a clean filter zone...*
>
> *Generally, crushed rock is first placed* (with a front-end loader) *against the rock wall around the entire perimeter of the pit and then a layer of sand is spread beside it. Another coarse layer of crushed rock is then placed followed by another layer of sand. The progression, alternate,*

> *operations of rock and sand placement are carried out until the envelope reaches a pit level-bench elevation* (see Figure 3).
>
> *The pit level-benches are then trimmed and any debris is removed. The bench floor is covered with a minimum of three feet of crushed rock which is tied into the crushed rock that was placed against the lower pit wall. A minimum of three feet of sand is then placed over the crushed rock, and this sand is tied into the sand filter-zone from below.*
>
> *The nominal height of the pervious envelope above the tailings is at least four feet; however, construction has been maintained at a somewhat greater height. Precautions are taken not to increase the height too far above the tailings so as to prevent sloughing of the filter sand embankment and to minimize the amount of sand overlapping the tailings at the toe of the filter sand sidewall.*
>
> *If winter construction is required, all ice build-up on the pit wall in the areas of crushed rock placement, and all snow accumulation on the top of the pervious envelope is removed. This ensures that continuity throughout the envelope is maintained..."*

## 4.0 Monitoring

The current monitoring program at Rabbit Lake includes the following components (Cameco, 1994):

- physical properties of pervious envelope material;
- grade elevation surveys of envelope and tailings;
- tailings instrumentation: clusters of instruments for settlement and pore water pressure;
- other instrumentation: piezometer clusters installed at the base of the pit for monitoring after decommissioning;

- physical properties of tailings;
- water pumped from a raise connected to the pit; and
- groundwater quality.

The monitoring program was expanded to include investigations to characterize the following (Cameco, 1994):

- tailings chemistry;
- pore water sampling;
- ice formation and thawing;
- tailings segregation;
- water balance for the pit; and
- adsorptive capacity of the filter material.

In addition to the above established programs, the following are in various stages of implementation (Cameco, 1994):

- sampling lysimeters in the sand filter envelope;
- multi-level sampling piezometers located up-gradient and down-gradient of the Rabbit Lake pit;
- additional and replacement pore pressure and consolidation instrumentation;
- variability of precipitates and solids in tailings chemistry; and
- hydraulic properties of unsaturated tailings.

## 5.0 Potential Costs

The costs for in-pit disposal will depend upon numerous factors. The major costs are related to the placement of the filter and the final cover. Over the operating period, the total amount of material imported for building the filter has been about 0.15 $m^3$/t of tailings. This material is all processed (crushed) and likely costs about \$15/$m^3$ or \$2.25/t of tailings (\$1995). Other costs for operation of the filter plant would be additional.

The other major cost will be placement of the surface barrier at closure. A 0.5 m barrier would require about 280,000 $m^3$ of material and would add $4,200,000 to the total cost. Based on 8.8 million tonnes of tailings, the direct cost for placing the cover would be about $0.48/t.

Therefore, based on the above estimates, the cost for placing wastes in the pit using this disposal concept (exclusive of water treatment and the operation of the filter plant) is about $2.62/t of tailings.

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# CASE STUDY 3: COLLINS "B"

## 1.0 Background Information

The Collins Bay B-Zone is located in Northern Saskatchewan on Harrison Peninsula of Wollaston Lake (Figure 1) approximately 10 km north of the Rabbit Lake pit described in Case Study #2. Cameco Corporation completed mining of uranium from the B-Zone pit in 1991 and has implemented a decommissioning program.

The B-Zone pit dimensions are approximately 910 m by 305 m by 40 m deep with the northern end extending 150 m into Collins Bay of Wollaston Lake. The pit is separated from the bay by a steel dyke filled with sand and till. More details on the pit characteristics are given in Table 1 along with details on the amount of waste disposed in the open pit prior to flooding.

Table 1

**COLLINS BAY B-ZONE PIT CHARACTERISTICS**

| Pit Feature | Value |
|---|---|
| Length (m) | 910 |
| Width (m) | 305 |
| Depth (m) | 40 |
| Surface Area ($m^2$) | $28 \times 10^4$ |
| Volume ($m^3$) | $52 \times 10^5$ |
| Steel Dyke Cell Diameter (m) | 10.7 |
| Volume of Waste Rock ($m^3$) | $4.3 \times 10^5$ |
| Volume of Environmental Special Waste ($m^3$) | $9.8 \times 10^4$ |
| Drainage Area of B-Pit ($m^2$) | $4.25 \times 10^5$ |
| Depth of Waste Rock in the Pit(m) | 20 |
| Depth of Environmental Special Waste in the Pit (m) | 5 |

Source: SENES, 1995.

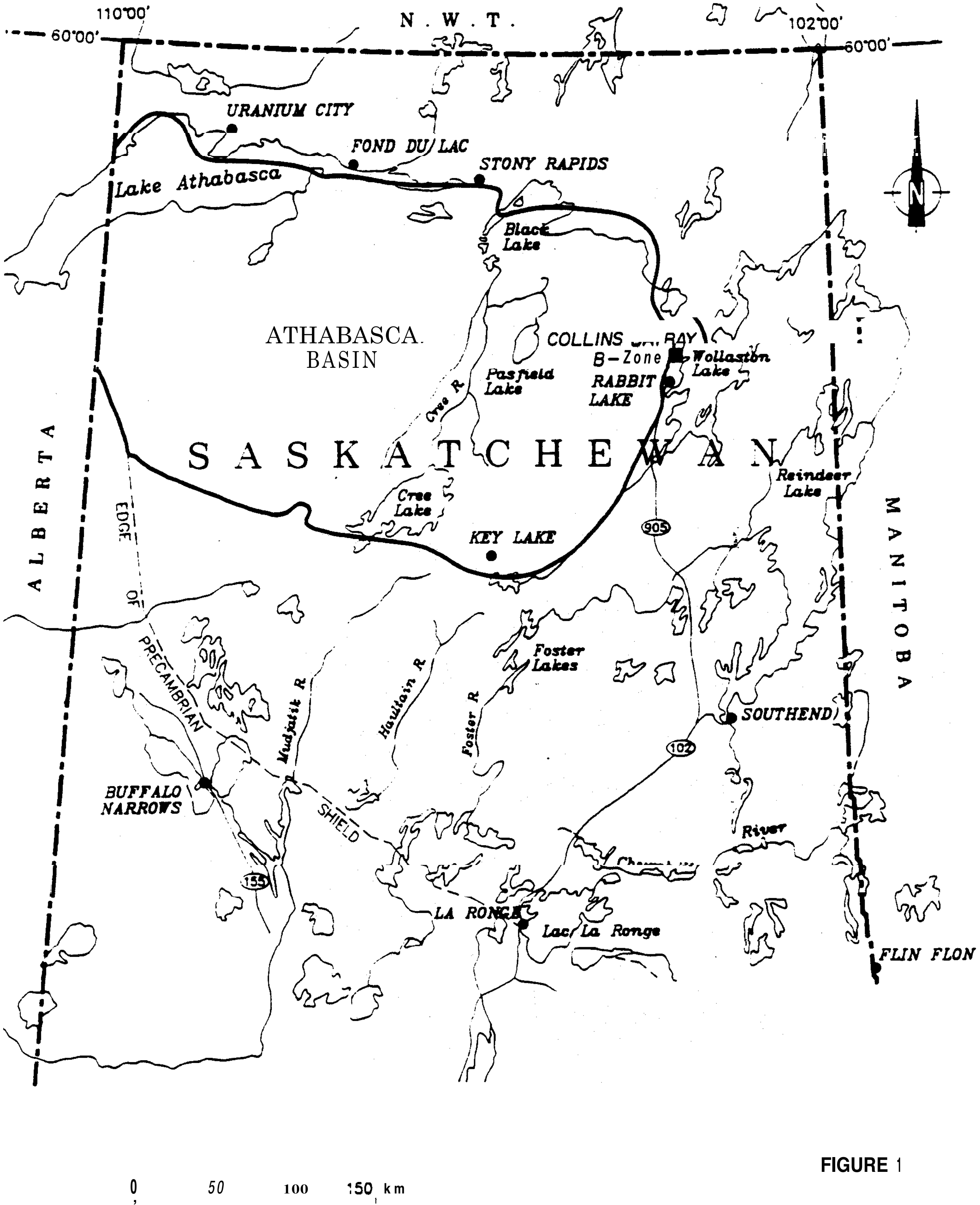


FIGURE 1

LOCATION MAP
COLLINS BAY B-ZONE PIT

SOURCE: CAMECO (1994)

Since decommissioning plans began for the Collins Bay B-Zone, a number of studies have been submitted to the regulatory agencies for review (Cameco, 1993, 1991, 1990, 1989; SENES, 1989, 1988).

Conditional approval to place special waste in the pit bottom and to flood the open pit was given in September, 1991. Environmental special waste is waste that contains elevated arsenic, nickel, sulphur or uranium content.

Environmental special waste that was stockpiled adjacent to the B-Zone pit was placed in the south end of the pit and covered with 2 m of till. Other mine waste was left in the north end of the pit towards the end of the mining cycle. The pit was then flooded between November 26, 1991 and March 14, 1992. The flooding was completed by pumping water from Collins Bay, this allowed the pit to be flooded in a relatively short period of time.

The B-Zone waste rock pile, located southeast of the flooded open pit, is assumed to have contaminated seepage pathways which will eventually report to the B-Zone pit and to Ivison Bay of Wollaston Lake (Figure 2). Surface runoff/seepage from the waste rock is collected in a perimeter ditch/sump system. The predictions of pit water quality includes the effect of contaminant flux from waste rock left behind in the north end of the pit, special waste placed under a till cover in the south end of the pit, and mineralized zones exposed on the walls of the pit.

One year after the decommissioning of the B-Zone pit, Cameco submitted a report that detailed the monitoring data, completed and proposed investigative studies, and proposed pit target levels for water quality based on the protection of the environment (Cameco, 1993). This included a risk assessment of the impact due to metal and radionuclide concentrations in the B-Zone pit. A revised pathways analysis of the decommissioning alternatives was prepared for Cameco in January, 1995 (SENES, 1995).

## 2.0 Technical Data and Evaluation

*Waste Characterization:*

During 1992, Cameco initiated field investigations at the B-Zone pit and B-Zone waste rock pile to obtain information on the chemical and radiological characteristics of mine wastes at these sites. Special waste was sampled as the material was placed in the pit prior to flooding (Jarrell, 1995). The program included analysis of bulk samples of the major rock units, drill cutting samples and special waste samples. Key constituents included, arsenic, nickel , uranium, lead-210 and radium-226, which were found at elevated levels in several mine water and waste pile seepage samples. The sulphur content of the B-Zone waste materials was found to be generally less than 0.05% and consequently the acid generation potential has been assessed to be low (SRK, 1993).

A summary of the geochemical data on the waste rock and environmental special waste samples collected during the field investigation is provided in Table 2. The head grade analysis used in the leach test studies are also shown in Table 2, for comparison purposes.

The rock analysis data indicates that the waste rock typically has a low metal and radionuclide content although the drill cuttings indicate that the grab samples subjected to leach testing may not be truly representative of the overall characteristics of the B-Zone waste rock pile.

## 3.0 Environmental Monitoring

There is a large amount of data from the monitoring of the flooded pit. This includes sampling and analysis of the surface water quality and groundwater quality in the surrounding strata, and sedimentation in the pit.

Table 2

## CHEMICAL AND RADIOLOGICAL CHARACTERISTICS OF B-ZONE WASTE ROCK AND SPECIAL WASTE

| | | **Waste Rock Samples** | | **Special Waste Samples** | | **Leach Test Samples** | |
|---|---|---|---|---|---|---|---|
| **Element** | | **Bulk Samples of Major Rock Units**[a] | **Drill Cuttings from Waste Rock Pile**[b] | **Composite Sample from Pile**[c] | **Average of 5 Individual Samples**[d] | **Dynamic Column Test Samples**[e] | **Humidity Cell Composite Sample**[f] |
| Arsenic (mg/kg) | $\bar{X}$ | 10.5 | 90.8 | 1,250 | 468 | 277.1 | 13.1 |
| | $\sigma_x$ | 7.2 | 151.8 | - | - | 123.9 | - |
| | n | 6 | 30 | - | - | 8 | - |
| Nickel (mg/kg) | $\bar{X}$ | 17.7 | 105.5 | 1,055 | 289 | 385.6 | 10.1 |
| | $\sigma_x$ | 15.6 | 270.8 | - | - | 72.6 | - |
| | n | 6 | 30 | - | - | 8 | - |
| Uranium (mg/kg) | $\bar{X}$ | 22.5 | 203.7 | 1,600 | 1,524 | 126.6 | 21.6 |
| | $\sigma_x$ | 16.9 | 412.0 | - | - | 21.0 | - |
| | n | 6 | 30 | - | - | 8 | - |
| Lead-210 (Bq/kg) | $\bar{X}$ | 375 | 6,430 | 15,000 | 19,800 | 2,800 | 340 |
| | $\sigma_x$ | 350 | 5,610 | - | - | 2,800 | - |
| | n | 6 | 6 | - | - | 8 | - |
| Radium-226 (Bq/kg) | $\bar{X}$ | 220 | 6,125 | 17,000 | 16,000 | 1,900 | 215 |
| | $\sigma_x$ | 110 | 5,530 | - | - | 300 | - |
| | n | 6 | 6 | - | - | 8 | - |

Notes:

$\bar{x}$ arithmetic mean, √x - standard duration, n - number of observations.

[a] Bulk samples obtained from walls of B-Zone pit and waste rock pile.

[b] Drilling cuttings taken from five boreholes drilled in waste rock pile.

[c] Special waste samples collected daily when waste moved and composited for analysis.

[d] Special waste samples (5) collected for leach test work in 1991.

[e] Waste rock pile samples collected for leach test work in 1989.

[f] Bulk samples noted in a) above were composited in proportion to the amount of each rock unit for use in humidity cell test work.

Source: SENES, 1995

*Surface Water Quality:*

Monitoring of the surface water quality is done at four locations in the B-Zone pit as well as four other locations (see Figure 2). Parameters measured include temperature, dissolved oxygen, conductivity, pH and redox. Figures 3, 4 and 5 (temperature, dissolved oxygen and pH) illustrate the changes in conditions at different times of the year. During the summer, the surface water in the pit is warm and slightly alkaline; the effects of algal growth during the summer are being investigated.

Key water quality constituents are also measured at the monitoring locations. These include many trace metals, radionuclides, nutrients and major constituents. Arsenic, nickel, solids, radium-226 and uranium concentrations for one of the pit monitoring locations are shown in Figure 6; these analyses show that many of the constituents concentrate near the bottom of the pit.

*Groundwater Quality:*

Monitoring is undertaken to assess the movement of the constituents through the groundwater from the waste rock pile. Piezometers were set up at various locations around the stockpiled waste rock as shown in Figure 7.

Piezometers close to the perimeter of the waste rock pile show little evidence of contaminant migration to date. For example, the average levels of the contaminants of interest in 1994 in the overburden and bedrock samples from piezometer RP24 located adjacent to north edge of the pile were: 0.9 µg/L arsenic, 3.2 µg/L nickel, 6.7 mg/L sulphate, 2.6 µg/L total uranium and 0.006 Bq/L radium-226. These contaminant levels are typical of the levels measured at other piezometer nests near the B-Zone waste rock pile. These contaminant levels are not substantially elevated above background.

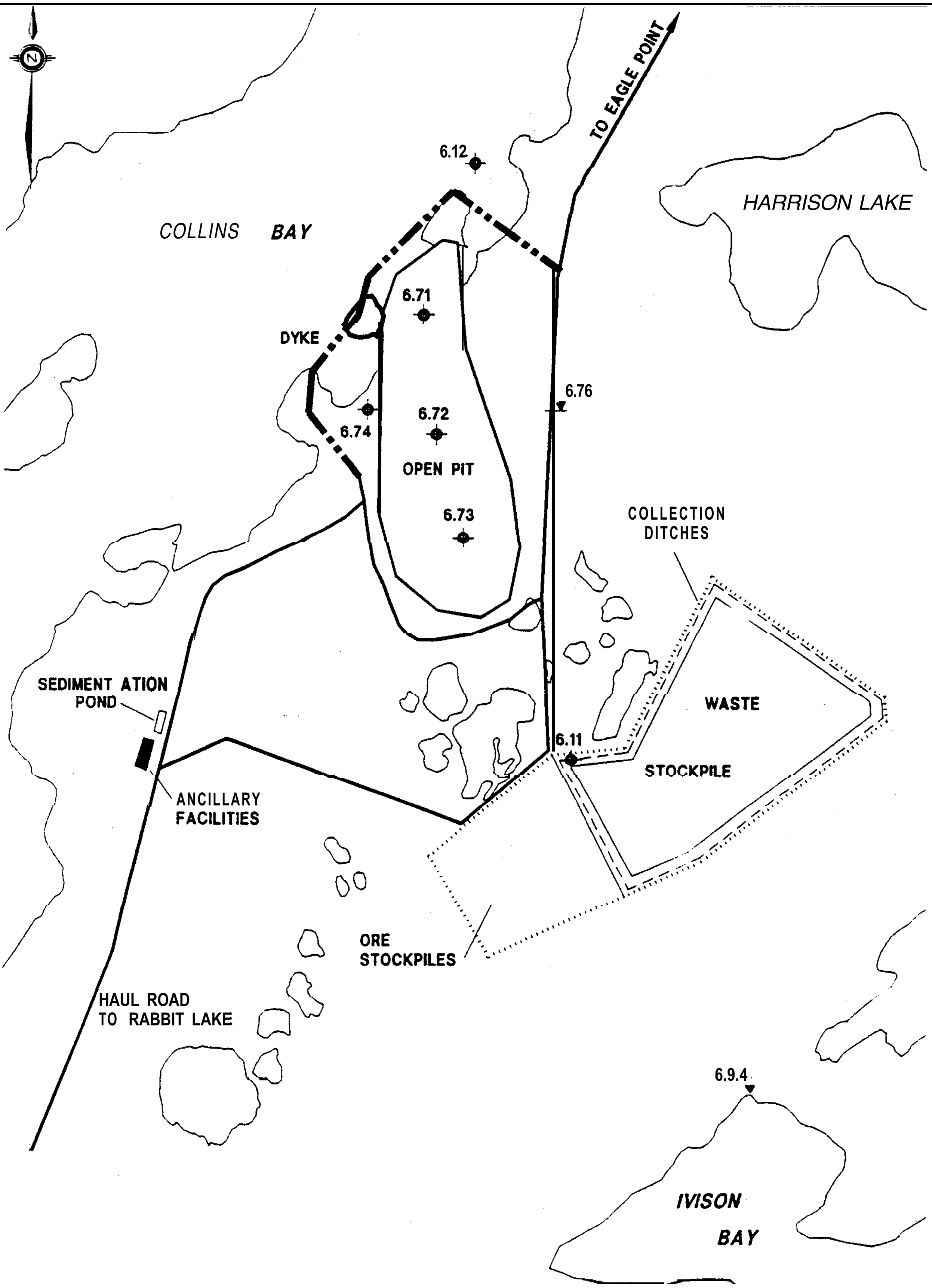


FIGURE 2

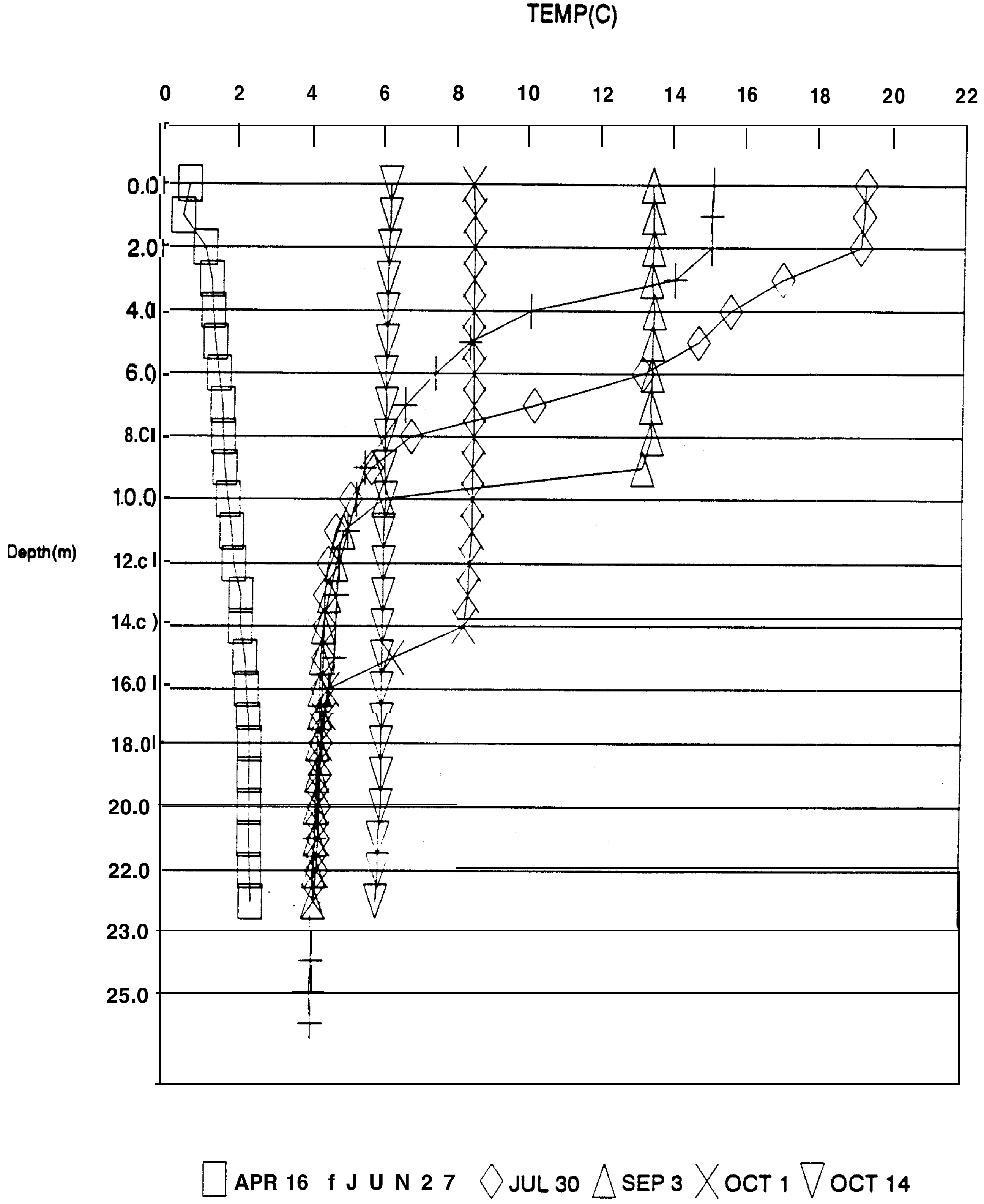
SURFACE WATER SAMPLING LOCATIONS

SOURCE: CAMECO (1994)

FIGURE 3

## WATER TEMPERATURE PROFILE

STATION 6.71 – 1994

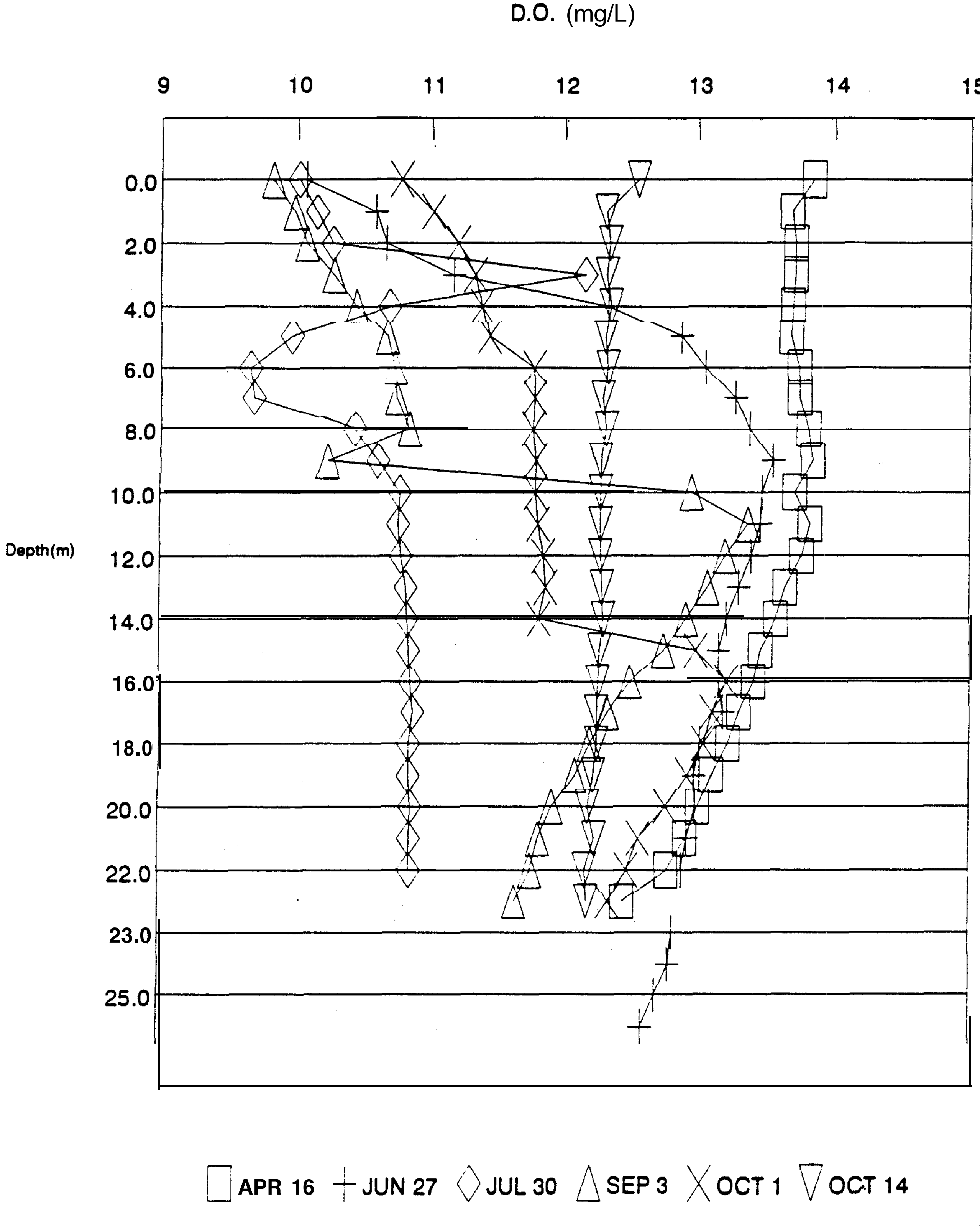


SOURCE: CAMECO (1994)

FIGURE 4

## DISSOLVED OXYGEN PROFILE

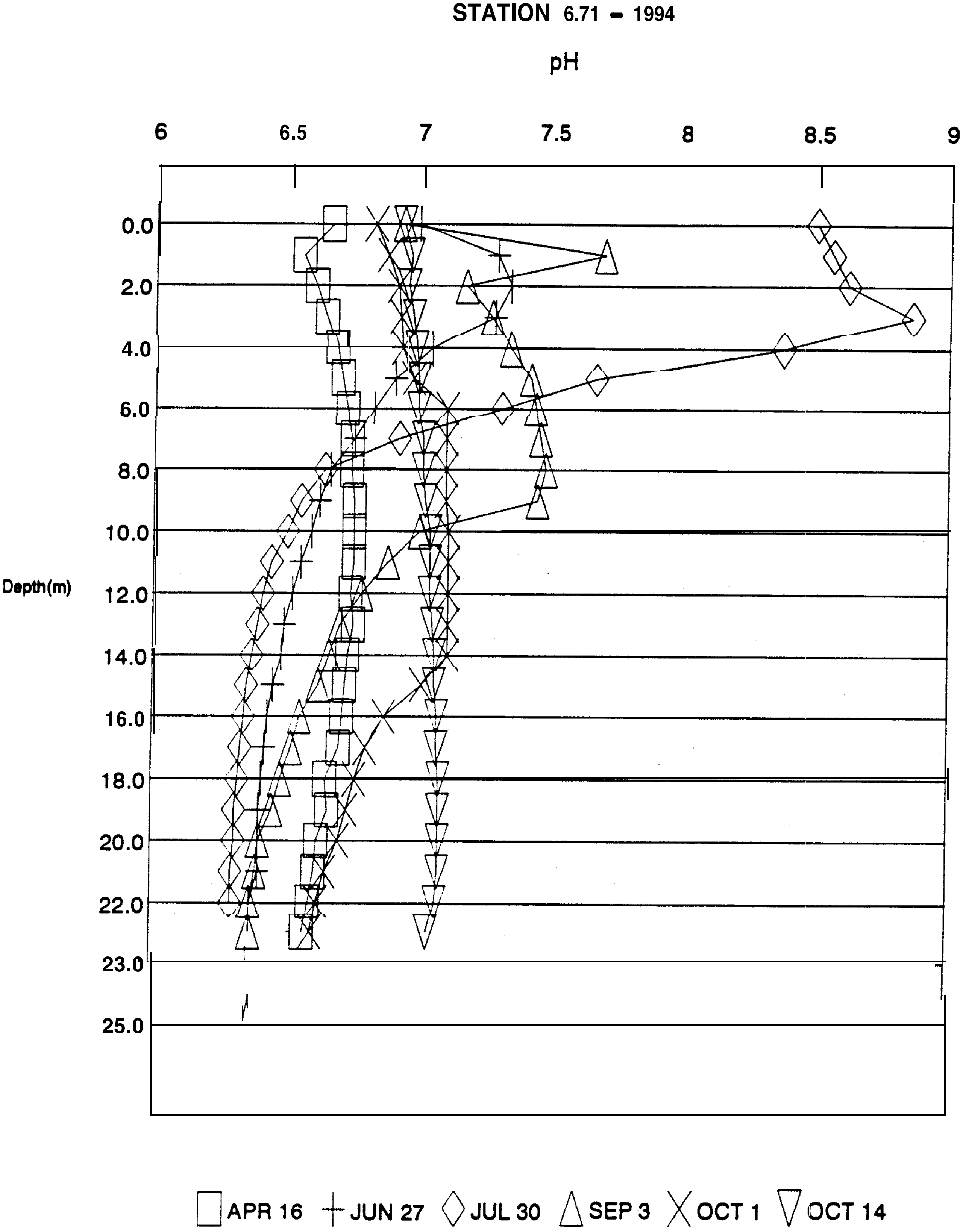
STATION 6.71 - 1994



SOURCE: CAMECO (1994)

FIGURE 5

## pH PROFILE

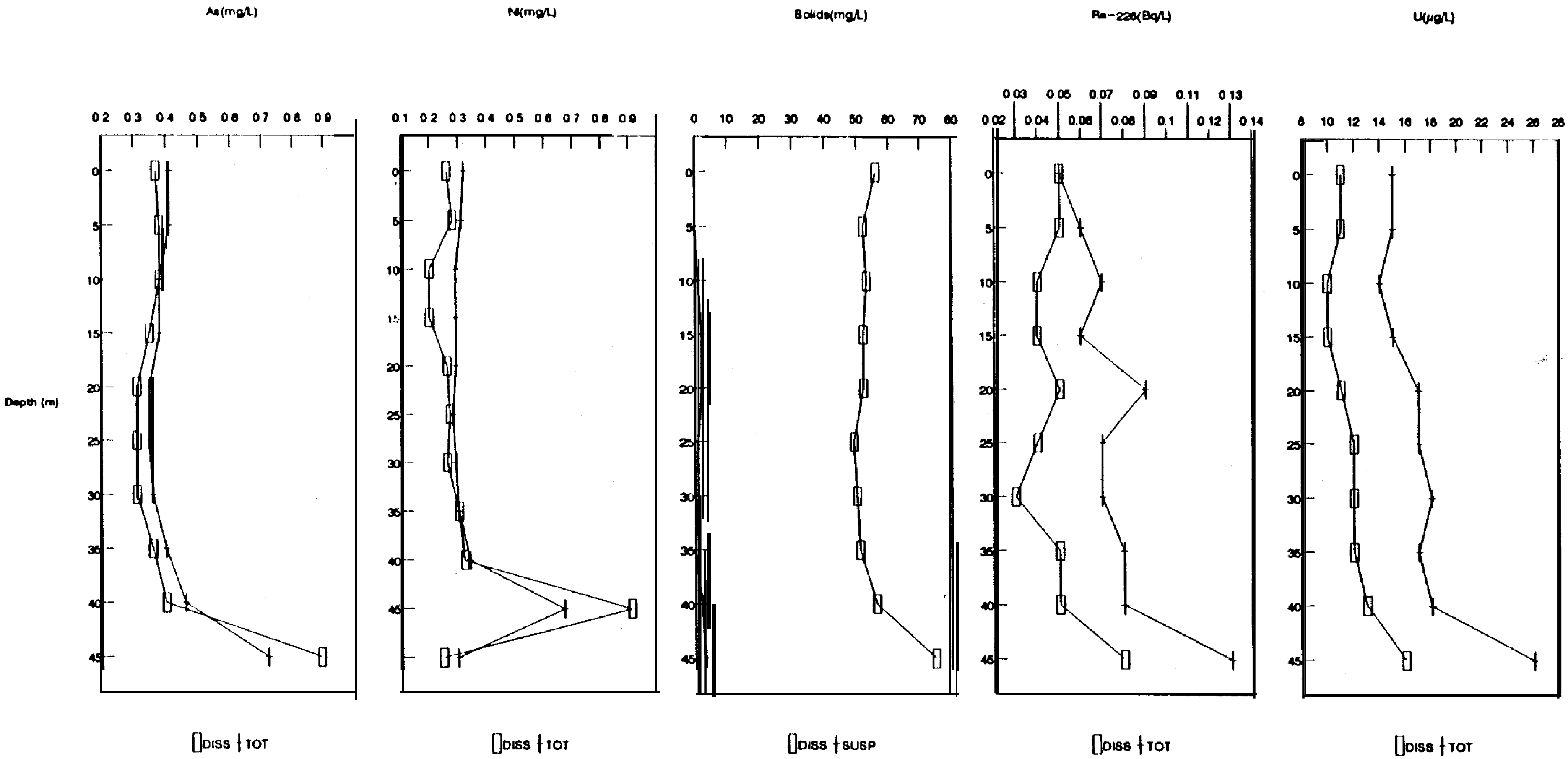


SOURCE: CAMECO (1994)

FIGURE 6

## ARSENIC, NICKEL, SOLIDS, RADIUM-226 AND URANIUM PROFILES

STATION 6.72 - APRIL 17, 1994



SOURCE: CAMECO (1994)

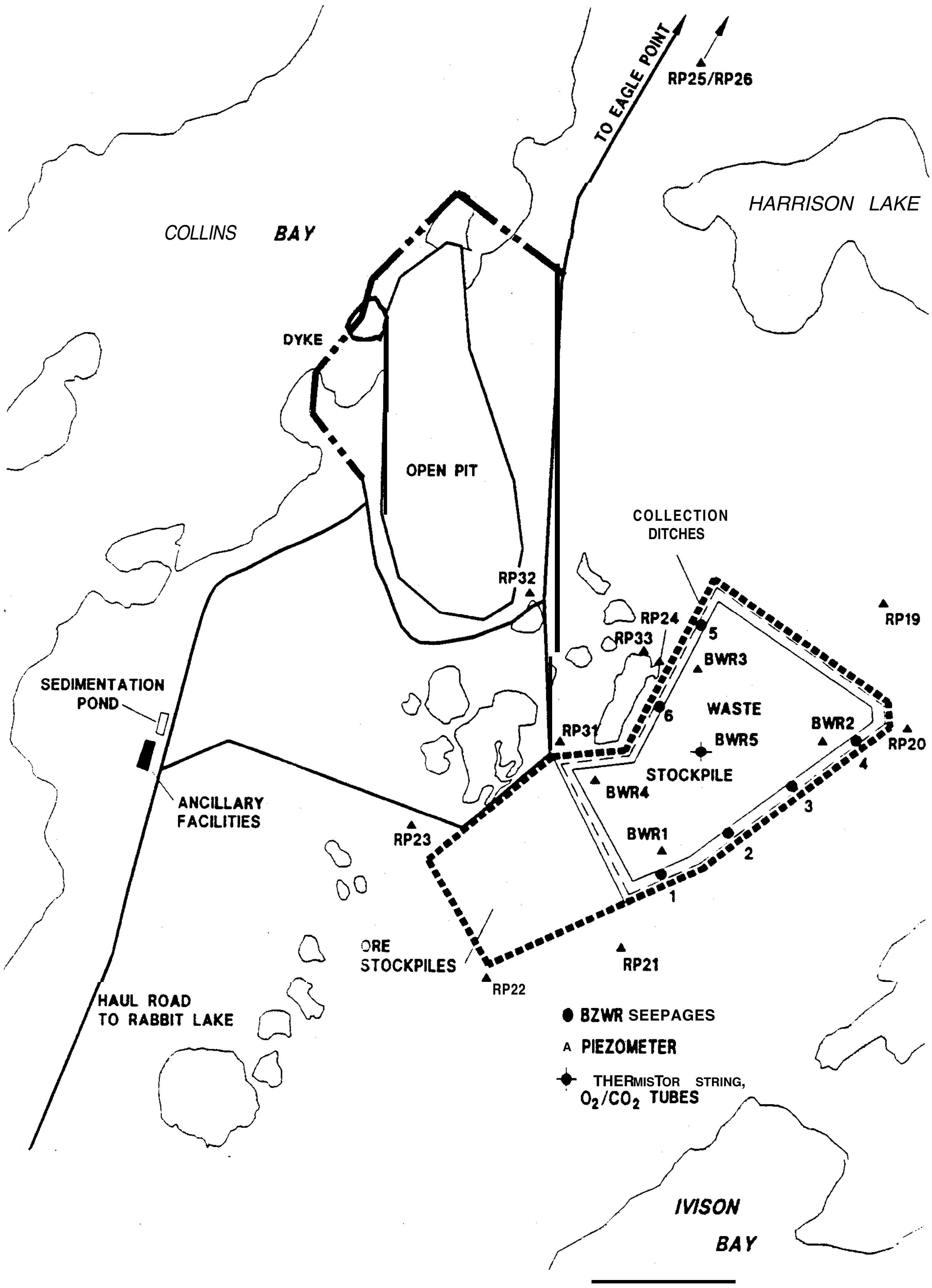


FIGURE 7

GROUND WATER SAMPLING LOCATIONS

SOURCE: CAMECO (1994)

*Sedimentation:*

The concentration of contaminants in the pit water column will be influenced by water flow through the pit and contaminant removal by settling solids. It is generally accepted that dissolved contaminants concentrate in the sediments either by adsorption to solid particulates or by biological removal mechanisms. A monitoring program was undertaken to assess these parameters.

In addition to monitoring pit water quality, sediment traps have been set each summer to determine sedimentation rates. Two sets of sediment samples have been sent to the laboratory for element analysis. The solid matter in one sample was separated into organic and inorganic solids for separate analyses. The results showed that the organic matter (i.e. algae) contained much higher levels of arsenic and nickel than the inorganic solids. The sediment and water chemistry data were used therefore to calculate site specific water-to-solids partitioning coefficients ($k_D$ values) as follows:

Table 3

**SITE-SPECIFIC WATER-TO-SOLIDS PARTITIONING COEFFICIENTS**

| **Element** | **Measured Element Concentrations** | | **Calculated $k_D$ Values** | |
|---|---|---|---|---|
| | **Organic Solids** | **Pit Water** | **mL/g** | **$m^3/g$** |
| Arsenic | 520 µg/g | 0.323 µg/mL | 1,610 | 0.0016 |
| Nickel | 1,700 µg/g | 0.259 µg/mL | 6,565 | 0.0066 |
| Uranium | 109 µg/g | 0.015 µg/mL | 7,300 | 0.0073 |
| Radium-226 | 0.7 Bq/g | 0.0001 Bq/mL | 7,000 | 0.0070 |

In addition to the $k_D$ term, contaminant removal is influenced by the sedimentation rate. Field measurements made between 28 June 1994 and 9 September, 1994 gave an algae sedimentation rate of 1.5 g (dry wt)/($m^2 \cdot d$). For a six-month open water season, the annual sedimentation flux equals approximately 275 g/($m^2 \cdot a$). This flux is comparable to levels measured on many whole lake systems (Beak, 1988).

## 4.0 Modelling

A computer simulation was performed by SENES (1995) using the Uranium Tailings Assessment Program (UTAP) which was developed under contract to CANMET, Energy Mines and Resources Canada (SENES, 1984, 1985, 1986, 1987). The simulation included prediction of the water quality in the B-Zone pit, Collins Bay and Wollaston Lake, and provided estimates of the potential radiological dose to human receptors in the area. A schematic representation of the modelling components of the aquatic environment is presented in Figure 8.

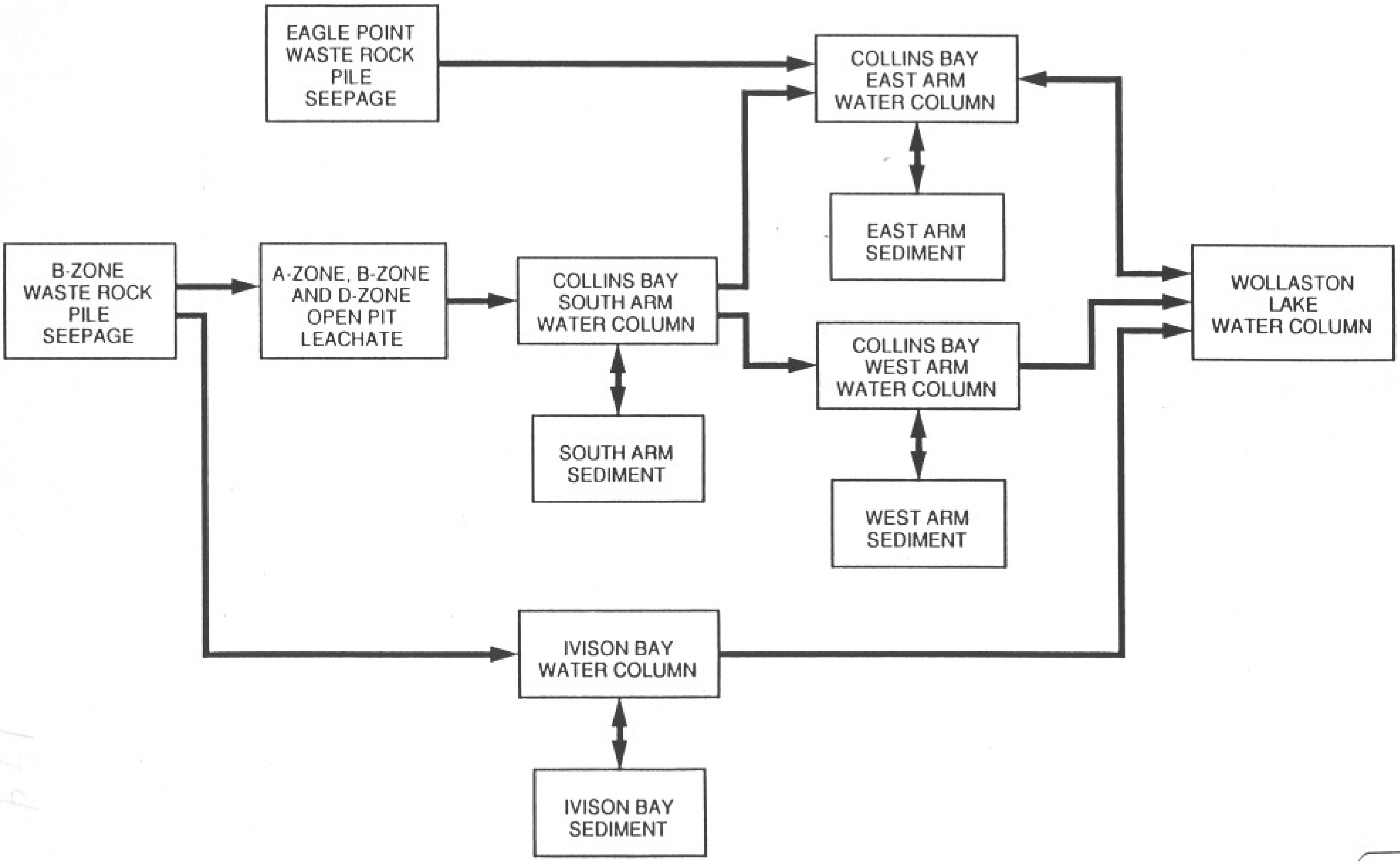
The quality of water in a flooded pit is influenced by the rate of water exchange with Collins Bay, leaching of contaminants from waste rock or environmental special waste left behind or placed in the pit at closeout, and from leaching of mineralized zones exposed on the walls and floors of the pit as well as the fractured surfaces of the pit. Chemical stratification would be expected to occur within the waste rock pore volume. The modelling of this process assumed that the dispersion across the chemocline would have transport properties similar to dispersive transport in thermally stratified waters. The placement of a 2 m till cover over the environmental special waste eliminates the convective flow through this waste. The calculation of the mass transfer for submerged wastes covered with a till cover was performed taking into account diffusive mass transport.

*Comparison of Model with Measured Data:*

The comparison of the predicted concentrations from the UTAP modelling with those measured in 1994 (3 years after flooding B-Zone pit) for six constituents of interest are in Table 4.

FIGURE 8

## AQUATIC ENVIRONMENT MODEL COMPONENTS



SOURCE: CAMECO (1994)

Table 4

**COMPARISON OF PREDICTED AND MEASURED CONCENTRATIONS**

| Element | Units | Mean Measured Dissolved Level in 1994 | Average Predicted Dissolved Level Year 3 |
|---|---|---|---|
| Arsenic | mg/L | 0.359 | 0.248 |
| Nickel | mg/L | 0.303 | 0.252 |
| Sulphate | mg/L | 10.5 | 10.0 |
| Lead-210 | Bq/L | 0.11 | 0.076 |
| Radium-226 | Bq/L | 0.06 | 0.091 |
| Uranium | mg/L | 0.014 | 0.020 |

Source: SENES, 1995; Jarrell, 1995.

The measured levels are average, volume-weighted values of four sets of measurements made on samples from the main sampling station (Station 6.72) in the B-Zone pit during 1994. Comparison of measured and predicted levels indicates excellent agreement in the sulphate levels, overprediction of the radium-226 and uranium levels and underprediction of the arsenic, lead-210 and nickel levels. Overall the agreement was assessed to be good.

## 5.0 Principal Findings

It is Cameco's belief that, in time, the ecosystem in the flooded pit will be similar to that of Collins Bay, with respect to species diversification and biomass of both flora and fauna. The trends in the monitoring data suggest that water quality is improving with time.

Levels of arsenic and nickel in the pit water do not meet the objectives set by the provincial government for the protection of aquatic life. Monitoring has shown that aquatic life in the pit is limited to primary producers. The reason that higher life forms are not present is believed to be due to physical rather than chemical factors.

Present constituent concentrations are stressful but not deleterious to aquatic biota.

The effect of breaching the dyke between the pit and Collins Bay was investigated by modelling (SENES, 1995). Breaching of the dyke was predicted to result in lower contaminant levels in the pit due to the influence of water exchange with Collins Bay. However, it would still take time for arsenic and nickel to meet Provincial objectives.

Studies are continuing on means of accelerating both biologic diversity and productivity in the pit water. At the end of the proposed 5-year monitoring period, a review of the conditions will be conducted to allow for new target levels to be developed based on the welfare of existing or expected biological communities.

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# CASE STUDY 4: ISLAND COPPER

*Most of the information presented in this case study was derived from the Island Copper Closure Plan (BHP Minerals Canada, 1994).*

## 1.0 Background

*Operating History:*

The Island Copper Mine is an open pit located at the northern end of Vancouver Island B.C., on the north shore of Rupert Inlet, 16 kilometres south of Port Hardy. Construction started in June 1969 and the first concentrates were produced in 1971. The mine has operated continuously, at an initial production rate of 108,000 tonnes per day, which was increased to 157,000 tonnes per day in the early 1980's. Current production rate is 85,000 tonnes per day and will continue at this rate until the planned closure in 1996.

A total of about 325 million tonnes of ore have been mined and processed, to recover more than one million tonnes of copper, 27,000 tonnes of molybdenum, 28 million grams of gold and 312 million grams of silver. The thickened tailings are discharged via a submarine outfall into Rupert Inlet. A continuous oceanographic monitoring program and numerous research studies conducted since 1969 indicate minimal effect.

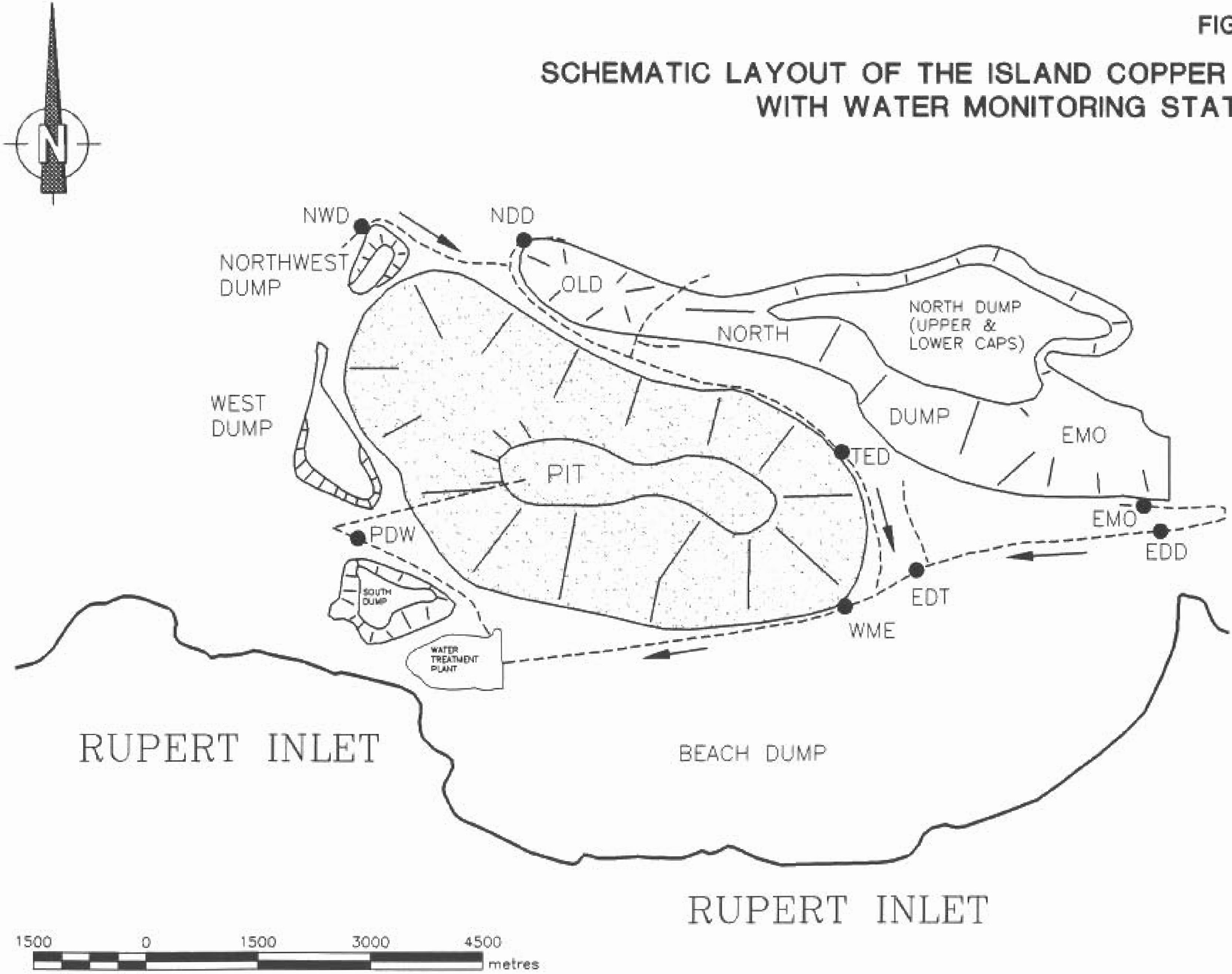
This operation has produced 630 million tonnes of waste rock which is trucked to dumps for disposal. Four on-land dumps and a beach dump have been used; currently, all waste rock is placed on in-pit waste dumps (about 20 million tonnes to end of mine life). Figure 1 shows a schematic layout of the pit and adjacent waste piles.

*Environmental Setting:*

The area supports commercial fishing (salmon, crabs and shrimps) and local fish farms. Forestry is the major source of income and employment, based on the densely treed

## FIGURE 1

# SCHEMATIC LAYOUT OF THE ISLAND COPPER MINE WITH WATER MONITORING STATIONS



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coniferous west coast rain forest. The weather is mild (mean 8˚C) and humid (annual mean 1800 mm).

The geology is dominated by a thick sequence of Middle Triassic to Lower Jurassic rocks. The Island Copper island-arc type porphyry Cu-Mo-Au deposit was formed by intrusion of a Mid-Jurassic, dike-like body of rhyodacite porphyry into Bonanza Group volcanic rocks.

The ore mainly occurs in an upright, horseshoe-shaped shell in volcanic rocks. The overlying glacial tills, sands and gravels are typically 0 to 30 m deep with a top layer of forest soil. These materials were stockpiled for waste-rock dump reclamation.

Drainage is primarily south into Rupert Inlet. The disturbed land area was principally coniferous forest (e.g western hemlock, western red cedar, Douglas fir.), with marshes along the rivers. The area supports a wide range of mammals and birds, as well as trout, steelhead and several types of spawning salmon.

*Inventory of Waste Materials:*

The beach waste dumps extend into Rupert Inlet and contain 540 million tonnes of waste rock. They cover 261 ha, of which 56 ha have been vegetated (including red alders on 15 ha). Intensive monitoring of water quality within the dump indicates levels above background but within permit concentration for discharge, with no tendency to increase over the seven-year survey period.

The land dumps around the perimeter of the pit contain 90 million tonnes of waste rock distributed over 193 ha; 170 ha have been revegetated and 90 ha totally restored to wildlife habitat. Acidic seepage only became evident from these dumps in late 1985; since 1990, the water has been collected and used in the mill. After closure, water from the land dumps will be directed to the flooded pit. This is discussed further in Section 3.0, Pit Closure Options.

All land and beach waste rock areas will be restored by 1997.

*Major Closure Concerns:*

The major closure challenges for this site are:

i) the long term status of the marine environment;
ii) general restoration of the site as wildlife habitat;
iii) the acidic drainage from the land waste rock areas; and
iv) the management of the pit;

The marine environment has been closely evaluated throughout the operation of the mine, and the indication is that there will be a rapid transition from minimal effect to no effect after closure. Similarly, the surface restoration should be essentially complete by 1997. The last two concerns are discussed in detail in the following sections.

## 2.0 Acidic Drainage from Land Waste Rock

*Historical:*

Water flowing from the land dumps showed no sign of acidity from 1971 to 1985, at which time elevated zinc concentrations became evident in the North Dump drainage ditch. Steps were taken to intercept all drainage and transfer it to a Water Management Pond. This combined flow is identified as WME (Water Management East). The water is accumulated in a water management pond and most is used as process water in the mill. In accordance with the mine's waste management permit, water discharged has to be *equivalent to or better than:*

| | |
|---|---|
| *pH* | *6.5 to 11.5* |
| *Dissolved Arsenic* | *0.01 mg/L* |
| *Dissolved Molybdenum* | *0.50 mg/L* |
| *Dissolved Cadmium* | *0.01 mg/L* |
| *Dissolved Copper* | *0.05 mg/L* |
| *Dissolved Lead* | *0.05 mg/L* |
| *Dissolved Zinc* | *1.00 mg/L* |
| *Toxicity (96 hour LC-50)* | *100% Effluent concentration* |

The monthly mean flows and loadings for WME in 1993 are shown in Table 1.

Table 1

**WME MONTHLY MEAN FLOWS AND METAL LOADINGS - 1993**

| Month | Flow (L/s) | Cu Conc. (mg/L) | Cu Load (Kg/day) | Zn Conc. (mg/L) | Zn Load (Kg/day) | pH |
|---|---|---|---|---|---|---|
| January | 103.20 | 0.049 | 0.44 | 2.90 | 25.90 | 6.66 |
| February | 77.30 | 0.025 | 0.17 | 2.48 | 16.60 | 7.19 |
| March | 164.60 | 0.104 | 1.48 | 3.19 | 45.40 | 6.45 |
| April | 93.10 | 0.053 | 0.43 | 2.84 | 22.80 | 6.77 |
| May | 84.20 | 0.029 | 0.21 | 2.57 | 18.70 | 7.03 |
| June | 55.20 | 0.018 | 0.086 | 1.61 | 7.68 | 7.39 |
| July | 38.30 | - | - | - | - | - |
| August | 39.40 | 0.046 | 0.16 | 1.04 | 3.54 | 7.62 |
| September | 25.10 | 0.021 | 0.046 | 0.32 | 7.00 | 7.82 |
| October | 11.20 | 0.056 | 0.05 | 1.14 | 1.10 | 7.10 |
| November | 154.10 | 0.103 | 1.37 | 3.93 | 52.30 | 6.63 |
| December | 260.20 | 0.090 | 2.02 | 3.86 | 86.80 | 6.81 |

To determine the source of the contamination, an extensive sampling and testing program was conducted of the waste rock piles. This included acid/base accounting and kinetic testing to examine both the acid generating potential and the geochemical reactivity of the samples. The key finding was that the North Dump (49 million tonnes of waste rock) is the major current and future source of acidity. About 10% of the waste rock contains >2% pyrite and is already strongly acid generating, a further 50% is weakly alkaline at present but will gradually become acid generating, while the remaining 40% is not expected to become acid generating for at least 25 years. The other three dumps contain about 13 million tonnes of waste rock which is mainly weakly alkaline but is expected to generate some acidity in due course. The sampling, testing and evaluation of the waste rock piles are described by Li (1991) and Lister (1994).

*Predictions:*

To predict future water chemistry from the land waste rock piles, the historical water data at eight sampling stations were evaluated (Morin and Hutt, 1994). At all stations (Figure 1), eleven parameters were examined: pH, conductivity, alkalinity, acidity, copper, zinc, cadmium, sulphate, calcium, magnesium, and aluminum. This resulted in a database of 60,000 numbers which provided a solid basis for predictions. Scatter plots of all the data indicated that the other ten parameters could be estimated from pH. The general prediction is that all stations will gradually decrease to pH 4 and slowly recover over the next 200 years to pH 7. Mean annual and high-low mean monthly concentrations were calculated from the predictive water-chemistry model. At pH 4, the mean annual concentration of copper, for example, was predicted to be 0.73 mg/L, with mean monthly extremes of 0.14 to 3.7 mg/L. At pH 7, the predicted copper level is 0.034 mg/L. At these two pH values, the annual mean levels predicted for zinc are 18 and 0.68 mg/L.

Maximum future water flows are estimated at 120 L/s, with a ten-year instantaneous flow rate of 2,000 L/s. For comparison, the average flow at WME for 1992/93 was 100 L/s, with a monthly range of 10 to 340 L/s.

## 3.0 Pit Closure Options

*Basic Considerations and Constraints:*

The pit has a surface area of 215 ha and is excavated more than 350 m below sea level. The volume below sea level is 287 million cubic metres. A 1,200 m slurry wall in the Beach Dump provides a barrier to water from Rupert Inlet entering the pit; there is some concern about the stability of a section of this wall during filling of the pit with seawater (SRK, 1993). Also, some sections of the pit wall may generate acidic drainage, although the risk is greatly decreased if submerged in seawater.

As indicated in previous sections, the drainage from the waste rock piles and other areas in vicinity of the open pit is expected to be contaminated with acidic rock drainage (ARD) for several hundred years. This water can be directed to the pit.

The quantity of waste rock in the on-land dumps is about 90 million tonnes. Revegetation of most of the 193 ha surface area is underway or completed. Relocation of all this material to the pit would represent a very large cost (perhaps $100 million) and would necessitate repetition of the revegetation work. However, trucking to the pit of a small amount of more reactive material (e.g. NW Dump, 1 million tonnes) might be warranted.

The pit could prospectively be used as a municipal solid waste landfill. This alternative has been examined but would require the championship of the appropriate levels of government. The company has therefore set this concept aside.

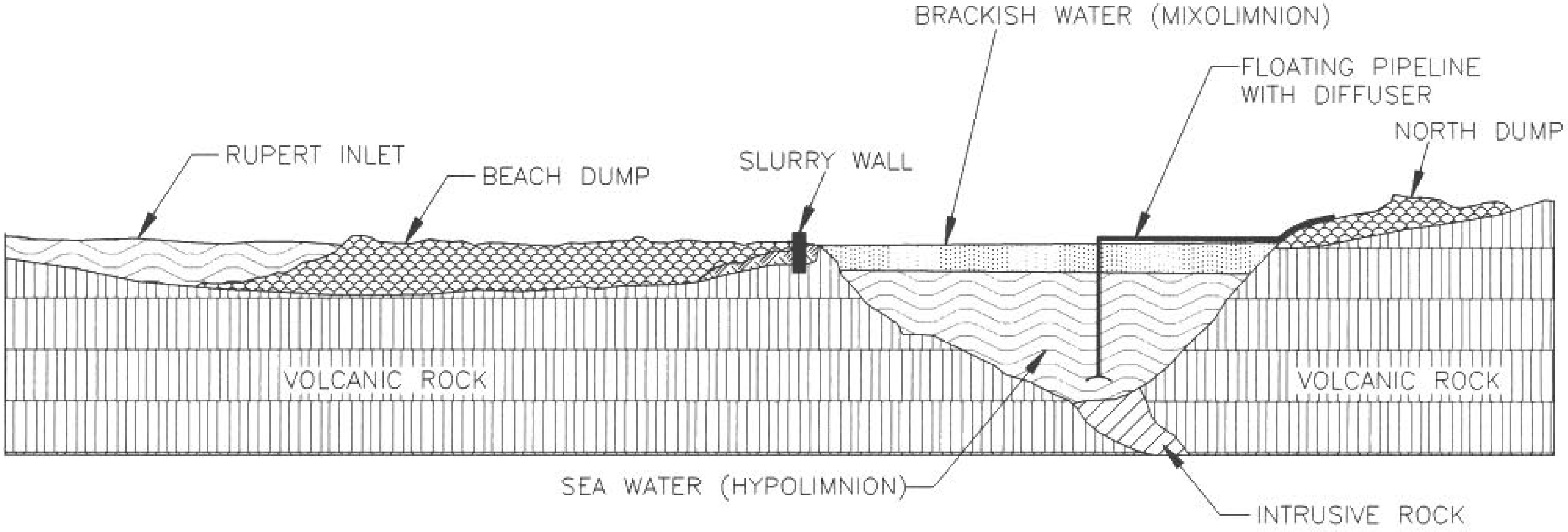
An initial proposal was to open a navigable channel to Rupert Inlet and flood the pit with seawater. The result would be a deep-water anoxic zone overlain by an oxygenated near-surface zone. There would be limited mixing between the zones, intrusions of oxygenated water every 15 to 30 years, and an overturn every 100 years. The Department of Fisheries and Oceans were concerned about the quality of the fish habitat and required that there be a barrier to marine organism ingress during and after the filling operation.

The above considerations suggest that the best option involves rapid flooding of the pit with seawater and direction of waste rock drainage into the pit, in such a way that contamination of the adjacent marine environment would not be significant (Parsons and Zeng, 1994; Perry, 1993). The following section discusses the closure plan that has been proposed by the company (Figure 2).

31607/MAY.25,95/FIG2.DWG/M.T.N.

## FIGURE 2

## THE MEROMICTIC LAKE CONCEPT



N.T.S.

## 4.0 Preferred Option, Creation of a Meromictic Lake

If the pit is flooded with seawater and then the flooding channel is closed off, the only inputs would be from fresh water as precipitation and runoff. This would result in two layers that would not mix due to their great difference in densities and the small surface area of the “lake” compared to its depth (e.g. formation of a meromictic lake with an upper mixolimnion layer and a lower hypolimnion layer). The upper layer would mix within itself due to wind and thermal effects, and remain well oxygenated; it might be somewhat saline due to some shearing at the seawater interface. The lower seawater layer would not mix and would gradually become anoxic due to bacterial respiration, accelerated by the presence of organic matter. This environment would be favourable to sulphate reducing bacteria (SRB) as long as there was adequate organic substrate. The SRB generate hydrogen sulphide gas which could cause dissolved heavy metals to precipitate as insoluble sulphides.

If acidic drainage were discharged deep in the lower layer, the seawater would neutralize and dilute it, and the SRB could precipitate some of the dissolved heavy metals. Because there is no mixing, the contaminants would not overflow or seep laterally into Rupert Inlet. This would therefore be a passive treatment system in both the short and long term.

It is intended to flood the pit as rapidly as possible via a channel from Rupert Inlet, and then close the channel. Summer is the preferred time, because salinity is highest and salmon are absent. There is some risk of partial failure of the slurry wall, which would create a near-surface hydraulic connection but would not affect the concept.

Over a period of 3 to 5 years, precipitation and surface runoff would form an increasingly freshwater cap (the mixolimnion). At the same time, the lower layer would gradually become anoxic. It is proposed to add organic matter initially, to accelerate the process and encourage the development of SRB.

After the anoxic conditions are established, the North Dump drainage, which is the major flow and loading, would be gravity discharged via a floating pipe into the bottom of the anoxic lower layer. Flow in excess of 2000 L/s, along with the less significant flows from the other dumps would be discharged on the surface.

If the slurry wall remains intact and the pit forms a lake, surface water will overtop the slurry wall or the flooding channel control structure and flow out into Rupert Sound. If the slurry wall is breeched during flooding there will be two-way flow via the Beach Dump.

In either case, the predicted water quality will meet or be better than the current permitted requirements for discharge from the Water Management Pond.

Physical oceanographic modelling indicated that the pit should remain meromictic for more than 1,000 years, while acidic drainage is predicted to cease within 200 years. Also, assessment of the net neutralizing potential of the pit walls indicates that the brackish water cap should remain alkaline despite acidic drainage inputs from the walls (Morin, 1992).

*Conclusion:*

Island Copper has selected flooding the pit with seawater and injecting ARD from the North Dump into the bottom of the pit as the best closure option for the pit. The chemical buffering capacity of the lower seawater layer, along with anticipated metal removal as sulphides due to the activity of SRB, is expected to result in surface waters which will meet the current discharge criteria for the Water Management Pond.

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# CASE STUDY 5: THE SOLBEC OPEN PIT

## 1.0 Background Information

*Production History:*

The historic Solbec base metal mine, located in the Eastern Township region of Québec, operated from 1962 to 1970. The mine produced approximately 1.75 million tonnes of ore including 1.4 million tonnes from underground cut and fill stopes, and 0.35 million tonnes from an open pit. The open pit which was mined from 1964 to 1965 is the subject of this Case Study.

The Solbec Mine and mill were located approximately 3 km from Lake Aylmer - a large and popular fresh water lake. As indicated in Figure 1, the mine site was drained by two streams (hereafter referred to as the east stream and west stream) which flowed to Solbec Creek and eventually to Lake Aylmer.

The Solbec mill was also used to custom mill ores from other mines in the area. The mill continued to operate for 7 years (to December 1977) after the end of ore production from the Solbec Mine in 1970. Over the operating life of the Solbec mill a total of approximately 4.9 million tonnes of ore were processed with an overall average run-of-mine grade of 2.17% Cu, 0.60% Pb, 3.52% Zn, 0.44 g/t Au, and 41 g/t Ag.

When the Solbec Mine was in production about 100,000 tonnes of mill tailings were used annually to hydraulically backfill stopes; the balance of the tailings (260,000 tonnes/yr) was disposed in the tailings area located 3 km north of the mill.

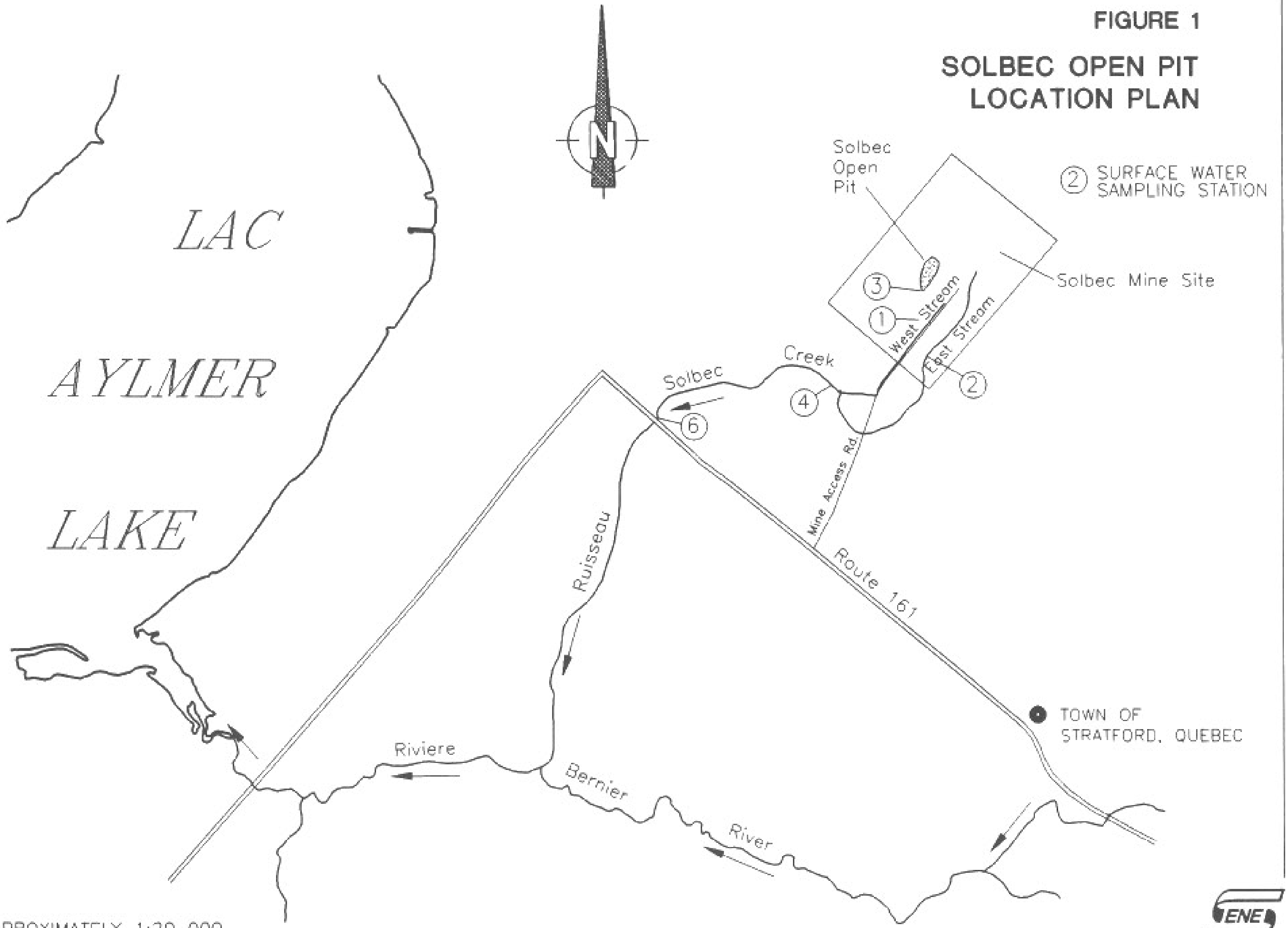
The Solbec orebody was a massive sulphide deposit. Predominant sulphide minerals included pyrite ($FeS_2$), sphalerite ($ZnS$), chalcopyrite ($CuFeS_2$), and galena ($PbS$).

Some waste rock was reported to contain fine grained, disseminated pyrite. An

31607/27MAR95/FIG_SOLB.DWG/PJR

# FIGURE 1

## SOLBEC OPEN PIT LOCATION PLAN



SCALE APPROXIMATELY 1:20 000

unknown volume of waste rock from the underground and open pit operations was used on the property in the construction of roads, yard areas, etc.

The mine site was decommissioned between 1977 and 1979 by the owner of the mine at that time. The decommissioning work completed at the mine site included:

- the demolition of surface structures and backfilling of foundations to grade;
- the contouring of waste dumps and the grading of former building sites; and
- the capping (0.2 m layer of soil) of mine waste followed by seeding.

*Post Decommissioning Regulatory Involvement:*

In October 1983, the Québec Ministry of Environment, le Ministère de L'Environnement de Québec (MENVIQ) announced the formation of a special group to study and address wastes of concern. This group, known as le Groupe d'étude et de restauration des lieux d'élimination des déchets dangereux (GERLED) was to develop a listing of sites where waste materials of concern may have been disposed. Sites were to be classified according to the level of potential risk to: i) public health, and ii) the environment. Sites were to be generally classified under 3 categories as follows:

| **Category** | **Risk Potential** | |
|---|---|---|
| | **Public Health** | **Environment** |
| 1 | Medium to High | High |
| 2 | Low | Medium |
| 3 | None | Low |

The quality of surface water at several stations in the vicinity of the Solbec Mine had been monitored since 1972 by regulatory agencies. These data indicated that acidic flows from the open pit were adversely affecting the water quality of the east creek that eventually flowed to the Bernier River which in turn flowed to Aylmer Lake. In 1985, after a review of water quality and other data, GERLED classified the Solbec mining complex (consisting of the Solbec Mine and the Solbec tailings disposal area) as being Category 1 - presenting a high risk of contamination to the downstream environment. The Cupra Mine was classified as being Category 3.

The main source of the acid mine drainage at the Solbec Mine site appeared to be a relatively small volume of oxidized waste rock located next to the flooded open pit.

In 1987, the ownership of the Solbec Mine was transferred to another mining company as part of a corporate acquisition. An agreement was subsequently concluded between MENVIQ and the new mine owner to evaluate the feasibility of relocating the oxidized waste rock to the pit where it would remain submerged. A number of technical studies were then carried out.

## 2.0 Investigative Procedures

*Bathymetric Survey of the Flooded Pit:*

It was soon determined that the pit had been partially filled in. Approximately 10,000 $m^3$ of tailings had apparently been disposed in the pit during the last few weeks of mill operation in 1977. The maximum depth of the pit down to the surface of the tailings and other mine waste was measured to be 26 m. Mine section drawings indicated that the pit had been excavated to a depth of 40 m. It was subsequently calculated that:

- the pit lake surface area was 14,300 $m^2$; and
- the total volume of the pit (above the tailings) was 365,600 $m^3$ of which the pit lake occupied 181,700 $m^3$.

A plan and two sections of the pit are provided in Figure 2. The pit was located above underground workings as shown in Figure 3.

31607/27MAR95/F2SOLBEC.DWG/PJK

FIGURE 2

PLAN AND SECTIONS OF THE SOLBEC OPEN PIT (CIRCA 1987)

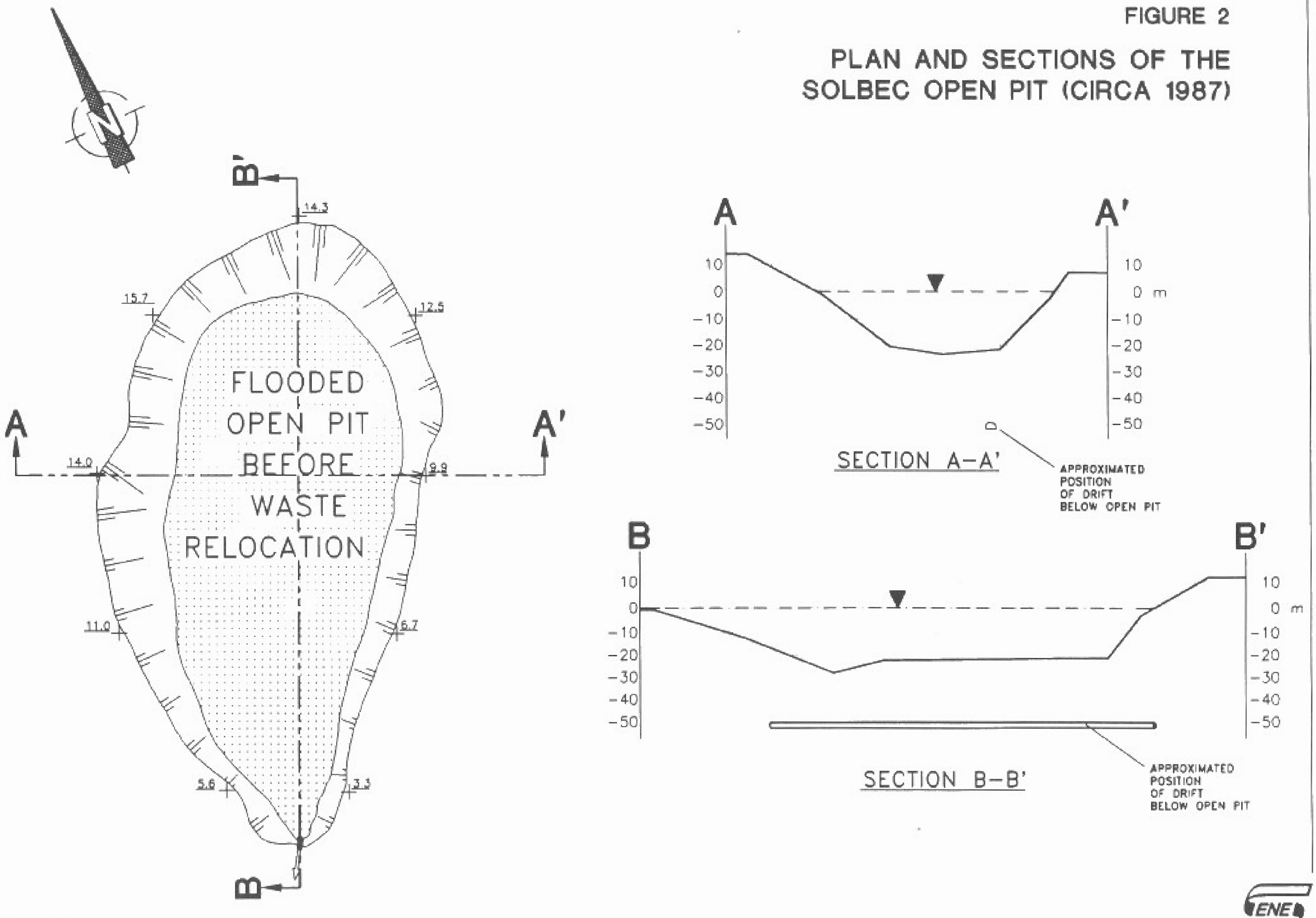


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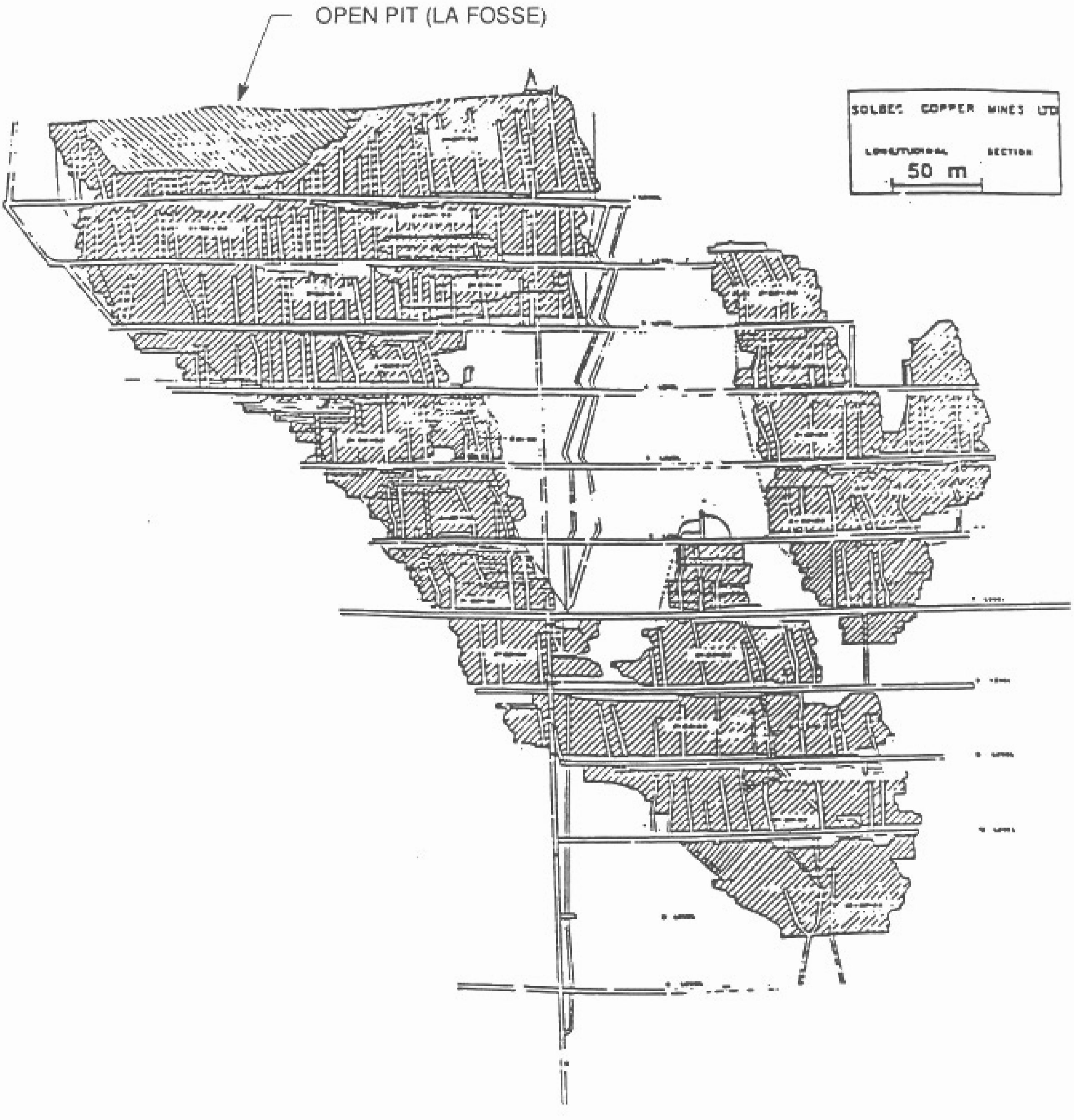
FIGURE 3

## LONGITUDINAL SECTION OF THE SOLBEC MINE



SOURCE: FIGURE 6, Serrener, Créalab, HGE (1993)

*Pit Water Characterization:*

Eighty five water samples were collected at different depths in the pit lake over a 20 m x 20 m grid pattern. Table 1 presents the minimum, maximum, and average values for 12 water quality parameters. The table also includes a column that indicates the effluent quality limits specified by MENVIQ for mine effluent.

Table 1

**SOLBEC PIT WATER QUALITY(A)**

| Parameter | Range of Measurements | | | Measurements According to Depth | | | | Effluent Quality Limits |
|---|---|---|---|---|---|---|---|---|
| | Minimum | Maximum | Average | At Surface | 5 m | 10 m | 20 m | |
| pH | 5.7 | 6.6 | 6.3 | 6.31 | 6.31 | 6.25 | 6.08 | 6.5 to 9.5 |
| Cu (mg/L) | 0.05 | 1.91 | 0.18 | 0.21 | 0.21 | 0.13 | 0.18 | 0.30 |
| Pb (mg/L) | 0.00 | 0.50 | 0.12 | 0.12 | 0.09 | 0.07 | 0.05 | 0.20 |
| Zn (mg/L) | 0.64 | 1.89 | 1.02 | 1.02 | 0.98 | 1.10 | 0.96 | 0.50 |
| Fe (mg/L) | 0.32 | 41.9 | 3.50 | 0.69 | 1.23 | 2.34 | 18.53 | 3.00 |
| Mn (mg/L) | 2.3 | 8.20 | 4.05 | 3.42 | 3.46 | 4.49 | 6.18 | - |
| Cd (mg/L) | 0.0 | 0.20 | 0.04 | 0.03 | 0.05 | 0.05 | 0.03 | - |
| Temperature (°C) | 5.0 | 7.0 | 5.7 | 5.4 | 5.0 | 5.7 | 6.9(B) | - |
| Conductivity (µmhos/cm) | 1,600 | 2,050 | 1,755 | 1,750 | 1,694 | 1,790 | 1,890 | - |
| Alkalinity, as $CaCO_3$ (mg/L) | 134 | 196 | 145 | 143 | 143 | 149 | 170 | - |
| Dissolved Oxygen (mg/L) | 1.1 | 9.8 | 6.1 | 9.2 | 8.2 | 5.2 | 1.7(B) | - |
| Total Dissolved Solids (mg/L) | 1,154 | 2,819 | 1,660 | 1,581 | 1,588 | 1,685 | 2,053 | - |

(A) Source: Tables 2.2.1 and 2.2.2 Desrochers (1990).
(B) At 14 m depth.

The temperature profile reflected the time of sampling, fall of 1987. The pH of the pit lake was found to be higher than that measured in other surface water on the mine site, which was likely lower due to the influence of reactive mine wastes spread around the site. The average values of heavy metal concentrations were determined to be in compliance with MENVIQ effluent quality limits (Directive 019) with the exception of zinc (and iron in one case).

Profiles of water temperature, pH, and dissolved oxygen in the pit lake are provided in Figure 4.

*Open Pit Sediment Sampling:*

Nine sediment samples were collected and analyzed for 10 chemical parameters. Selected data are shown in Table 2.

Table 2

**OPEN PIT SEDIMENT ANALYSES**[A]

| Parameter | Range of Measurements | | |
|---|---|---|---|
| | Minimum | Maximum | Average |
| Cu (mg/kg) | 82 | 4,087 | 1,110 |
| Pb (mg/kg) | 31 | 1,304 | 426 |
| Zn (mg/kg) | 165 | 1,069 | 318 |
| Mn (mg/kg) | 434 | 2,887 | 761 |
| Cd (mg/kg) | 15 | 37 | 20 |
| As (mg/kg) | 2.4 | 3.8 | 7.4 |
| $SO_4$[B] | 537 | 2,154 | 838 |

[A] Source: Table 2.2.3, Desrochers (1990).

[B] Likely in form of gypsum $CaSO_4 \cdot 2H_2O$.

*Discussion:*

The average pH value of the pit lake was 6.25 and the researchers indicated that acid production from submerged reactive wastes was occurring at a very slow rate even in the presence of oxygenated water. The situation was, however, the opposite on the land surface adjacent to the pit where reactive waste rock readily oxidized to produce acidic drainage.

The concentration of metals within the pit lake water in many cases met effluent quality limits, but not receiving water quality objectives.

It was noted that water flowing from the pit quickly became acidic with elevated metal concentrations, which was likely due to contribution of AMD from reactive waste rock on surface. Approximately 2 km downstream, the stream pH improved. This was explained by the effects of dilution and other conditions favourable to contaminant precipitation.

Water quality data also indicated that the metal concentrations remained elevated (yet generally below MENVIQ effluent quality limits). The dilution of the contaminated stream from the Solbec Mine site at the mouth of the Bernier River was determined to be insufficient to meet receiving water quality objectives.

AMD from the reactive mine waste rock spread across the mine site was clearly adversely affecting the quality of water flowing from the open pit.

## 3.0 Waste Management Options

The open pit contained 181,700 m$^3$ of water and was estimated to have another 178,300 m$^3$ of storage capacity above the pit lake level. The relocation of the reactive waste rock to the open pit appeared feasible. A study was carried out to assess environmental impacts associated with the following in-pit disposal options (Veillette et Desrochers, 1991):

OPTION A: No dewatering of the pit prior to waste rock relocation.

OPTION B: Partial dewatering of the pit prior to waste rock relocation.

OPTION C: Complete dewatering of the pit prior to waste rock relocation.

At the time of the study (1987) there were no historical data available from similar programs regarding the depth of water cover required to inhibit the sulphide oxidation reactions and maintain acceptable water quality in the overflow from the open pit.

### OPTION A - NO DEWATERING

In this option, waste rock would be directly dumped into the pit. It was expected that fine particles in the wastes and pit bottom sediments would become suspended. The pH of the pit water would decrease and result in unacceptable effluent quality. A system would be required to control the release of water during the pit filling program. Water would require treatment prior to release to the environment.

### OPTION B - PARTIAL DEWATERING

It was considered that the partial dewatering of the pit prior to the relocation of the mine wastes would reduce the risk of further contamination to the downstream environment.

The pit would be dewatered about halfway (in the order of 100,000 $m^3$ of water would be pumped out). The withdrawal of water from the pit during waste placement operations would be controlled to limit erosion effects and the suspension of particles. The water level in the pit could be lowered daily, between working shifts to allow for some settling of particles. Water pumped from the pit would be discharged to a series of settling ponds.

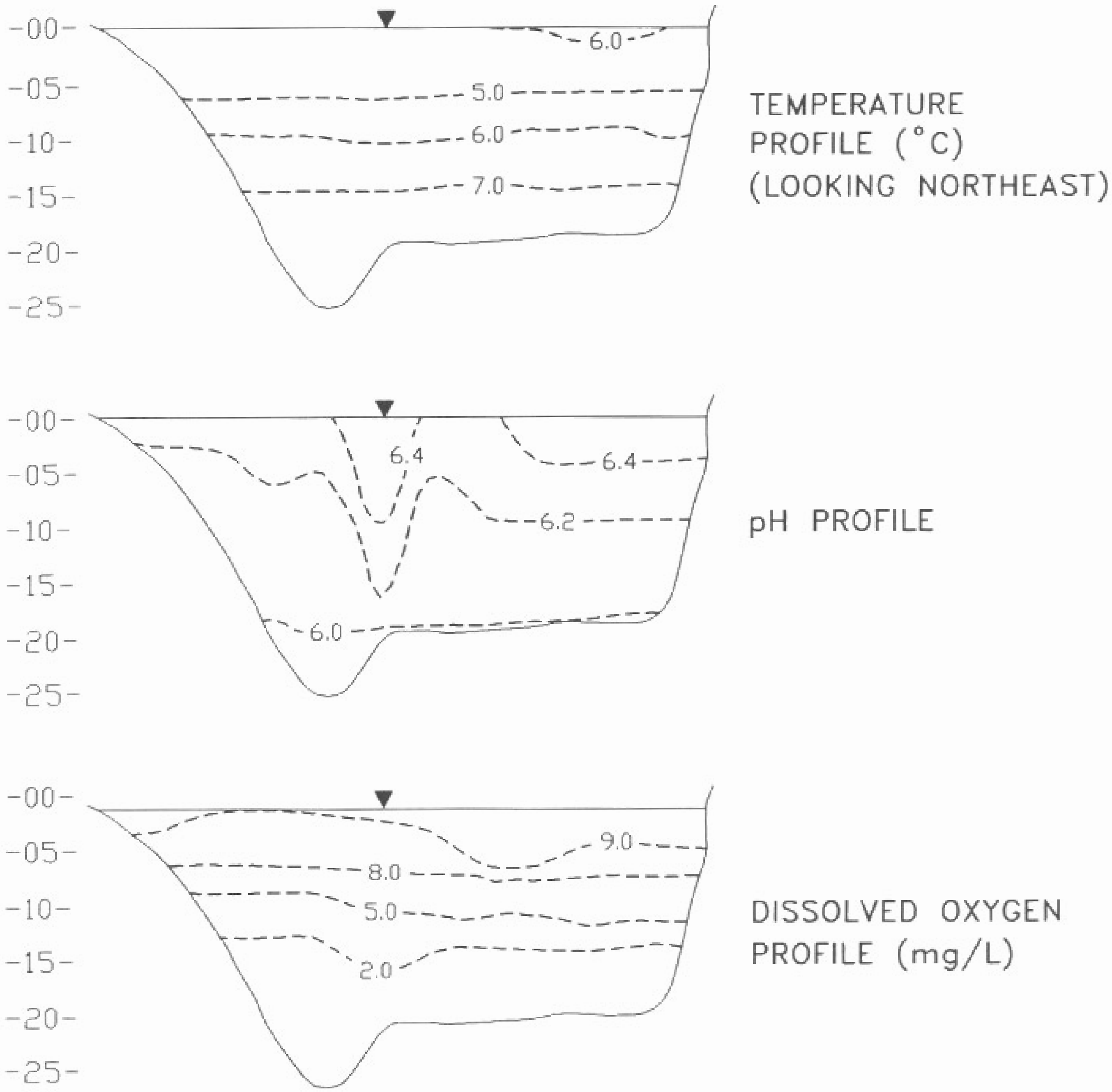
### OPTION C - COMPLETE DEWATERING

The complete dewatering of the open pit prior to the relocation of mine wastes would, in concept, allow equipment to enter the pit and compact the wastes. The compaction of wastes was considered to be beneficial in that it would improve the stability of the wastes, and reduce groundwater flow through the wastes.

This option required that 180,000 to 200,000 $m^3$ of water be pumped from the pit. Flows would be treated and released at a controlled rate.

FIGURE 4

## PROFILES OF TEMPERATURE, pH, AND DISSOLVED OXYGEN ALONG LONGITUDINAL CENTER SECTION OF THE SOLBEC OPEN PIT (B)



(A) ADAPTED FROM SERRENER (1988)

(B) THIS LONGITUDINAL SECTION CORRESPONDS TO SECTION B–B' ON FIGURE 2.

31607/28MAR95/FIG4/PJH

*Decision to Proceed:*

The decision to proceed was based on partial dewatering of the pit to the most practical or reasonable extent prior to relocation of the wastes. The project was authorized to proceed in two phases by MENVIQ. In the first phase, the acid generating mine wastes would be relocated to the partially dewatered pit and the cleaned surface areas would be revegetated. Flooding would be authorized in the second phase once it was demonstrated that a water cover could be maintained over the reactive wastes.

## 4.0 Implementation of In-Pit Disposal Program

A 6,000 $m^3$ settling pond was constructed downstream of the open pit. The pit was then dewatered at a pumping rate of 250 $m^3$/hour. A total of 150,000 $m^3$ of water were pumped out over 6 weeks (beginning in June 1988) after which time the water level in the pit had been lowered by 19 m. The sloped bottom of the pit was then used as a sump/settling pond which was thereafter pumped down on a weekly basis.

An initial estimate of the volume of reactive waste rock to be relocated to the open pit was made based on a topographic survey, a few test holes, and visual inspections. It was initially determined that 115,400 $m^3$ of wastes were spread over a 7.4 ha area. A total of 276,000 $m^3$ of wastes including contaminated soil were ultimately removed from a 12.1 ha area. Two areas in particular, had considerably more reactive waste than originally estimated due to use of an estimated original ground profile, and the presence of a cover of inert waste rock over reactive waste.

The waste rock relocation work commenced in August 1988 and was completed in 12 weeks.

The underestimation of the waste volume, and the limited pit volume available to flood the reactive waste was a concern. At the completion of the wastes relocation program the level of waste in the pit was 2 m above the original water table elevation. Fortunately, a 2 m water cover could be maintained over the wastes by constructing

PHOTOGRAPH OF PIT FILLING OPERATION
AT SOUTH END OF THE SOLBEC OPEN PIT

a water retaining dyke across the south end of the pit.

Prior to natural flooding, the surface of the waste in the pit was levelled and covered with a 5 cm layer of minus 5 mm agricultural type calcite limestone to provide a neutralizing barrier to the upward transport of acidic water.

## 5.0 Monitoring

In May 1988, in advance of pit dewatering, a water quality monitoring program was established involving five stations. The locations of the five stations are described in Table 3 and are shown in Figure 1.

Table 3

LOCATIONS OF WATER QUALITY SAMPLING STATIONS

| Station № | Location |
|---|---|
| 1 | Settling pond overflow |
| 2 | Downstream on east stream |
| 3 | Open pit overflow |
| 4 | Final mine effluent (1988) |
| 6 | Final mine effluent (1985) |

Water quality data for selected stations are summarized in Table 4. The 1989 data represent the situation before revegetation of the cleaned surface areas. The 1990 data represent the situation after revegetation when measured parameters with the exception of zinc, were found to be in compliance with MENVIQ effluent quality limits.

# Table 4

## SUMMARY OF WATER QUALITY MONITORING DATA FOR SOLBEC OPEN PIT$^{(A)}$

| Station | Parameter | Before In-Pit Disposal$^{(B)}$ | During Pit Dewatering$^{(B)}$ | During Waste Transfer$^{(B)}$ | Post In-Pit Disposal | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | 1988$^{(B)}$ | 1989$^{(C)}$ | 1990$^{(C)}$ | 1991$^{(C)}$ | 1992$^{(C)}$ |
| Station Nº. 3 Open Pit Overflow | Flow ($m^3$/h) | -- | -- | -- | -- | 1.07 | 1.38 | 1.15 | 0.76 |
| | pH | 6.7 | 6.8 | 4.8 | -- | 7.1 | 6.6 | 6.0 | 6.7 |
| | Suspended Solids (mg/L) | -- | -- | -- | -- | 5.8 | <10 | 6.7 | 4.6 |
| | Cu (mg/L) | 0.14 | 0.18 | 11.57 | -- | 0.05 | 0.04 | 0.10 | 0.07 |
| | Pb (mg/L) | 0.05 | 0.29 | 0.45 | -- | 0.06 | -- | -- | -- |
| | Zn (mg/L) | 2.79 | 11.90 | 67.98 | -- | 6.08 | 5.6 | 5.0 | 2.6 |
| | Fe (mg/L) | 0.71 | 5.40 | 106.93 | -- | 0.62 | 1.36 | 2.40 | 1.07 |
| | Ni (mg/L) | 0.10 | 0.12 | 0.44 | -- | 0.13 | -- | -- | -- |
| Station Nº. 1 Settling Pond Overflow | Flow ($m^3$/h) | Pond Constructed for In-Pit Disposal Program | -- | -- | -- | 1.59 | 4.1 | 1.4 | 1.4 |
| | pH | | 6.8 | 5.7 | -- | 7.1 | 6.8 | 6.7 | 7.0 |
| | Suspended Solids (mg/L) | | 19.0 | -- | -- | 7.9 | 13.0 | 15.3 | 5.8 |
| | Cu (mg/L) | | 0.21 | 3.27 | -- | 0.09 | 0.09 | 0.10 | 0.07 |
| | Pb (mg/L) | | 0.09 | 0.33 | -- | 0.04 | - | -- | -- |
| | Zn (mg/L) | | 13.10 | 36.38 | -- | 9.02 | 7.40 | 6.4 | 4.0 |
| | Fe (mg/L) | | 4.01 | 15.77 | -- | 0.60 | 1.58 | 1.69 | 1.82 |
| | Ni (mg/L) | | 0.09 | 0.28 | -- | 0.15 | -- | -- | -- |
| Station Nº.4 Final Mine Effluent | Flow ($m^3$/h) | -- | -- | -- | -- | 37.53 | 19.95 | 17.74 | 5.35 |
| | pH | 3.4 | 5.5 | 3.4 | 5.7 | 6.9 | 7.3 | 6.6 | 7.0 |
| | Suspended Solids (mg/L) | -- | -- | -- | -- | 26 | <10 | 8.6 | 5.8 |
| | Cu (mg/L) | 53.0 | 2.96 | 9.13 | 0.59 | 0.39 | 0.08 | 0.18 | 0.16 |
| | Pb (mg/L) | 0.05 | 0.20 | 0.25 | 0.08 | 0.06 | -- | -- | -- |
| | Zn (mg/L) | 9.24 | 17.22 | 26.54 | 3.95 | 4.38 | 1.27 | 2.42 | 1.33 |
| | Fe (mg/L) | 56.09 | 26.25 | 44.88 | 4.76 | 3.58 | 2.13 | 0.98 | 1.06 |
| | Ni (mg/L) | 0.67 | 0.17 | 0.22 | 0.08 | 0.18 | -- | -- | -- |

(A) **Source: Tables 7, 8, and 9 (Veillette and Desrochers, 1991), and Tables 7, 8 and 9 (Vezina et al., 1993).**

(B) **Average value of weekly measured parameters.**

(C) **Average value of monthly measured parameters.**

## 6.0 Cost of In-Pit Disposal

The total cost of the in-pit disposal program to the end of 1992 was $1,069,100 as indicated in Table 5.

Table 5

**IN-PIT DISPOSAL COSTS**[(A)]
**(BASED ON 276,000 m$^3$ OF RELOCATED WASTE)**

| Items | 1988 | 1989-1992 | Total | Unit Cost |
|---|---|---|---|---|
| Material relocation | $543,000 | $ 7,700 | $ 550,700 | $1.99/m$^3$ |
| Site revegetation | -- | 79,000 | 79,000 | 0.29 |
| Effluent treatment | $41,000 | 63,800 | 104,800 | 0.38 |
| Environmental monitoring | 70,350 | 80,500 | 150,850 | 0.55 |
| Planning & Supervision | 77,750 | 106,000 | 183,750 | 0.66 |
| Total | $732,100 | $337,000 | $1,069,100 | $3.87/m$^3$ |

(A) Source: Table 10 (Vezina et al., 1993).

## 7.0 Conclusions Reached In 1993

The following conclusions were reached in 1993, by the mining company (Cambior) that acquired the mine site in 1987 (Vezina et al., 1993).

- *"The proposed solution for the Solbec site reclamation has proven to be efficient in inhibiting acid rock drainage. Dewatering of the open pit before waste rock relocation and the construction of a settling pond to collect the water minimized the environmental impact of high loads of oxidation products. The relocation of oxidized waste rock has almost totally eliminated surface acid rock drainage activity from the mine site. Lime conditioning and revegetation of the bare soil have* *permitted to reach the level of decontamination required to meet the mining industry environmental guidelines.*

- *Flooding of oxidized waste rock under a shallow cover of water is still under evaluation and it is premature to draw final conclusions. Zinc concentration level in the pit effluent is decreasing but still over effluent limit. Filtration through a multi-media passive filter* (at the outlet of the settlement pond) *is currently evaluated on a full scale basis and is showing positive results. The use of such a filter is contemplated as a mean to reduce zinc concentration under the effluent limit until such a level is naturally obtained."*

## 8.0 Comprehensive Hydrogeological Study

A hydrogeological elevation of the Solbec pit was carried out from 1992 to 1994 as part of the MEND program by Serrener, Gréalab, HGE (1994). The cost of this program was reported by Belle-Isle (1994) to be approximately $210,000.

The terms of reference were to characterize the pit and the adjacent groundwater regime from a hydrogeological perspective. No prior studies had been carried out at the Solbec pit. The MEND study involved:

- review of historical information regarding the pit's physical setting, the orientation of the pit and nearby underground mine workings, and surface drainage;

- the installation of piezometers in boreholes (locations and elevations were surveyed);

- collection of continuous samples from boreholes located in and around the pit;

- conducting permeability tests in boreholes to determine the permeability of the waste material and tailings;

- performing flow measurements during the drilling of boreholes located downstream of the pits;
- conducting granulometric analyses of the waste;
- performing a rock quality designation (RQD) evaluation of drill core; and
- characterizing the physicochemical conditions of groundwater (including the pit lake, interstitial water in the wastes contained in the pit, and peripheral groundwater/pore water).

Five boreholes were drilled in and adjacent to the filled open pit as shown in Figure 5. Boreholes F-1 and F-2 were drilled within the pit confines and through the waste material to the underlying rock. Boreholes F-3, F-4, and F-5 were drilled through rock. Piezometers were installed in these holes as indicated in Table 6.

Table 6

**PIEZOMETER INSTALLATIONS**

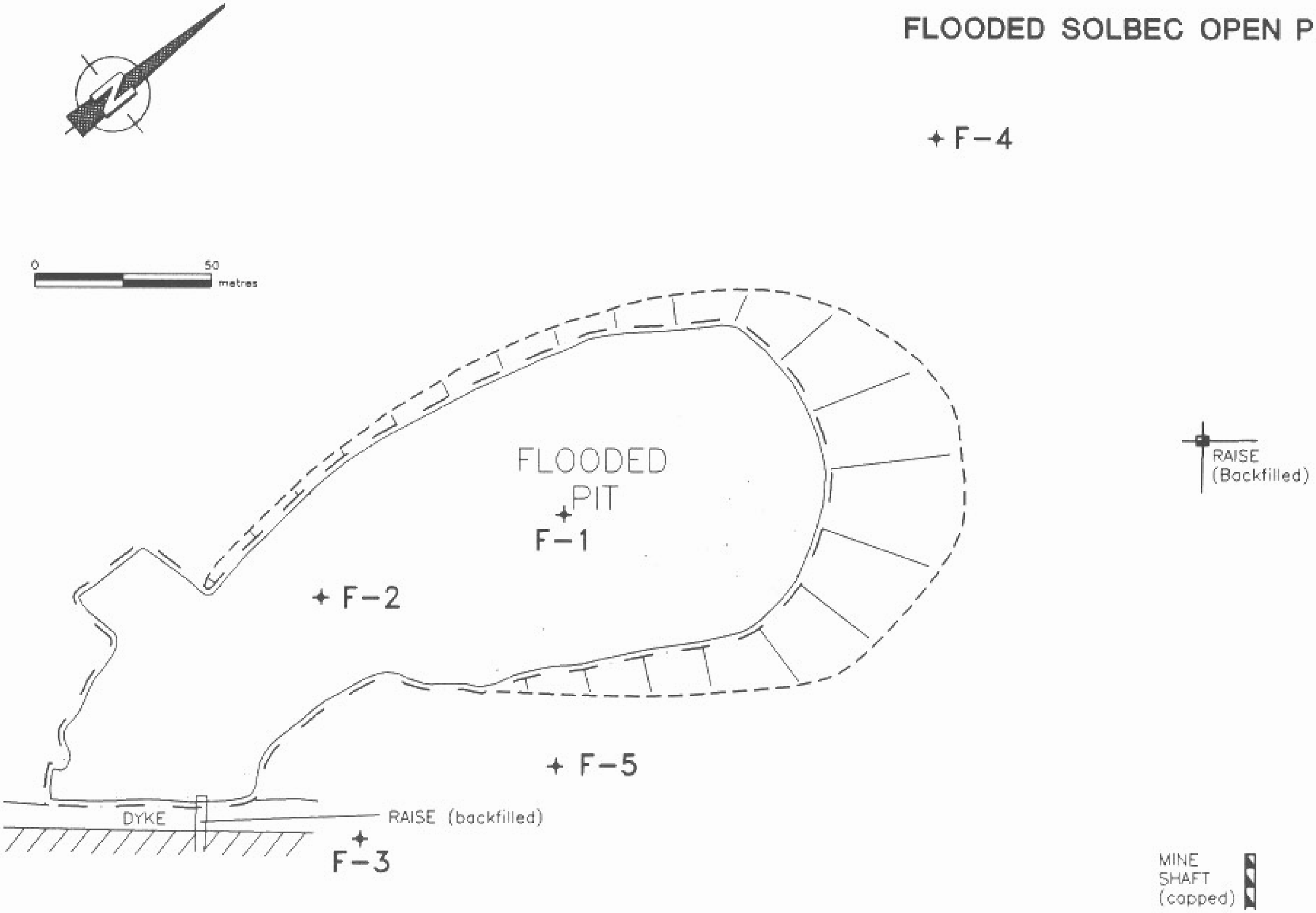
| Borehole | Piezometer Designation | Formation |
|---|---|---|
| F-1 | PZ-3<br>PZ-2<br>PZ-1 | Waste Rock<br>Tailings<br>Rock |
| F-2 | PZ-2<br>PZ-1 | Waste Rock<br>Rock |
| F-3 | PZ-4<br>PZ-3<br>PZ-2<br>PZ-1 | Rock<br>Rock<br>Rock<br>Rock |
| F-4 | PZ-1 | Rock |
| F-5 | PZ-4<br>PZ-3<br>PZ-2<br>PZ-1 | Rock<br>Rock<br>Rock<br>Rock |

Adapted from Tables 2 and 5, (Serrener, Créalab, HGE 1993).

Detailed descriptions of the piezometer installations including borehole logs are included in the Serrener, Créalab, HGE (1993) report.

## FIGURE 5

## FLOODED SOLBEC OPEN PIT



Source: Figure 10, Serrener, Crealab, HGE (1993)

31607/27MAR95/FIG5/PJK

The site geology consisted of metavolcanic schistose formations that dipped 45 to 75° along a N30E strike. The rock in borehole F-4 (NNW of the pit) was found to be of excellent quality with few fractures. However, boreholes F-3 and F-5 are located in fractured rock. Blast damage was described as being a possible cause of the fractures. A major fault runs along the east wall of the pit on the contact of the mineralized formations; boreholes F-3 and F-5 are located in that zone and intersect the fault, which is another possible cause of the fractured rock (Cambior, 1995).

### *Hydraulic Gradient:*

Water tables were measured monthly from February 1992 to September 1992. The data were used to develop water tables contour (hydraulic gradient) maps and groundwater flow lines. A map based on data obtained in June 1992, is provided in Figure 6. The groundwater movement (vertical downward gradient in the pit and generally southward) was generally consistent with the topography. The water table was found to be within 2 m of surface.

Using an estimated permeability of between $10^{-4}$ to $10^{-5}$ cm/s and a porosity of 0.01, and a hydraulic gradient of 0.03, the groundwater flow rate was calculated to be within a range of 10 to 95 m/yr.

### *Groundwater Balance Of The Open Pit:*

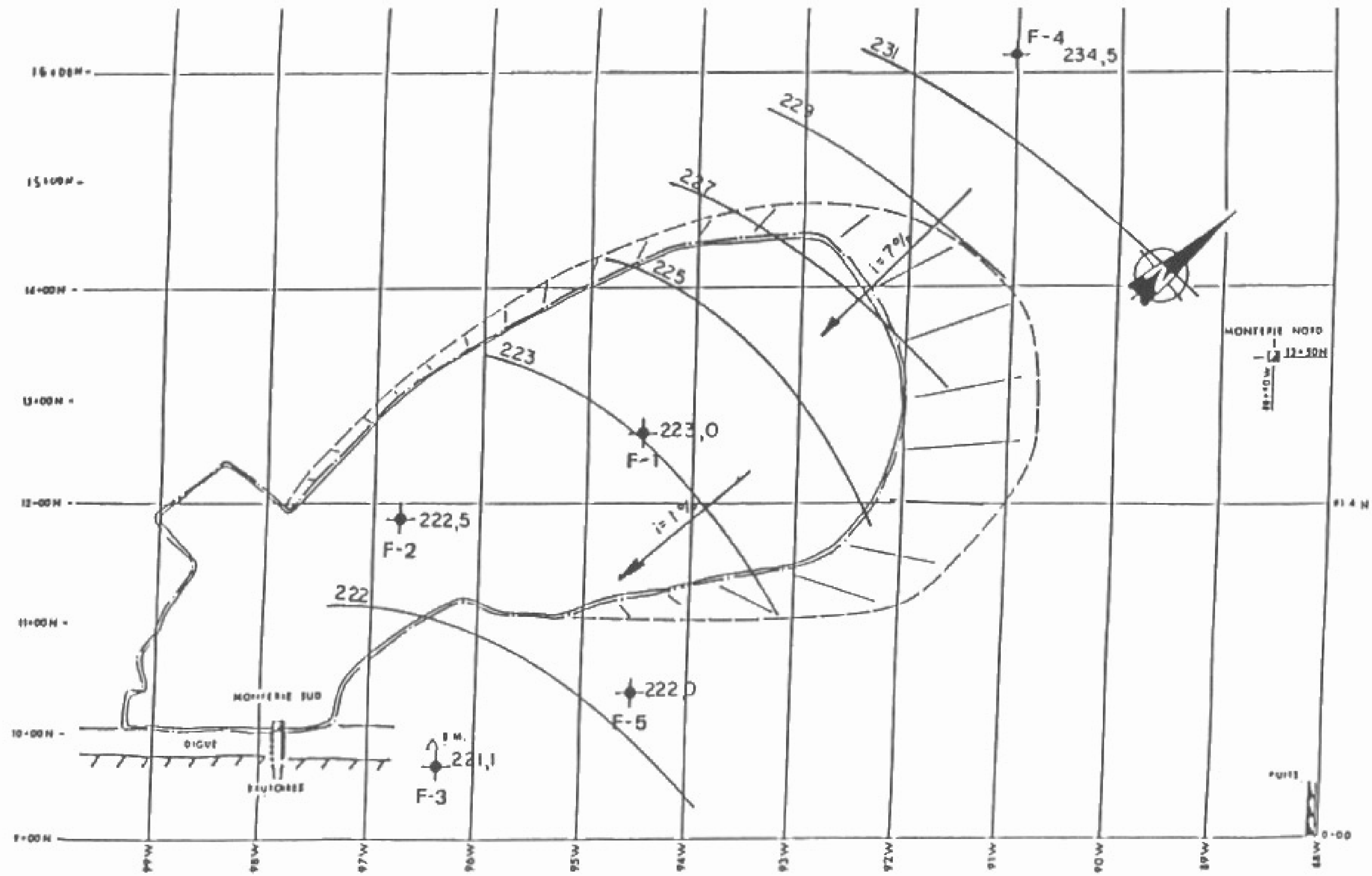
The following equation was derived for the pit water balance.

$$I = P + R - E - Q$$

where I = Infiltration to groundwater regime ($m^3$)
P = Precipitation ($m^3$)
R = Runoff ($m^3$)
E = Evaporation from the pit lake ($m^3$)
Q = Water overflowing from the pit lake ($m^3$)

FIGURE 6

## HYDRAULIC GRADIENT AND GROUNDWATER FLOW



SOURCE: FIGURE 14, Serrener, Créalab, HGE (1993)

Data from to the period 19 May 1992 to 26 September 1992 provided the following result.

$$\begin{aligned} I &= 9{,}500 + 600 - 3{,}800 - 2{,}300 \\ &= 4{,}000\ m^3\ (\mathit{approximately}\ 1{,}000\ m^3/\mathit{month}) \end{aligned}$$

Mining records indicated that the first level of the underground mine was located about 10 m below the pit. The raises that broke through to surface in the vicinity of the pit were filled with waste rock and covered with till as part of the site restoration program. The south raise collar (Figure 5) was located within the flooded pit area.

As none of the piezometers were located at the drift elevation, the influence of the underground mine on the pit hydraulics could not be determined.

Samples of host rock collected from the boreholes were submitted for analytical testing including acid-base tests which showed that the host rock offered some buffering capacity. Samples of the waste rock and tailings contained within the pit were similarly submitted for analytical testing including acid-base testing; the tests results indicated that at least a third of the waste samples had the potential to produce acid.

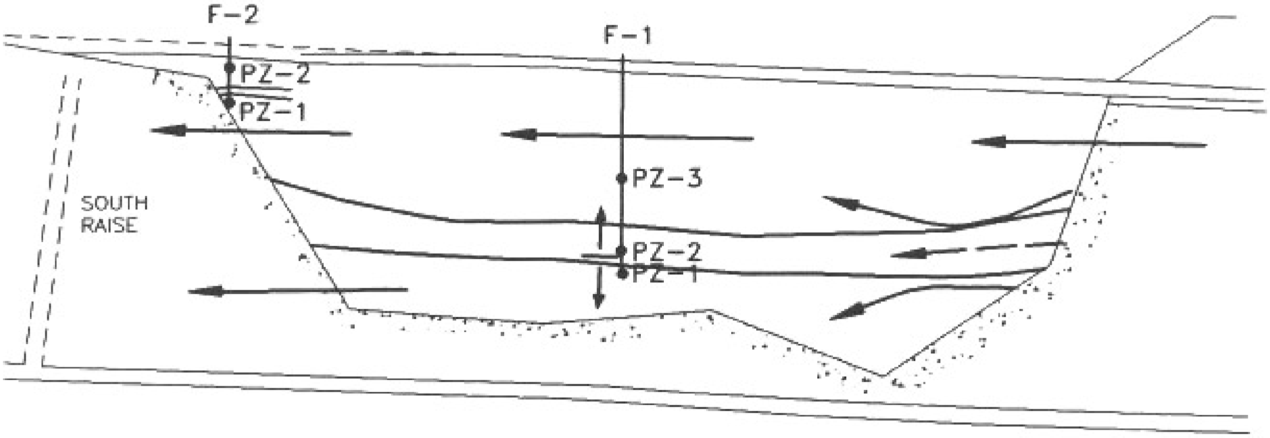
*Summary Of Progress To March 1993:*

Water samples were collected on a monthly basis from the nested piezometers from February to October 1992 and submitted for analytical testing. The groundwater quality data indicated that the pit water had migrated downgradient (southward and slightly down).

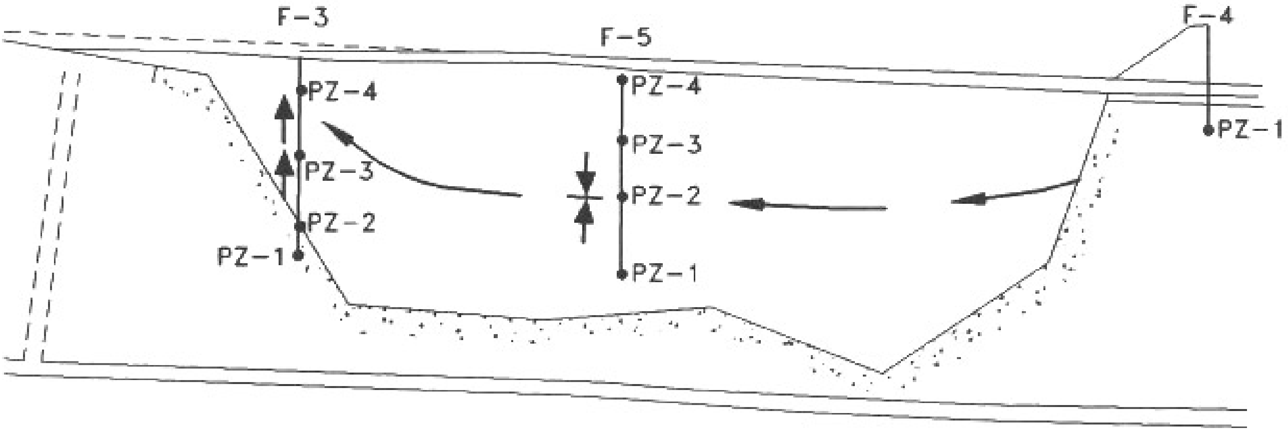
Figure 7 shows that the movement of groundwater through the waste layer within the pit was generally horizontal. As the interstitial water in the pit water layer contained elevated levels of contaminants, it was expected that contamination in the groundwater would migrate downgradient of the pit. This effect was in fact observed in the groundwater analytical data, and was consistent with the groundwater flow gradients determined earlier.

## FIGURE 7

## GROUNDWATER FLOWS WITHIN AND AROUND THE SOLBEC PIT



IN THE PIT



AROUND THE PIT

31607/27MAR95/FIG7/PJK

ADAPTED FROM SERRENER, CREALAB (1994)

The report by Serrener, Créalab, HGE (1993) contains the extensive groundwater quality data collected at this site. Selected groundwater data from boreholes F-4 (upgradient of pit), F-1 (within pit confines) and F-5 (downgradient of pit) are presented in Table 7. Interstitial water recovered from the zone of waste within the pit had elevated concentrations of iron, zinc and sulphate; and the levels of sulphate, zinc, iron and arsenic are higher closer to surface (see Table 7). The levels of sulphate and iron in the groundwater downgradient from the pit increased with depth. Figure 8 is a schematic section of the pit showing the average calcium concentrations at various locations.

The researchers were unable to determine if preferential flow paths existed from the pit to the adjacent flooded underground mine drifts and raises. Additional boreholes and piezometers would have been required for further study in this area.

The quality of the shallow water cover over the flooded wastes (and limestone top layer) was also assessed. Elevated concentrations of sulphate and zinc were measured in the water cover. The pH of the water cover was between 6 and 7, and was favourably affected by the presence of the limestone top layer and inflows of clean runoff.

## 9.0 Principal Findings

*Summary of Progress to March 1994:*

The monitoring of the groundwater quality carried out from February to October 1992 was continued until November 1993. Key conclusions from Serrener and Créalab (1994) are summarized below.

- The groundwater upgradient of the open pit was not contaminated.

Table 7

## SELECTED GROUNDWATER QUALITY DATA OBTAINED FROM PIEZOMETER SAMPLING AT SOLBEC PIT FROM FEBRUARY TO OCTOBER 1992(A) (B)

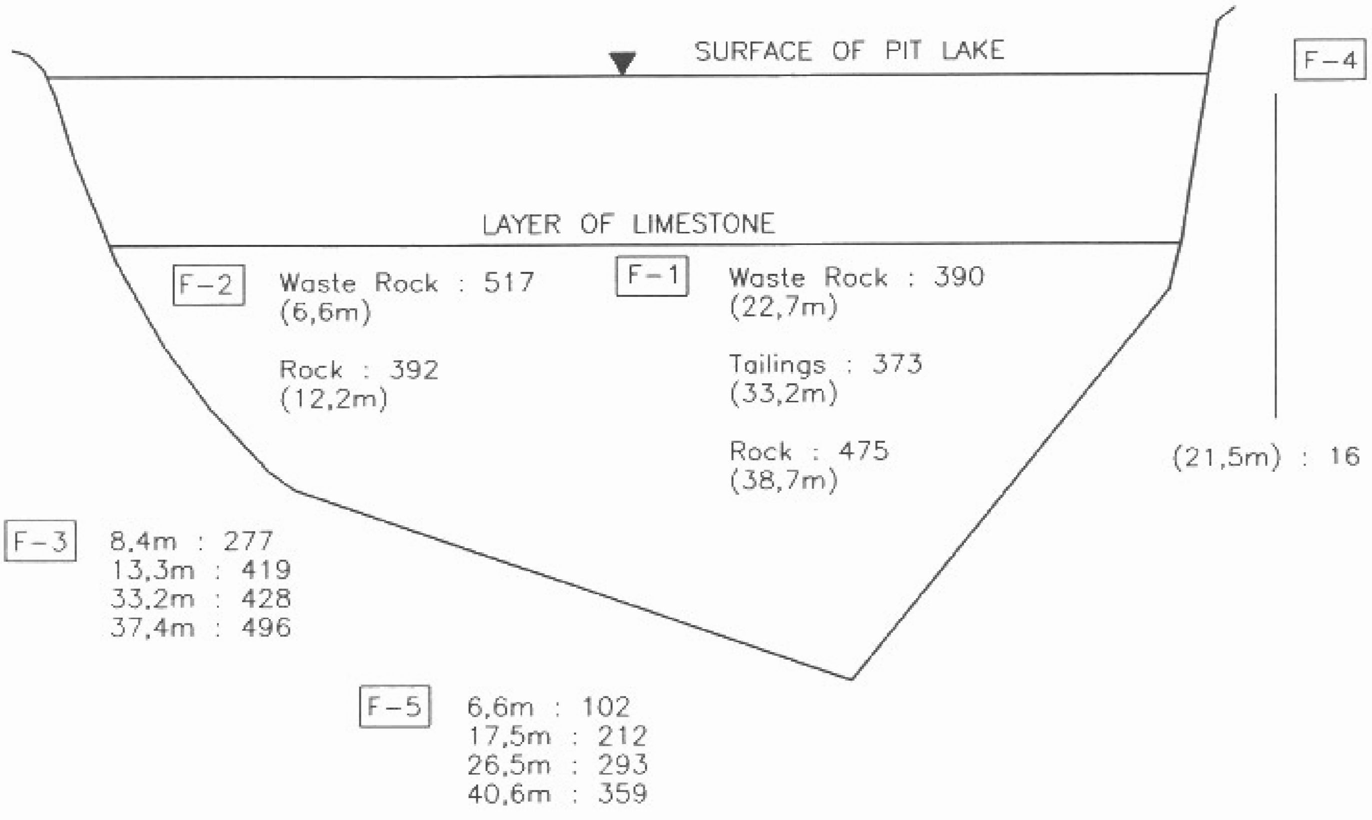
| **Parameter** | **Borehole F-4 (Located Upgradient)** | | **Borehole F-1 (Located Within Pit)** | | | | **Borehole F-5 (Located Downgradient from Pit)** | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Piezometer PZ-1** | | **Piezometer PZ-1** | | **Piezometer PZ-3** | | **Piezometer PZ-1** | | **Piezometer PZ-3** | |
| | **Feb 1992** | **Oct 1992** | **Feb 1992** | **Oct 1992** | **Feb 1992** | **Oct 1992** | **Feb 1992** | **Oct 1992** | **Feb 1992** | **Oct 1992** |
| Temperature (°C) | 1.3 | 5.1 | 5.40 | 7.80 | 6.40 | 7.10 | 3.0 | 6.7 | 2.7 | 6.9 |
| Conductivity (µmhos/cm) | 238 | 257 | 3,800 | 3,710 | 6,710 | 6,760 | 3,590 | 3,730 | 2,800 | 1,620 |
| Redox Potential (mv) | 46 | -132 | -35 | -12 | -7 | 1 | 102.0 | 47.0 | 120.0 | 71.0 |
| pH | 7.05 | 7.70 | 6.21 | 6.32 | 5.88 | 5.78 | 5.89 | 5.9 | 6.2 | 6.39 |
| Dissolved Oxygen (mg/L) | 9.70 | 1.20 | 2.9 | 3.7 | 2.0 | 2.5 | 5.8 | 2.9 | 6.2 | 4.8 |
| Sulphate (mg/L) | 22.7 | 24.0 | 2110 | 2,350 | 4,330 | 5,350 | 3,290 | 2,200 | 1,500 | 725 |
| Zinc (mg/L) | 0.12 | 0.14 | 18 | 16 | 34 | 24 | 51.0 | 49.0 | 42.0 | 34.0 |
| Iron (mg/L) | 0.09 | 2.10 | 36 | 41 | 820 | 1,450 | 11.00 | 120.00 | 0.25 | 2.60 |
| Copper (mg/L) | <0.03 | <0.03 | 0.15 | 0.04 | 0.05 | 0.06 | 0.17 | 0.37 | 0.46 | 0.43 |
| Cadmium (mg/L) | <0.02 | <0.02 | 0.02 | <0.02 | 0.02 | 0.03 | 0.20 | 0.28 | 0.20 | 0.14 |
| Lead (mg/L) | <0.05 | 0.07 | 0.14 | 0.22 | 0.22 | 0.41 | 0.12 | 0.14 | 0.09 | 0.13 |
| Arsenic (mg/) | <0.20 | 0.80 | 0.73 | 0.30 | 4.90 | 6.00 | <0.20 | <0.20 | <0.20 | 0.60 |
| Calcium (mg/L) | 17.0 | 13.5 | 600 | 332 | 495 | 330 | 385 | 350 | 285 | 295 |

(A) Data from Annexe G (Serrener, Créalab, HGE, 1993).

(B) Locations of Piezometers are shown in Figures 6 and 7.

## FIGURE 8

# SCHEMATIC SECTION OF SOLBEC OPEN PIT SHOWING AVERAGE CALCIUM CONCENTRATIONS (mg/L) IN GROUNDWATER



31607/27MAR95/FIG8/PJK

ADAPTED FROM SERRENER, CREALAB, HGE, (1993)

- The groundwater "plume" below and downgradient of the pit is characterized by heavy metal and sulphate concentrations which originated from the waste rock placed in the pit.

- The influence of the flooded underground mine workings (drifts, raises, stopes) on the pit hydrogeological regime could not be determined.

- The effects of the lime top layer was to elevate pH in the water cover (at least in the short term); and to act as a barrier (see calcium concentrations in pit waters shown in Figure 8).

- It was considered too early to reject the hypothesis that flushing of the wastes during their placement in water had led, at least in part, to the release of contaminants to the groundwater. Similarly, it was considered that the oxidation of sulphides below the limestone top layer could have led to the release of contaminants to the groundwater.

*Concluding Remarks:*

The mining company considers the boreholes F-3 and F-5 were located too close to the pit, and that these piezometers were in effect in direct contact with the groundwater within the pit. Therefore, these two boreholes may not be considered to be truly representative of downgradient groundwater quality.

Geophysical surveys (EM-34 and EM-81) were performed (Serrener and Géophysique Sigma Inc. 1993) and did not detect any anomaly in the locations of boreholes F-3 and F-5. The two anomalies detected were at the locations of the pit discharge and at the 6,000 m$^3$ settling pond.

The decision to discontinue the monitoring project was essentially based on these findings (Cambior Inc., 1995).

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# CASE STUDY 6: THE UDDEN OPEN PIT

## 1.0 Background Information

Boliden Mineral AB has developed a comprehensive in-pit disposal program involving fifteen open pit mine sites in Sweden (Lindvall, 1994, 1995a, b, c and d). The program involves the relocation of reactive waste rock and tailings to open pits and the inhibition of further acid generation by:

- flooding of the reactive wastes; or
- installation of dry covers over the reactive wastes; or
- combined flooding/cover.

The status of the fifteen open pits is as follows: five are being actively mined; one is on standby; three have ceased production; five are in various stages of decommissioning; and the decommissioning of one has recently been completed. The latter, the Udden open pit is the subject of this case study.

As indicated in Table 1, the waste storage capacity of the fifteen open pits varies from 100,000 tonnes to 400 million tonnes. The tonnage planned to be relocated to the pits varies from 50,000 tonnes to 50 million tonnes. In the latter case, Aitik, the waste rock will be deposited in an abandoned part of the pit, without intermediate stockpiling on surface. The mine wastes include reactive waste rock, low grade mineralization, and tailings. The cumulative total tonnage of reactive wastes planned to be relocated to the fifteen pits is approximately 55 million tonnes. Decommissioning plans have not yet been developed for a sixteenth open pit, a part of the Kristineberg Mine. This mine has a waste storage capacity of 1 million tonnes.

Strategies have been selected for twelve of the fifteen open pits: seven will use flooding; three will use dry covers; and two will use a combination of flooding and cover.

# Table 1

## BOLIDEN MINERAL AB, IN-PIT DISPOSAL PROJECTS

| | Status of Pit | Type of Waste | Waste Storage Capacity (Mt) | Tonnage Planned to be Disposed In-Pit (Mt) | Tonnage To Date Disposed In-Pit (Mt) |
|---|---|---|---|---|---|
| **Boliden Area** | | | | | |
| Boliden Pit | Filling in progress | Sulphidic tailings sand, misc. | 5 | 4 | 1 |
| Udden Pit | Recently finished | Weathered, sulphidic waste rock | >5 Mt | 0.05 | 0.1 |
| Långdal Pit | Mining | Sulphidic waste rock | 1 | 0.2 | 0 |
| Långsele Pit | Decommissioning | Sulphidic tailings sand & waste rock, misc. | 1 | 0.6 | 0.5 |
| Kankberg Pit | Mining | Weathered sulphidic waste rock | 0.5 | | - |
| **Kristineberg Area** | | | | | |
| Rävliden | Decommissioning | Waste rock | 0.2 | | 0.1 |
| Rävlidmyran | Decommissioning | Waste rock | 1 | | 0.1 |
| Näsliden | Finished 1991 | Waste rock | 0.4 | | 0.2 |
| Hornträsk | Decommissioning | Waste rock | 0.2 | | 0.1 |
| Kimheden | Closed 1974 | Weathered sulphidic waste rock | 0.1 | 0.1 | 0.05 |
| Rockejaur | Standby | Weathered sulphidic waste rock & ore | 1 | 0.2 | - |
| **Enåsen Mine** | | | | | |
| Enåsen | Closed 1992 | Waste rock, marginal ore, low mineralized | 1.5 | 0.2 | 0.2 |
| **Aitik** | | | | | |
| Aitik | Mining | Marginal ore & waste rock, low mineralized, sulphidic | 400 | 50 | - |
| **Garpenberg** | | | | | |
| Garpenberg Mine | Mining | Waste rock, misc. | 1 | | 0.2 |
| Garpenberg North Mine | Mining | Waste rock, sulphidic tailings sand | 1 | | - |

Source: (Lindvall, 1995a, d).

## Table 1 (Cont'd)

## BOLIDEN MINERAL AB, IN-PIT DISPOSAL PROJECTS

| | Waste Placement Method | Target Year Completion of | Acid Inhibition Strategy | Pit Lake Water |
|---|---|---|---|---|
| **Boliden Area** | | | | |
| Boliden Pit | Hydraulic | 2000 | Combined flooding/cover | Surplus water recovered to the Boliden mill |
| Udden Pit | Dumping + grading | 1994 | Flooding | pH rising: 4.7 (Nov 1993); 6.0 (Aug 1994) |
| Långdal Pit | Dumping + grading | 1997 | Flooding | The pit will be an extension of Skellefha River |
| Långsele Pit | Dumping + grading | 1997 | Combined flooding/cover | No overflow, infiltration to the Boliden mill shaft |
| Kankberg Pit | Dumping + grading | 1997 | Dry cover | Spring flow predicted |
| **Kristineberg Area** | | | | |
| Rävliden | Dumping + grading | 1997 | Flooding | No overflow to date |
| Rävlidmyran | Dumping + grading | 1997 | Flooding | No overflow to date |
| Näsliden | Dumping + grading | 1991 | Flooding | No overflow to date |
| Hornträsk | Dumping + grading | 1997 | Dry cover | No overflow to date |
| Kimheden | Dumping + grading | 1996 | Dry cover | Water treated in the mill tailings pond, low pH due to unprotected waste |
| Rockejaur | No plans established | Pending | Not established | Water perpetually treated |
| **Enåsen Mine** | | | | |
| Enåsen | Dumping + grading | 1995 | Flooding | No overflow to date |
| **Aitik** | | | | |
| Aitik | Dumping + grading | 2010 | Flooding | Initial treatment of drainage from dumps. No perpetual treatment after decommissioning |
| **Garpenberg** | | | | |
| Garpenberg Mine | No plans established | Pending | No plans established | Mine water treated in the mill tailings pond during production phase |
| Garpenberg North Mine | Dumping + grading | Pending | No plans established | Mine water treated separately |

Source: (Lindvall, 1995a, d).

Pit lakes will be created at the seven open pits where the wastes will be submerged by flooding. At five of these pits it is expected that the pit lake will remain contained with the pit and not normally overflow. The pit lakes at the other two pits are expected to overflow and the water may require treatment, in the short term, prior to discharge to the receiving environment. In general terms, Boliden aims at "walk away" solutions, where no water treatment is required.

The method to be used to transport and place mine wastes into the pits has been selected for thirteen of the fifteen open pits listed in Table 1. Haul trucks will be used at twelve pits to relocate rock and some tailings. Tailings at the Boliden Mine will be relocated hydraulically.

## 2.0 The Udden Pit

The Udden open pit was a base metal mine that produced zinc, and to a lesser extent, copper concentrates. The Udden orebody was a complex sulphide deposit. The principal ore mineral was sphalerite (ZnS). The ore was processed in the Boliden concentrator, some 35 km away.

The Udden ore and adjacent waste rock contained up to 40% pyrite. During the life of mine some of the pyrite was recovered for commercial acid production.

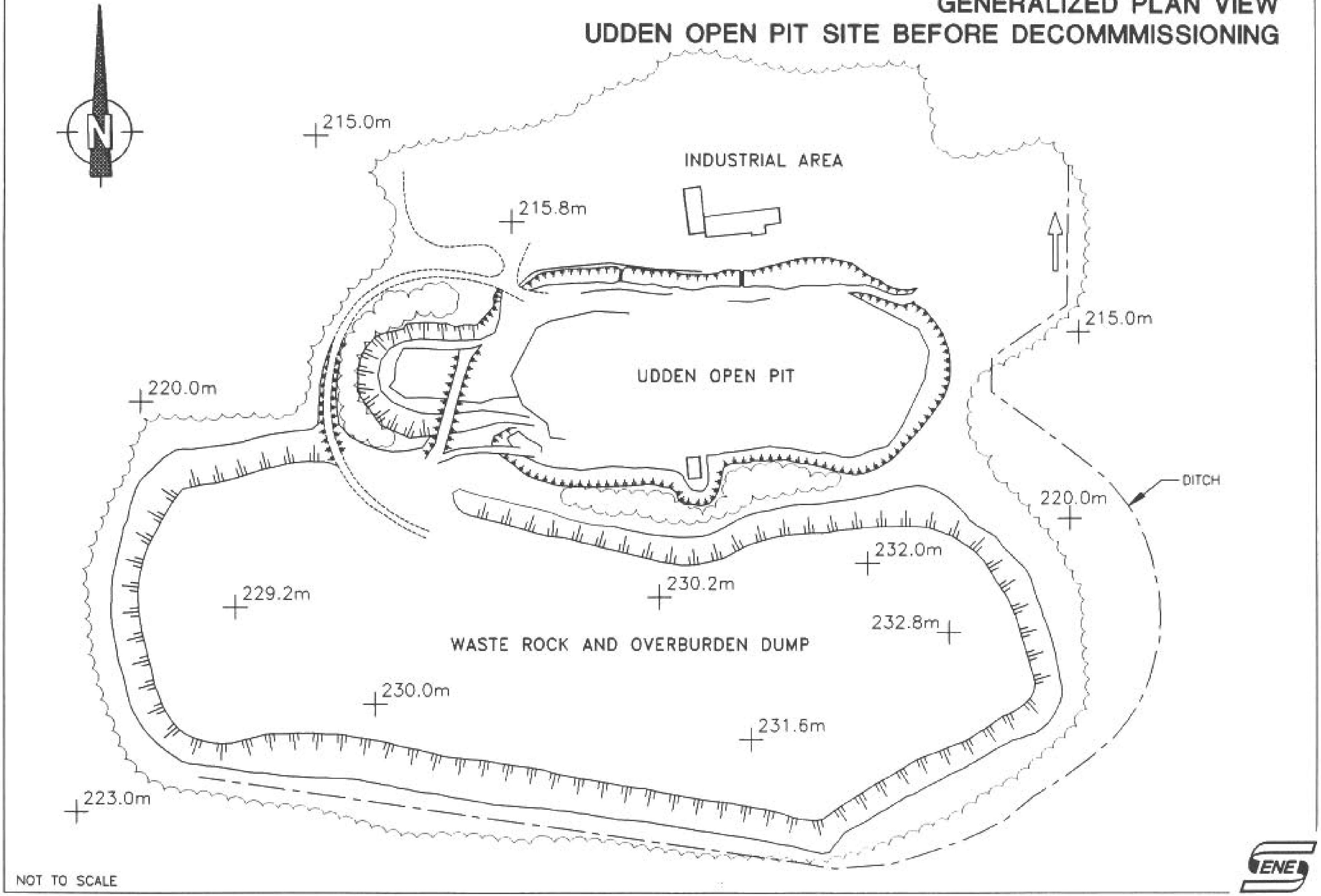
When the Udden pit was in operation overburden and waste rock were disposed in a combined overburden/waste rock dump located adjacent to the open pit. A generalized plan of the pit prior to decommissioning is shown in Figure 1.

The decommissioning plans for the Udden open pit called for the deposition of 50,000 tonnes of weathered, sulphidic waste rock in the pit. The pit would then be allowed to flood naturally. The surface of the waste dump located adjacent to the open pit would be revegetated. A generalized plan view of the open pit site after decommissioning is provided in Figure 2.

31807/27MAR95/F1UDDEN.DWG/M.T.N.

FIGURE 1

# GENERALIZED PLAN VIEW
# UDDEN OPEN PIT SITE BEFORE DECOMMMISSIONING



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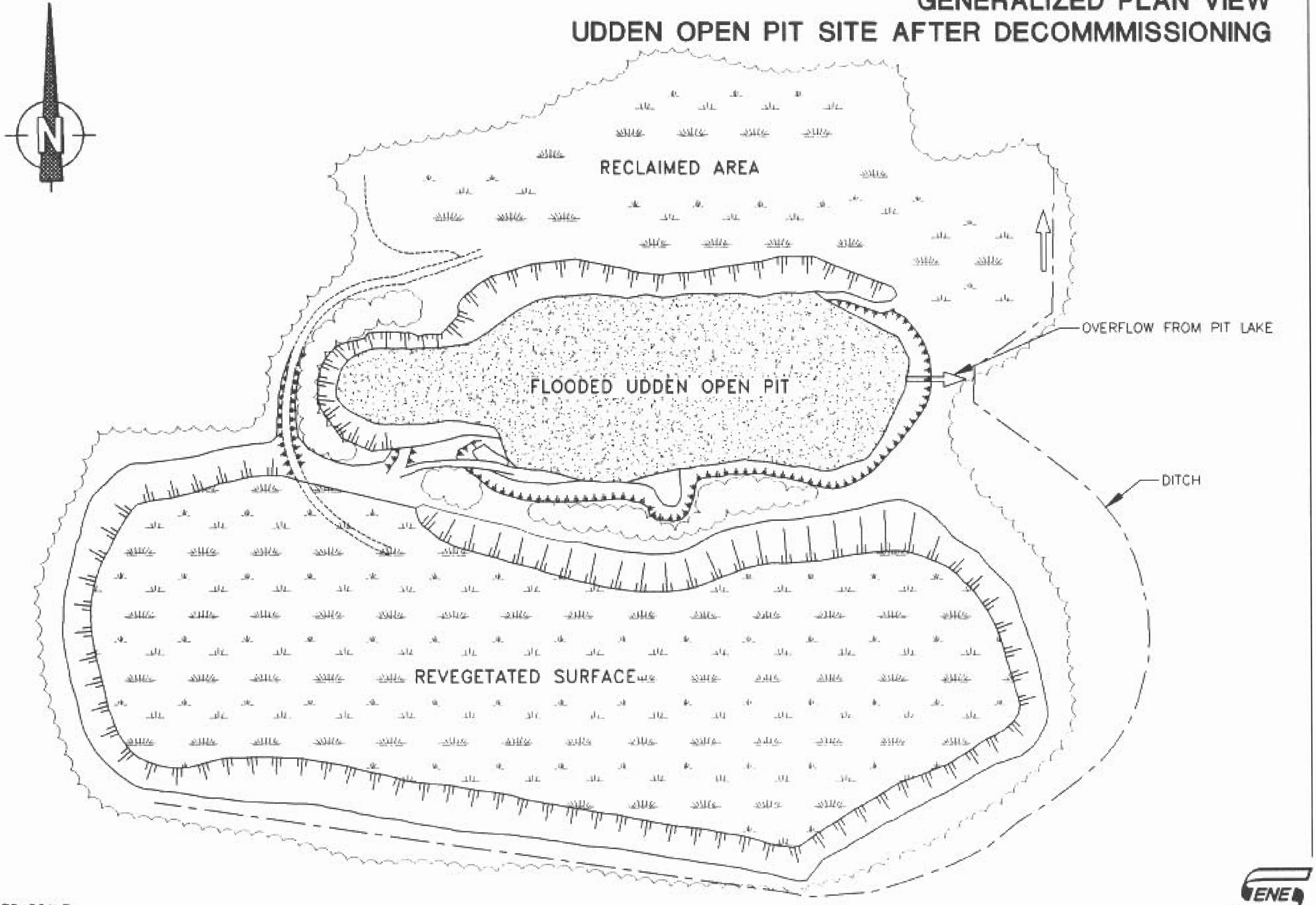
31607/27MAR95/F2UDDEN.DWG/M.T.N.

FIGURE 2

# GENERALIZED PLAN VIEW UDDEN OPEN PIT SITE AFTER DECOMMMISSIONING



NOT TO SCALE

SENES

## Table 2

## UDDEN OPEN PIT SURFACE WATER QUALITY

| Sample Date | Sample Description | pH | Suspended Solids mg/L | Conductivity mS/m | $SO_4$ mg/L | Cu mg/L | Pb mg/L | Zn mg/L | Cd mg/L | Flow L/s |
|---|---|---|---|---|---|---|---|---|---|---|
| 16 Nov 93 | Pit Water | 4.7 | 7 | 160 | 976 | 0.17 | 0.062 | 51.6 | 0.08 | ~ |
| 3 Aug 94 | Pit Water at Surface | 5.8 | <5 | 184 | 1270 | 0.17 | 0.010 | 81.1 | 0.13 | 1-2 |
| 3 Aug 94 | Pit Water at 10 m Depth | 6.0 | <5 | 195 | 1223 | 0.12 | 0.007 | 80.7 | 0.14 | - |
| 3 Aug 94 | Pit Water at 19 m Depth | 6.0 | <5 | 198 | 1133 | 0.10 | 0.006 | 80.8 | 0.14 | - |

Source: (Lindvall, 1995b).

A total of 100,000 tonnes of waste rock and contaminated soil from the industrial area, and waste rock from a nearby mine were relocated to the Udden open pit. The waste rock relocation was completed in June 1994. The open pit flooded rapidly and by August 1994 the pit lake level had risen to the point that water flowed (1-2 L/s) from the open pit.

## 3.0 Principal Findings

The water in the open pit was sampled in November 1993 at the start of the waste rock relocation program. The water quality data (Table 2) indicated an initial pH of 4.7.

The pit water was sampled again in August 1994 when the pit lake began to overflow at a low rate of 1 to 2 L/s. The pit lake was sampled down the water column with: one sample at surface; one at 10 m depth; and one at 19 m depth (bottom). Water quality data are presented in Table 2. The data indicate that the pH had improved to 6.0.

The pit water quality is expected to continue to improve and reach equilibrium in approximately two years. Further water quality sampling will be carried out in the spring of 1995.

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Lindvall, M. 1995a. Boliden Mineral, Letter to David Orava, SENES, 3 January.

Lindvall, M. 1995b. Boliden Mineral, Letter to David Orava, SENES, 3 February.

Lindvall, M. 1995c. Boliden Mineral, Personal Communications with David Orava, SENES, January-March.

Lindvall, M. 1995d. Boliden Mineral, Facsimile to David Orava, SENES, 21 March.

# CASE STUDY 7: THE STRATABOUND CNE OPEN PIT

## 1.0 Background Information

The Captain N Extension (CNE) open pit is located approximately 40 km southwest from Bathurst, New Brunswick. This lead/zinc open pit was decommissioned in 1993 using in-pit disposal of reactive waste rock. This case study is primarily based upon information provided by Whaley (1995a, b, c, d).

*History:*

During the exploration phase, it was observed that the waste rock in the potential open pit zone contained in the order of 10% fine pyrite. A decision was subsequently made by the mine developer (Stratabound Minerals Corp.) that any mine evaluation and planning activities would incorporate measures to control acid mine drainage (AMD) during production and provide for the inhibition of further AMD after mine closure. This decision was made without testing for acid generating/consuming potential (e.g. static testwork).

The CNE open pit was subsequently shown to be feasible and was mined between 1990 and 1992. A generalized site plan of the open pit is shown in Figure 1. Ore was hauled approximately 25 km away for custom milling.

*Operation:*

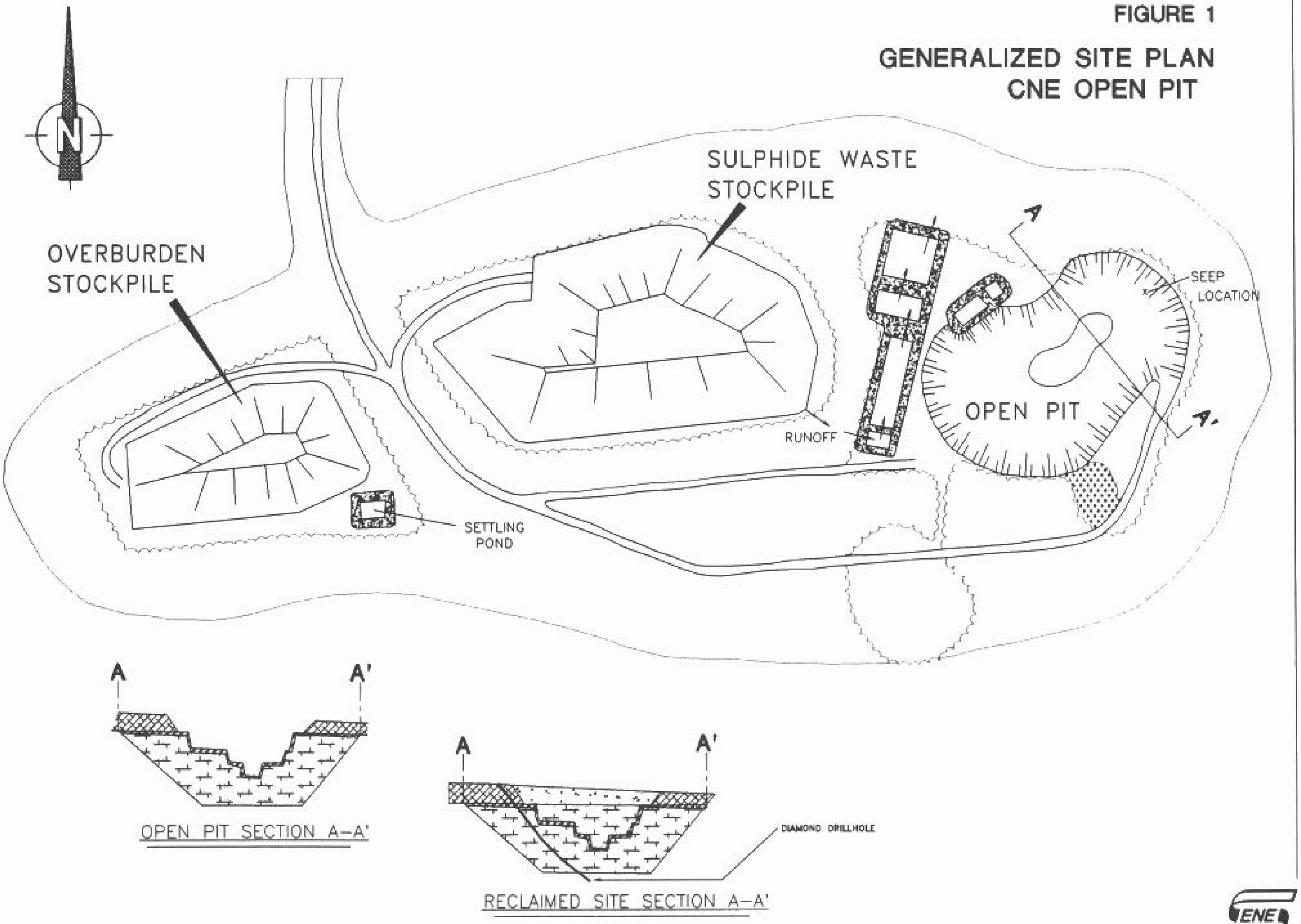
The orebody was covered by a 10 m layer of clay which was stripped and stockpiled separately. Waste rock was hauled from the pit and stockpiled in a location upgrade from the pit so that storm flows could be diverted to the pit if necessary. All production drilling was done using small diameter air track blastholes.

It is reported that the runoff from the waste rock stockpile became acidic very quickly. Runoff was collected by a perimeter ditch that led to a series of lime treatment/settlement ponds. The waste rock stockpile seepage was collected and treated over the operating life of mine.

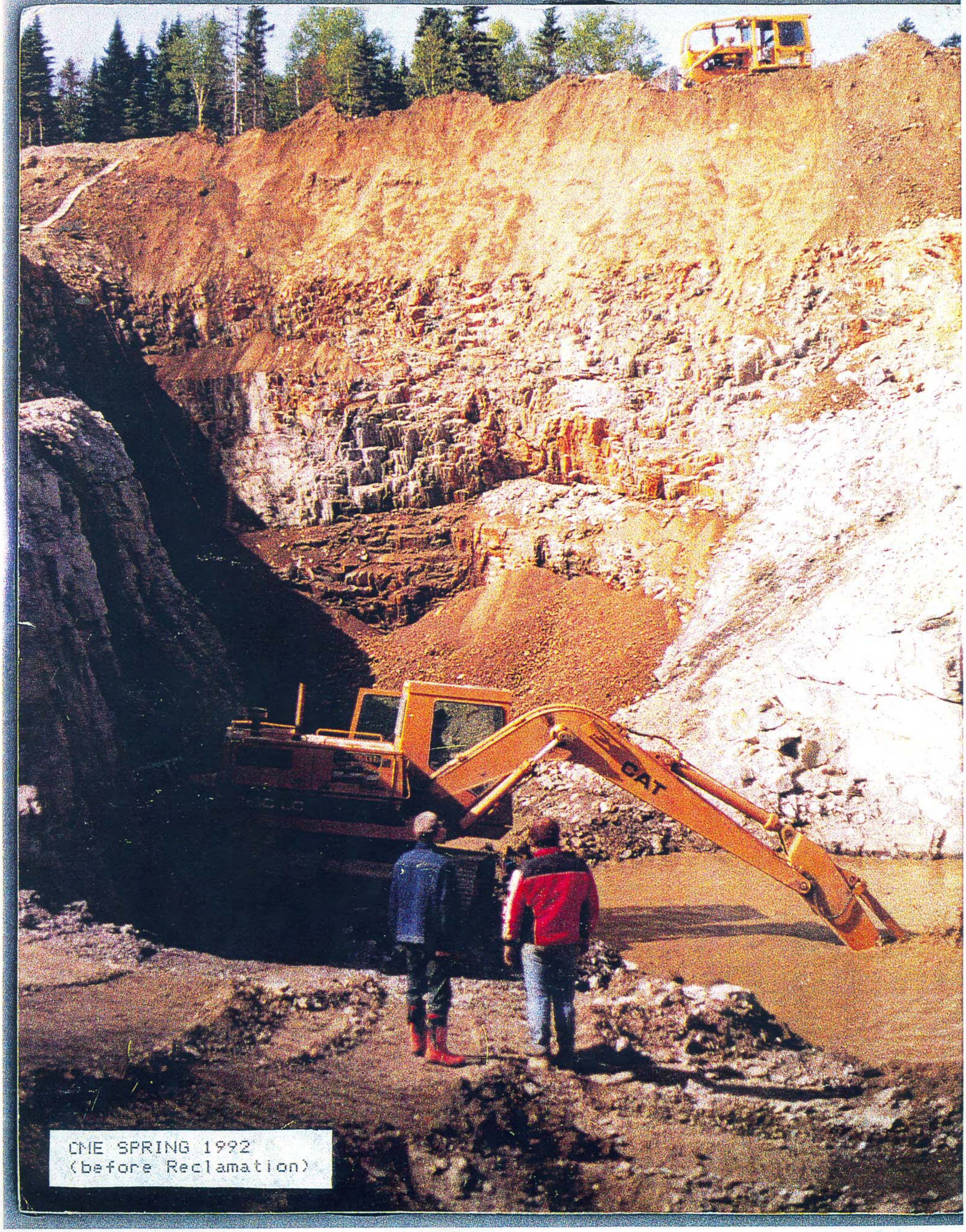
31807/27MAR95/F1.DWG/PJK

## FIGURE 1

## GENERALIZED SITE PLAN
## CNE OPEN PIT



NOT TO SCALE



CNE SPRING 1992
(before Reclamation)

CNE 1 YEAR AFTER RECLAMATION AUG 1993

## 2.0 Waste Rock Disposal

The open pit was mined as planned. Before the waste rock was relocated to the pit, the water in the pit was treated with lime and pumped to the settling pond. No additional lime was added to the open pit during the backfilling operation.

The surface of the waste rock within the pit is thought to be at or just below the water table.

The waste rock was capped using the stockpiled clay. The clay cap subsequently settled and a small seepage was observed and sampled.

The site reclamation costs were low, in the range of $2/ton for the clay cap, and $1/ton for the placement of waste rock in the pit. The total reclamation cost including seeding of the graded site was approximately $100,000.

The site was vegetated using grass seed. The grass surface is being replaced by invading natural plant species. The former pit site is reverting back to a natural state, and is occasionally used as a camp site by hunters.

The mine developer is evaluating the mining of an adjacent mineralized zone and is considering a similar approach for the disposal of reactive waste rock.

## 3.0 Water Quality Monitoring

The mine developer established and maintains two water quality monitoring stations at the open pit:

- seepage from the clay cap; and
- an inclined diamond drill hole that allows sampling of groundwater from about 10 m beneath the infilled open pit bottom bench.

## Table 1

## CNE OPEN PIT WATER QUALITY DATA

| Water Quality Sampling Station | Sampling Date | pH | Zn (ppm) |
|---|---|---|---|
| Seep (from clay cap) | 23 October 1992 | 7.05 | 3.02 |
| | 3 February 1993 | 6.50 | 2.24 |
| | 30 June 1993 | 7.30 | 1.01 |
| | 21 September 1993 | 6.40 | 1.42 |
| | 3 November 1993 | 6.90 | 1.45 |
| | 19 May 1994 | 6.75 | 1.03 |
| | 26 July 1994 | 6.65 | 1.10 |
| | 12 September 1994 | 6.60 | 1.76 |
| | 29 November 1994 | 6.60 | 0.98 |
| Diamond Drillhole (below open pit) | 22 June 1989 | 6.98 | 0.00 |
| | 1 November 1989 | 6.50 | 0.01 |
| | 19 January 1990 | 6.40 | 0.01 |
| | 5 June 1990 | 6.95 | 0.01 |
| | 12 September 1990 | 6.85 | 0.01 |
| | 29 October 1990 | 6.60 | 0.00 |
| | 22 February 1991 | 6.55 | 0.01 |
| | 6 June 1991 | 7.00 | 0.01 |
| | 30 October 1991 | 6.60 | 0.01 |
| | 7 May 1992 | 6.85 | 0.00 |
| | 22 October 1992 | 6.80 | 0.10 |
| | 3 February 1993 | 7.00 | 0.01 |
| | 30 June 1993 | 7.30 | 0.00 |
| | 17 September 1993 | 6.25 | 0.01 |
| | 29 November 1994 | 6.45 | 0.01 |

Source: (Whaley, 1995c).

The locations of the two stations are indicated in Figure 1. Water quality data obtained from June 1989 to November 1994 are shown in Table 1.

The data for the seepage from the clay cap indicate a pH range of 6.40 to 7.30, and a zinc concentration ranging from an initial 3.02 mg/L to the latest measurement of 0.98 mg/L. It is reported that the seepage has no effect on the surrounding drainage.

The data for samples from the diamond drillhole indicates that the groundwater pH has ranged from 6.25 to 7.30 while zinc concentrations have consistently ranged from 0 to 0.10 mg/L.

## 4.0 Principal Findings

The in-pit disposal of reactive waste rock was taken into consideration at the start of the project feasibility stage. This resulted in lower than otherwise expected costs for:

- the collection and treatment of the AMD during the operating life of the mine;
- the relocation of waste rock to the pit; and
- mine closure/site remediation.

### References

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Whaley, K. 1995c. Stratabound Minerals Corp, Facsimile to David Orava, SENES, 15 March.

Whaley, K. 1995d. Stratabound Minerals Corp, Facsimile to David Orava, SENES, 11 May.

# CASE STUDY 8: ROBINSON MINING DISTRICT

## 1.0 Background Information

Robinson Mining Limited Partnership (RMLP) proposes to reinitiate copper mining in the historic Robinson Mining District located near Ely, Nevada in the USA. It is proposed to expand and develop historic open pit copper mines, develop new copper concentration facilities, and expand existing gold heap leaching operations . A plan of the area and existing pits is shown in Figure 1. The pit dimensions are shown in Table 1.

Table 1

**PIT DIMENSIONS**

| | Veteran/Tripp | Liberty | Ruth | Wedge | Kimbley |
|---|---|---|---|---|---|
| Water Volume ($m^3$) | $8.25x10^6$ | $2.67x10^7$ | $2.44x10^7$ | $4.2x10^6$ | $5.30x10^5$ |
| Total wall rock area ($m^2$) | $5.9x10^5$ | $7.8x10^5$ | $5.9x10^5$ | $1.83x10^5$ | $5.7x10^4$ |
| Volume/Area ($m^3/m^2$) | 14 | 34 | 41 | 23 | 9.3 |

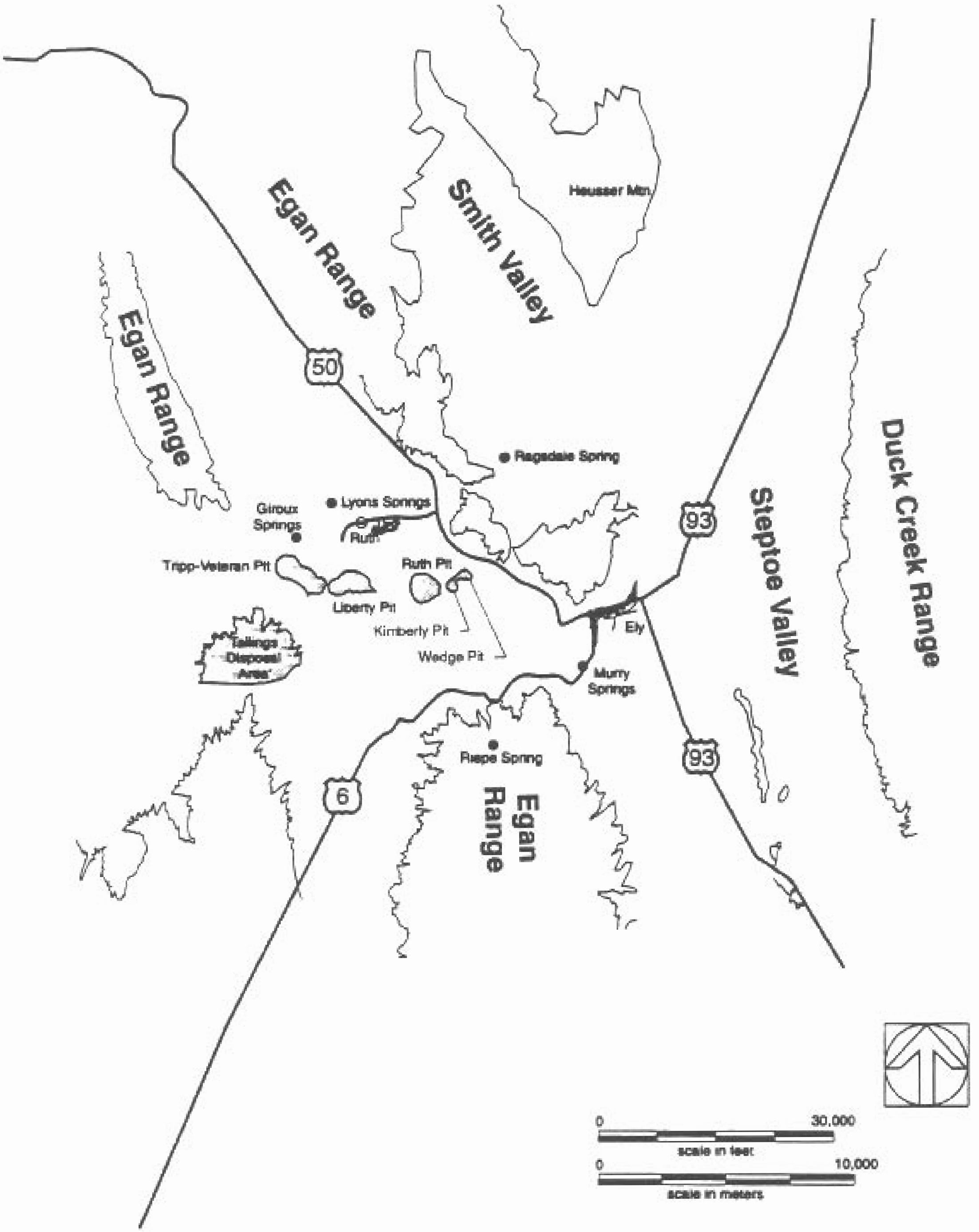
The plans are to mine ore reserves by widening and deepening the five existing open pits (Veteran/Tripp, Liberty, Wedge, Ruth and Kimbley). The closure of the open pits is predicted to result in the development of surface water bodies (pit lakes) in the pits as the groundwater table rebounds after dewatering ceases.

PTI Environmental Services Inc. of Boulder, Colorado were retained in 1994 to conduct a study of the hydrogeochemistry of the Robinson Project. The purpose of the study was to identify and assess water resources affected by the project. Major areas of the study include:

- waste rock dump geochemistry;
- pit-lake water quality; and
- groundwater quantity and quality.

FIGURE 1

GENERAL LOCATION PLAN
ROBINSON MINE



SOURCE: FIGURE 6-6 (PTI, 1994)

The study carried out by PTI is of interest due to the extensive hydrological modelling that was completed to support the prediction of environmental impacts.

## 2.0 Technical Data and Evaluation

*Waste Rock Piles:*

Historical mining activities produced a projected 980 million tonnes of waste, with waste rock dumps distributed for convenience in topographic depressions around the periphery of the pits. To address issues raised regarding the potential impact of waste rock piles on groundwater and surface water quality, evaluations were conducted on existing waste rock dumps (up to 60 years old) to assess on-site field geochemical conditions. The potential for future impacts was then evaluated. Representative samples of the various types of waste rock material were analyzed for acid generation potential using bottle tests, acid-base accounting, and humidity tests. Oxygen and metal profiles demonstrated that despite technical acid leaching, followed by more than 20 years of weathering, acidification reactions were limited to the top 150 cm of the waste rock pile.

The Simulation Model for Acid Sulphate Soils (SMASS), Bronswijk et al. (1993) and Ritsema and Groeneberg (1993), was used to estimate the potential for waste rock to generate acidic effluent and affect groundwater quality. SMASS was selected because it incorporates relevant transport phenomena such as unsaturated and saturated flow, solute transport, oxygen diffusion and pyrite oxidation, and multi-component equilibrium. The modelling confirmed that the chemical dump profiles were stable and would not result in future groundwater contamination.

*Pit-Lake Water Quality:*

Some of the pits are currently flooded. Pit Water Quality is provided in Table 2. The quality of the present pit lakes has been affected by historic in-pit and dump leaching. Acidic effluent is known to have been introduced into the Liberty and Kimbley pit lakes due to heap-leaching of perimeter waste rock. Cyanide tailings were added to the Ruth pit and acidic water was pumped from the Liberty pit into the Ruth pit in preparation for mining. The Veteran pit is considered to be the most representative of future pit lake conditions because, unlike the others the perimeter waste rock was not acidified historically.

Table 2

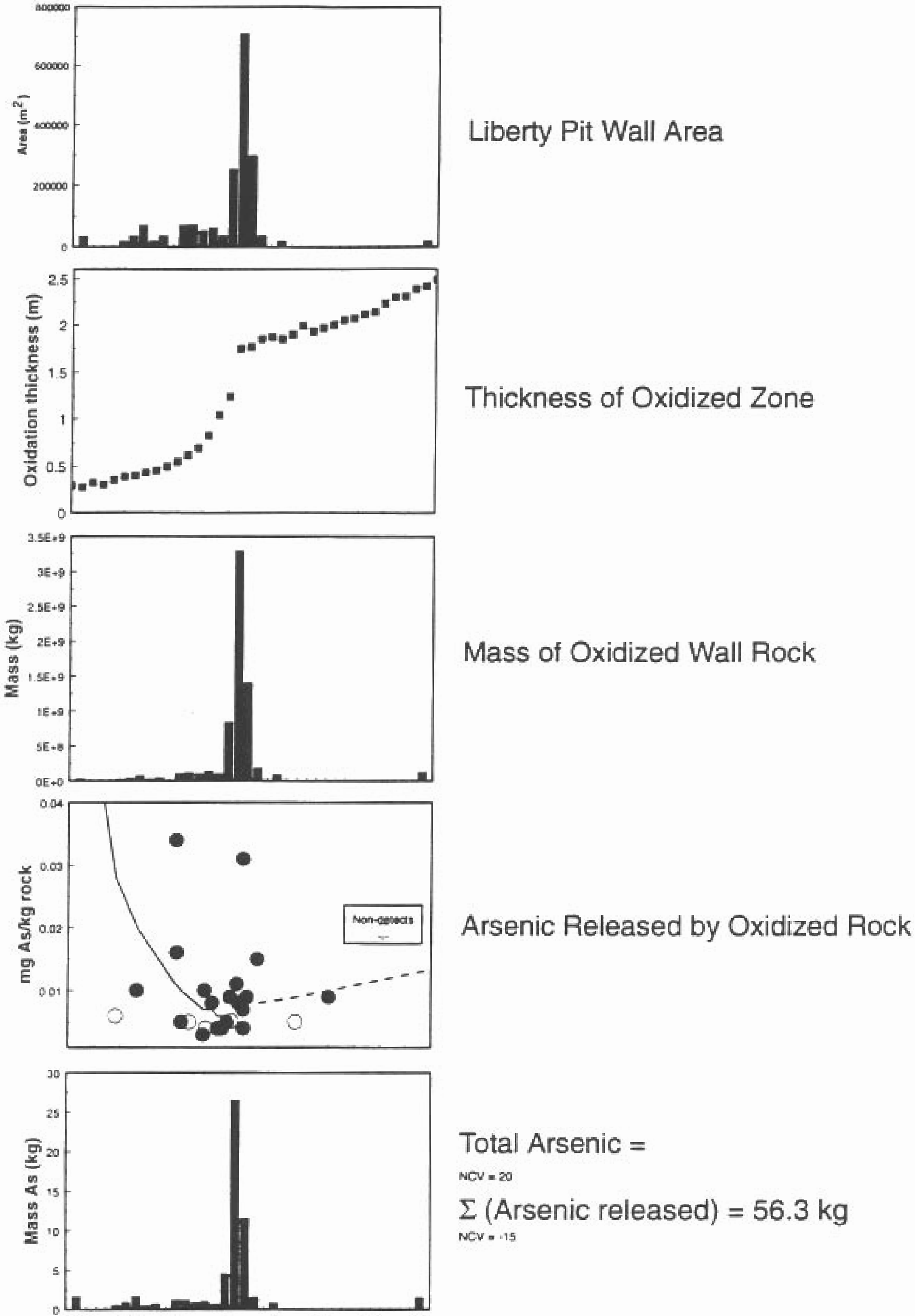
### PIT WATER QUALITY

| | Liberty August 1991 (mg/L) | Ruth September 1986 (mg/L) | Ruth August 1991 (mg/L) | Kimbley September 1991 (mg/L) |
|---|---|---|---|---|
| Arsenic | <0.001 | <0.004 | <0.001 | <0.180 |
| Barium | <0.01 | <0.3 | 0.02 | 0.009 |
| Cadmium | 0.412 | 0.148 | <0.005 | <0.007 |
| Chromium | 0.03 | 0.1 | 0.02 | <0.010 |
| Fluoride | 13 | 2.4 | 2.3 | 2.61 |
| Lead | 0.005 | <0.01 | 0.001 | <0.050 |
| Mercury | <0.0002 | <0.0001 | 0.0002 | 0.838 |
| Nitrate | <0.1 | 0.02 | 2.4 | <1.0 |
| Selenium | <0.002 | <0.004 | 0.04 | <0.130 |
| Silver | <0.01 | <0.01 | 0.04 | <0.020 |
| Chloride | 30 | 6.6 | 44 | 264 |
| Copper | 50.6 | 31 | 17.5 | 0.172 |
| Iron | 20.7 | 2.94 | 0.17 | 0.455 |
| Manganese | 77 | 108 | 0.611 | 0.31 |
| pH | 2.86 | 3.23 | 8 | 7.59 |
| Sulphate | 2,860 | -- | 1,330 | 1,607 |
| TDS | 3,480 | 2,130 | 1,820 | 3,310 |
| Zinc | 35 | 40 | 0.041 | 2.43 |

Source: Macdonald (1992) (Data originally reported by Woodward-Clyde Consultants, 1992).

FIGURE 2

## ALGORITHM FOR CALCULATING WALLROCK LEACHATE TO A PIT LAKE EXAMPLE IS ARSENIC IN LIBERTY PIT



Total Arsenic =

$$\sum_{NCV=-15}^{NCV=20} \text{(Arsenic released)} = 56.3 \text{ kg}$$

SOURCE: FIGURE 4.9 (PTI,1994)

Table 3

# PREDICTED 50th PERCENTILE INITIAL CHEMICAL COMPOSITION FOR EACH PIT LAKE

(mg/L unless otherwise noted)

| Parameter | Tripp/Veteran Pit | Wedge Pit | Kimbley Pit | Liberty Pit | Ruth Pit |
|---|---|---|---|---|---|
| Aluminum | 0.016 | 0.018 | 0.005 | 0.012 | 0.015 |
| Antimony | 0.073 | 0.073 | 0.110 | 0.081 | <0.001 |
| Arsenic | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |
| Barium | 0.004 | 0.008 | 0.004 | <0.001 | <0.001 |
| Beryllium | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 |
| Bismuth | 0.035 | 0.035 | 0.035 | 0.035 | 0.035 |
| Cadmium | 0.009 | 0.0001 | 0.021 | 0.010 | 0.009 |
| Calcium | 388 | 156 | 437 | 354 | 247 |
| Chromium | 0.026 | 0.021 | 0.003 | 0.001 | 0.001 |
| Cobalt | 0.005 | 0.005 | 0.005 | 0.021 | 0.005 |
| Copper | 0.233 | 0.248 | 0.498 | 0.257 | 0.250 |
| Gallium | 0.100 | 0.100 | 0.100 | 0.100 | 0.100 |
| Iron | 0.0004 | 0.0003 | 0.001 | 0.0004 | 0.0004 |
| Lead | 0.0002 | 0.0003 | 0.002 | 0.0002 | 0.0002 |
| Lithium | 0.020 | 0.022 | 0.024 | 0.018 | 0.018 |
| Magnesium | 22.0 | 28.7 | 26.7 | 15.2 | 10.2 |
| Manganese | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |
| Mercury | 0.0004 | 0.0005 | 0.001 | 0.001 | 0.001 |
| Nickel | 0.046 | 0.022 | 0.063 | 0.043 | 0.032 |
| Potassium | 2.32 | 4.26 | 3.58 | 4.34 | 8.91 |
| Scandium | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 |
| Selenium | 0.058 | 0.058 | 0.065 | 0.041 | 0.051 |
| Silver | 0.010 | 0.011 | 0.018 | 0.010 | 0.010 |
| Sodium | 16.9 | 16.7 | 23.2 | 23.6 | 20.6 |
| Strontium | 0.92 | 0.765 | 0.813 | 0.760 | 0.731 |
| Thallium | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 |
| Tin | 0.100 | 0.100 | 0.100 | 0.100 | 0.100 |
| Titanium | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 |
| Vanadium | 0.007 | 0.014 | 0.007 | 0.007 | 0.007 |
| Zinc | 0.156 | 0.206 | 1.01 | 0.438 | 0.383 |
| Chloride | 19.7 | 19.4 | 25.5 | 20.4 | 21.4 |
| Fluoride | 0.905 | 1.17 | 1.83 | 1.80 | 1.78 |
| Sulfate | 1,912 | 684 | 2,267 | 1,643 | 1,124 |
| Alkalinity, Total | 69.8 | 76.4 | 14.0 | 50.8 | 64.1 |
| pH (s.u.) | 7.88 | 7.95 | 7.13 | 7.74 | 7.86 |
| Total Dissolved Solids | 2,405 | 958 | 2,796 | 2,094 | 1,474 |

SOURCE: TABLE 4-17 (PTI, 1994)

The post-closure chemical composition would be largely influenced by the chemical composition of inflowing groundwater and the chemical reaction of the water with exposed wall rock. Investigations show that a portion of the wall rock that would be exposed in the expanded pits contains sulphides; oxidation could create the potential for generation of acid and leaching of certain metals, along with other elements. To quantify the acid generating reaction, a numerical model of pyrite oxidation was used to determine the thickness of the oxidized zone anticipated in the pit walls.

Bottle experiments and humidity cell tests were run on core material considered to be representative of future wall rock at the time of pit closure, to ascertain the reactivity and leachability of metals from post-mining oxidized wall rock and waste disposed underwater in the pits.

A computer program using the algorithm illustrated in Figure 2 was developed for calculating the bulk chemical composition of each pit lake. The aggregated release of acid and metals from the rock samples was used, in conjunction with the wall rock oxidation rind thickness, to calculate the bulk aqueous chemistry as the pit excavation flooded over time. The final pit lake composition was calculated by entering the generated bulk composition into the geochemical model MINTEQA2 (Allison et al., 1991). This quantifies the mineral precipitation, adsorption and carbonate buffering.

Concentrations predicted in the modelling for key constituents are presented in Table 3. The modelling results indicate that the ultimate water quality in all pit lakes will be benign due to carbonate alkalinity in inflowing groundwater. As well, the bottle tests used to simulate the effect of tailings and waste rock disposal on pit water quality indicated that these materials will result in additional buffering, if introduced to the pit lake.

*Groundwater Quality:*

Groundwater chemistry at the Robinson Mine site was examined to:

- determine existing groundwater quality;

- evaluate the quality of potential influent water to pit lakes to assist in predictive simulations; and

- assess the geographic distribution of water chemistry to aid in interpreting regional hydrology.

The geochemical model MINTEQA2 was used to determine the solubility constraints on the major groundwater constituents, and to calculate the total carbon and hydrogen from the alkalinity and pH, for use in predicting the influent water composition for the pit lakes. Using laboratory results for input parameters, the model predicted a ferrous/ferric ratio similar to that observed in the field. It was also concluded that the groundwater chemistry at the site is controlled by a combination of the different rock types in the area and technical mining-related activities.

From the data it could also be determined that the municipal water source for the city of Ely, is not hydraulically or geochemically connected to the mine site.

*Groundwater Quantity:*

The groundwater model MODFLOW (McDonald and Harbaugh, 1988) was used to provide a three-dimensional determination of groundwater flow, and to predict the effects on groundwater elevation and water quantity in response to the various phases of mining activities. A large body of hydrogeological data was available and additional field studies were undertaken to provide necessary model input data. Important physical aspects were incorporated into the groundwater flow model (i.e. faults, open pits, underground mining tunnels, and metamorphic geology). The model consisted of nine vertical layers (3300 m to 900 m above sea level) and contained more than 50,000 active cells (finite elements).

The proposed pumping for dewatering of the open pit mines will result in a draw-down cone. The water table will rebound after the cessation of pumping. It was predicted that 50 years after closure, the cone of depression will have recovered 87%, and after 100 years the cone will have recovered 91%.

Disposal of tailings in Liberty pit would result in localized mounding of the water table but is not expected to cause further deterioration in groundwater quality.

## 3.0 Commentary

Numerical modelling techniques are increasingly being used to predict post-closure surface water quality, and would normally be a component of any detailed closure proposal that would involve a pit lake.

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# CASE STUDY 9: THE GUNNAR PIT

## 1.0 Background

*History:*

The Gunnar uranium mine is located on the Crackingstone Peninsula on the north shore of Lake Athabasca in Northern Saskatchewan. The operations which occurred from about 1959 to 1964 included an open pit and an underground mine. After closure in 1964, the narrow ridge of bedrock separating the open pit from Lake Athabasca was breached and water from the lake flooded the open pit and the underground mine. The channel was closed in 1966. The open pit is currently separated from Lake Athabasca (St. Mary's channel) by a coarse rock-filled ditch. A general site plan is provided in Figure 1.

The pit contains residual mineralization from the mine walls, and a large inventory of waste rock that may contain some tailings used to backfill stopes. Fish processing plant wastes (waste water and fish offal) were discharged into the open pit from 1971 to 1981.

The pit is almost circular covering about 7 ha with a surface dimension of 300 m by 250 m and a depth in excess of 100 m. Almost all of the pit, except for a small portion of the high wall, is below the level of Lake Athabasca. Details of the investigations at this site are described in Tones (1982).

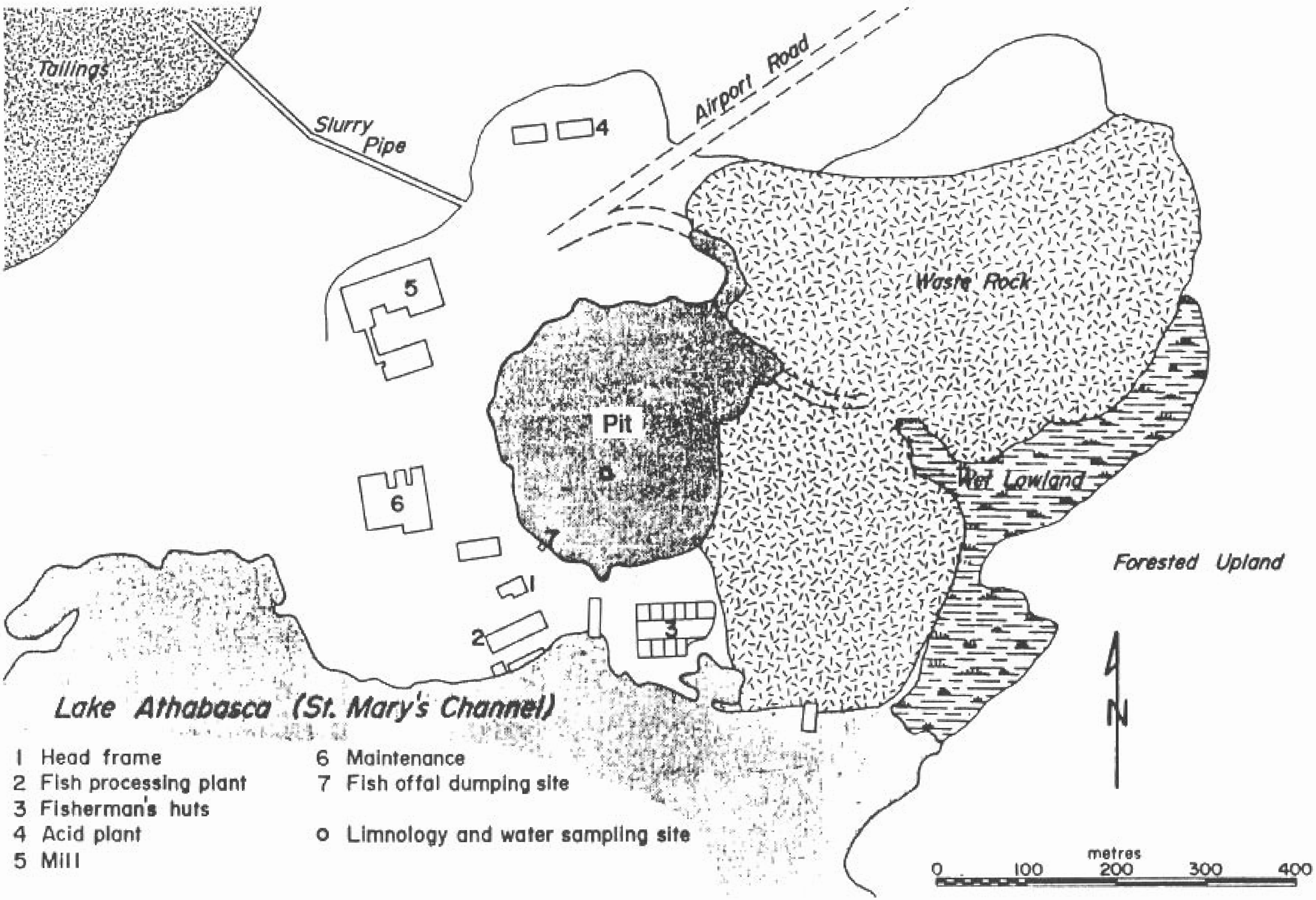
This pit is an interesting case study because of its unique limnological characteristics. The flooded pit was used for waste disposal and has five defined zones of stratification in the pit water column.

*Mineralogy:*

Most of the open pit, particularly towards the south (Lake Athabasca side), is underlain by granitic gneiss which is coarse-grained and contains quartz (30% to 40%),

FIGURE 1

GENERAL SITE PLAN
GUNNAR MINE



SOURCE: FIGURE 2.10, TONES (1982)

feldspar (50% to 60%), chlorite and minor mica. Syenitic granite gneiss and paragneiss outcrops occur along the northern edge. Syenite followed the paragneiss contact and was the exclusive host rock to the ore. The syenite was essentially an altered granite. The ore minerals were pitchblende, and to a lesser extent, uranophane. The grade of the ore was 0.175% $U_3O_8$ (Tones, 1982). The cut-off grade was estimated to be about 0.01% $U_3O_8$.

## 2.0 Investigative Procedures

Tones (1982) undertook detailed surveys of the Gunnar Pit water quality on three occasions, 23 August, 20 September and 8 November 1981. Detailed depth profiles were measured for temperature, dissolved oxygen and conductivity. The results of these data are reproduced in Figures 2a, b, c. Water quality samples were also collected at several depths and these data are summarized in Tables 1a, b. Sampling also included sediments, aquatic vegetation, aquatic organisms, invertebrates, and fish; sediment quality data is shown in Table 2.

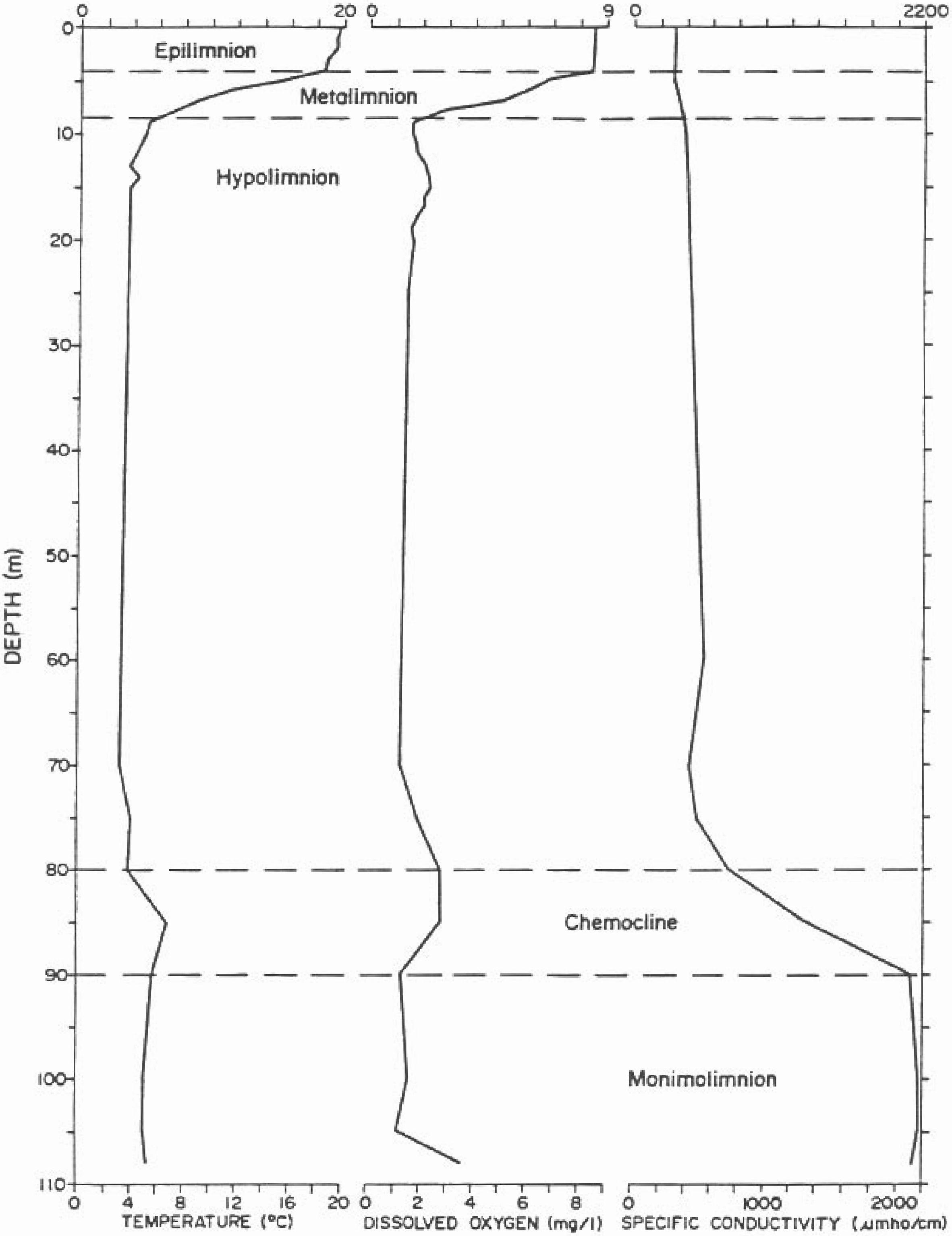
Tones (1982) identified up to five layers of stratification caused by density changes as a result of thermal and chemical layering. The thermal layers were unstable and broke down as the pit water cooled due to the approach of winter; however, the chemical stratification remained in place during all sampling periods, and it was concluded that the flooded pit is meromictic. The researcher also described the five layers observed during the summer (August and September) sampling as (from surface to pit bottom):

| | | |
|---|---|---|
| epilimnion | (0-4 m) | warm well-mixed upper layer with ample dissolved oxygen |
| metalimnion | (4-10 m) | transition zone |
| hypolimnion | (10-74 m) | large cold (3.5°C) stratum where oxygen was reduced or absent |
| chemocline | (75-90 m) | zone of increasingly higher concentrations and higher specific conductivity |
| monimolimnion | 90 m -$110^{+}$ m | deepest stratum, high conductivity, cold, no dissolved oxygen |

The epilimnion is warm and contains high levels of dissolved oxygen; these conditions

FIGURE 2a

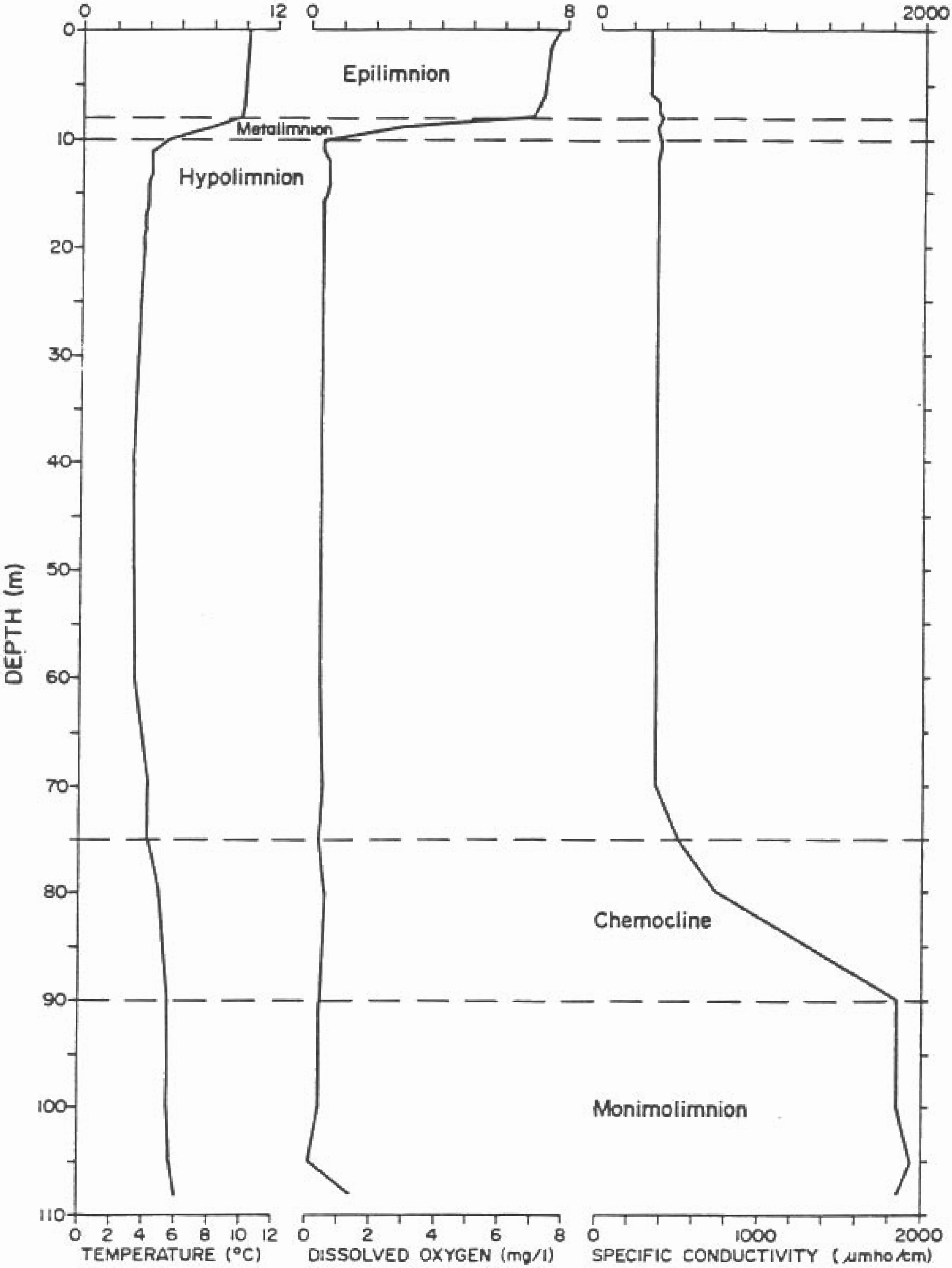
## DEPTH PROFILES OF TEMPERATURE, DISSOLVED OXYGEN AND SPECIFIC CONDUCTIVITY FOR FLOODED GUNNAR OPEN PIT, AUGUST 23, 1981



SOURCE: FIGURE 2.3, TONES (1982)

FIGURE 2b

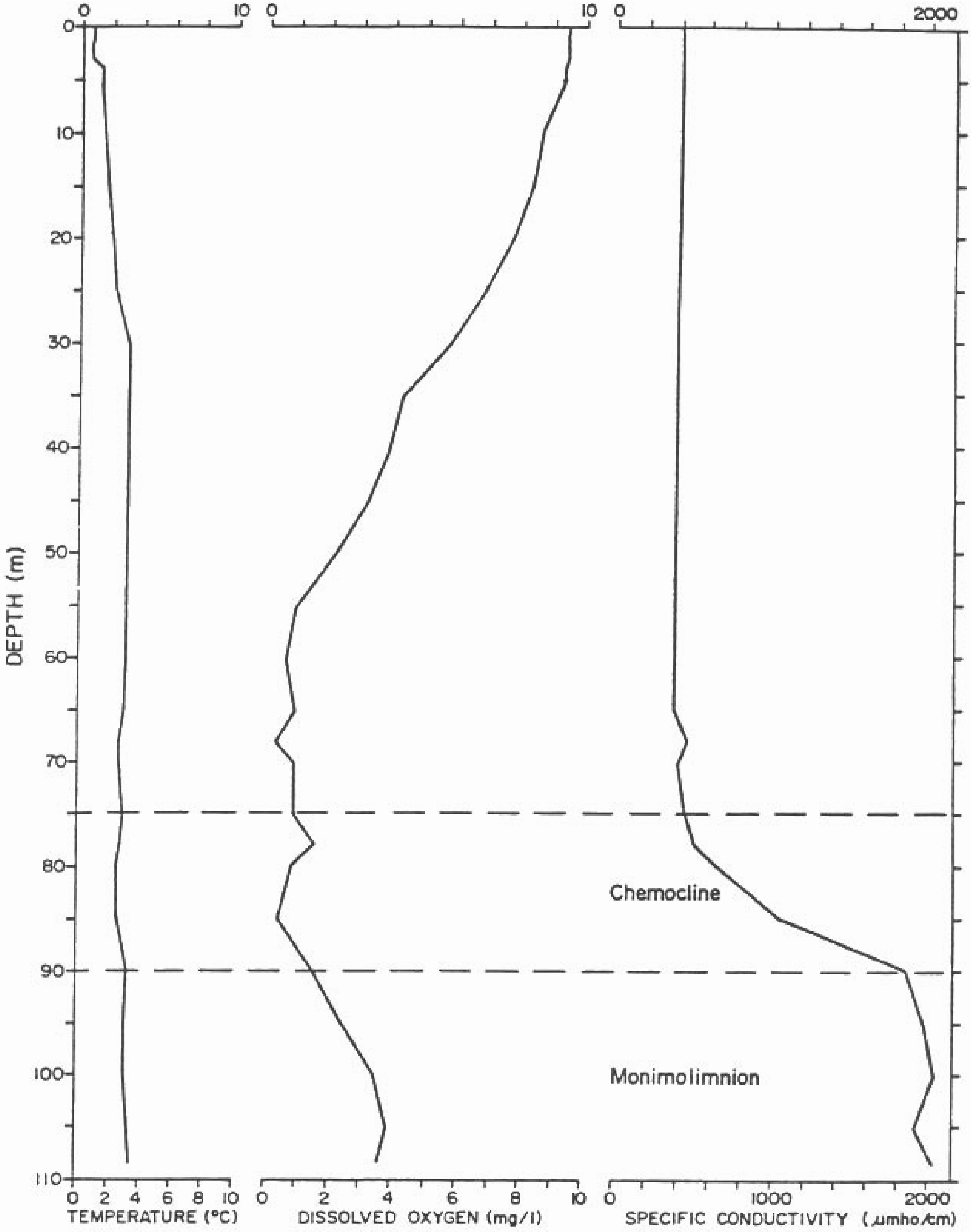
## DEPTH PROFILES OF TEMPERATURE, DISSOLVED OXYGEN AND SPECIFIC CONDUCTIVITY FOR FLOODED GUNNAR OPEN PIT, SEPTEMBER 20, 1981



SOURCE: FIGURE 2.4, TONES (1982)

FIGURE 2c

## DEPTH PROFILES OF TEMPERATURE, DISSOLVED OXYGEN AND SPECIFIC CONDUCTIVITY FOR FLOODED GUNNAR OPEN PIT, NOVEMBER 8, 1981



SOURCE: FIGURE 2.5, TONES (1982)

Table 1a

## WATER QUALITY DATA AT DIFFERENT DEPTHS, GUNNAR FLOODED PIT, AUGUST 23, 1981 AND SEPTEMBER 20, 1981

| | | August 23, 1981 | | | | September 20, 1981 | |
|---|---|---|---|---|---|---|---|
| | Units | 1 m | 50 m | 85 m | 108 m | 1 m | 108 m |
| Bicarbonate | mg/L | 70 | 68 | 190 | 251 | 68 | 251 |
| Calcium | mg/L | 34 | 36 | 128 | 208 | 35 | 187 |
| Chloride | mg/L | 10 | 10 | 59 | 73 | 10 | 75 |
| Magnesium | mg/L | 10 | 9 | 50 | 43 | 8 | 58 |
| Potassium | mg/L | 2.8 | 3.2 | 5.6 | 7.4 | 3.0 | 6.8 |
| Sodium | mg/L | 6.1 | 6.6 | 33 | 47 | 6.3 | 46 |
| Sulphate | mg/L | 74 | 80 | 288 | 511 | 75 | 458 |
| Arsenic | ug/L | 1.6 | 1.6 | 2.1 | 2.6 | 1.6 | 3.5 |
| Cyanide | ug/L | <0.1 | 3.0 | <0.1 | <0.1 | <0.1 | <0.1 |
| Mercury | ug/L | <0.05 | 0.92 | <0.05 | <0.05 | <0.05 | <0.05 |
| Selenium | mg/L | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |
| Cadmium | mg/L | 0.0018 | 0.0015 | <0.0005 | 0.0040 | 0.0099 | 0.0007 |
| Chromium | mg/L | 0.008 | 0.008 | 0.006 | 0.009 | 0.009 | 0.006 |
| Cobalt | mg/L | 0.002 | 0.002 | 0.001 | 0.004 | 0.004 | 0.002 |
| Copper | mg/L | 0.003 | 0.004 | 0.004 | 0.005 | 0.004 | 0.002 |
| Total Alkalinity | mg/L | 57 | 56 | 156 | 206 | 56 | 206 |
| Total Kjeldahl Nitrogen | mg/L | 0.72 | 0.51 | 0.23 | 2.6 | 0.49 | 1.7 |
| Ortho Phosphate | mg/L | 0.58 | 1.2 | 0.17 | 0.80 | 0.80 | 0.12 |
| Total Phosphate | mg/L | 1.3 | 2.1 | 1.7 | 0.94 | 1.5 | 0.94 |
| Total Inorganic Carbon | mg/L | 15 | 15 | 39 | 50 | 15 | 58 |
| Total Organic Carbon | mg/L | 3 | 1 | 2 | 5 | 3 | 6 |
| Total Dissolved Solids | mg/L | 175 | 169 | 645 | 1050 | 168 | 1020 |
| Total Suspended Solids | mg/L | 2 | 2 | 2 | 2 | 2 | 2 |
| Total Lead-210 | Bq/L | 0.12 | <0.02 | 0.30 | 0.09* | 0.05 | 0.45 |
| Total Radium-226 | Bq/L | 0.09 | 0.06 | 0.12 | 0.40 | 0.14 | 0.35 |
| Total Uranium | ug/L | 708 ± 89 | 320 ± 19 | 437 | 2900 | 511 ± 87 | 2800 |
| Iron | mg/L | 0.044 | 0.071 | 0.064 | 0.13 | 0.037 | 0.033 |
| Lead | mg/L | 0.018 | 0.016 | <0.002 | 0.024 | 0.021 | 0.009 |
| Manganese | mg/L | 0.014 | 0.39 | 0.81 | 0.87 | 0.010 | 0.67 |
| Nickel | mg/L | 0.003 | 0.004 | 0.003 | 0.009 | 0.006 | 0.005 |
| Zinc | mg/L | 0.009 | 0.009 | 0.016 | 0.012 | 0.003 | 0.006 |
| Aluminum | mg/L | 0.12 | 0.087 | 1.3 | 0.41 | 0.10 | <0.05 |
| Barium | mg/L | 0.061 | 0.036 | 0.11 | 0.030 | 0.039 | 0.049 |
| Molybdenum | mg/L | <0.005 | <0.005 | <0.005 | <0.005 | <0.005 | <0.005 |
| Total Thorium-232 | Bq/L | 0.01 | <0.01 | --- | 0.01 | 0.03 | 0.01 |
| Total Thorium-230 | Bq/L | 0.06 | 0.05 | --- | 0.05 | 0.20 | 0.05 |
| Total Thorium-228 | Bq/L | <0.01 | 0.02 | --- | 0.01 | 0.03 | 0.02 |
| Total Thorium-227 | Bq/L | <0.02 | <0.02 | --- | <0.02 | <0.02 | <0.02 |

* Result questionable

--- No data

SOURCE: TABLE 2.1, TONES (1982)

Table 1b

## WATER QUALITY DATA AT DIFFERENT DEPTHS, GUNNAR FLOODED PIT, NOVEMBER 8, 1981

| | Units | 1 m | 50 m | 85 m | 108.5 m |
|---|---|---|---|---|---|
| Bicarbonate | mg/L | 81 | 74 | 188 | 310 |
| Calcium | mg/L | 37 | 36 | 97 | 196 |
| Chloride | mg/L | 6.4 | 10 | 39 | 72 |
| Magnesium | mg/L | 8 | 10 | 24 | 62 |
| Potassium | mg/L | 2.4 | 2.3 | 3.6 | 5.5 |
| Sodium | mg/L | 6.0 | 5.9 | 23 | 42 |
| Sulphate | mg/L | 66 | 66 | 192 | 481 |
| Total Kjeldahl Nitrogen | mg/L | 0.86 | 0.79 | 6.4 | 5.3 |
| Ortho Phosphate | mg/L | 1.7 | 1.1 | 2.6 | 0.06 |
| Total Phosphate | mg/L | 1.7 | 1.6 | 3.2 | 0.99 |
| Total Inorganic Carbon | mg/L | 10 | 10 | 39 | 53 |
| Total Organic Carbon | mg/L | 8 | 8 | 6 | 5 |
| Total Dissolved Solids | mg/L | 176 | 180 | 496 | 1060 |
| Total Suspended Solids | mg/L | 2 | 1 | <1 | <1 |
| Total Lead-210 | Bq/L | <0.02 | 0.07 | 0.30 | 0.30 |
| Total Radium-226 | Bq/L | 0.13 | 0.16 | 1.2 | 1.2 |
| Thorium | mg/L | 0.044 | 0.048 | 0.073 | 0.21 |
| Total Uranium | ug/L | 382 | 362 | 262 | 2750 |
| Arsenic | ug/L | 1.6 | 1.5 | 2.5 | 3.0 |
| Cyanide | ug/L | 0.4 | 2.6 | <0.1 | <0.1 |
| Mercury | ug/L | <0.05 | <0.05 | <0.05 | <0.05 |
| Selenium | mg/L | 0.001 | 0.001 | 0.002 | 0.002 |
| Cadmium | mg/L | <0.0005 | <0.0005 | <0.0005 | 0.0019 |
| Chromium | mg/L | 0.005 | 0.002 | 0.008 | 0.011 |
| Cobalt | mg/L | 0.001 | 0.002 | <0.001 | <0.001 |
| Copper | mg/L | 0.017 | 0.006 | 0.002 | 0.006 |
| Iron | mg/L | 0.10 | 0.061 | 0.086 | 0.12 |
| Lead | mg/L | 0.052 | 0.011 | 0.13 | 0.006 |
| Manganese | mg/L | 0.030 | 0.057 | 1.2 | 0.66 |
| Nickel | mg/L | 0.021 | 0.004 | 0.014 | 0.027 |
| Zinc | mg/L | 0.078 | 0.018 | 0.019 | 0.011 |
| Aluminum | mg/L | 0.59 | 0.56 | 1.4 | 1.8 |
| Barium | mg/L | 0.028 | 0.030 | 0.12 | 0.036 |
| Molybdenum | mg/L | <0.005 | <0.005 | <0.005 | <0.005 |
| Total Alkalinity | mg/L | 66 | 61 | 155 | 254 |
| Specific Conductivity* | umho/cm | 280 | 283 | 745 | 1340 |

*Measured in the SRC Laboratory.

SOURCE: TABLE 2.2, TONES (1982)

## Table 2

## SEDIMENT QUALITY DATA, GUNNAR FLOODED PIT, AUGUST 24-25, 1981

| | | S-6 | S-3 | S-5 | S-1 |
|---|---|---|---|---|---|
| | Units | 7 m | 41.5 m | 82 m | 110 m |
| Total Kjeldahl Nitrogen | % | 0.057 | 0.13 | 0.13 | 0.078 |
| Total Phosphate | % | 0.35 | 0.63 | 0.63 | 0.40 |
| Total Carbon | % | NA* | NA* | NA* | NA* |
| Organic Carbon | % | NA* | NA* | NA* | NA* |
| Inorganic Carbon | % | 2.22 | 2.28 | 2.04 | 6.59 |
| Total Radium-226 | Bq/g | 1.5 | 4.0 | 4.0 | 5.5 |
| Total Lead-210 | Bq/g | 3 | 17 | 20 | 21 |
| Total Polonium-210 | Bq/g | 0.30 | 0.90 | 1.1 | 2.2 |
| Total Thorium | ug/g | 12 | 12 | 17 | 16 |
| Water Soluble Sulphate | % | 0.27 | 1.05 | 0.40 | 1.04 |
| Moisture | % | 84.0 | 98.7 | 97.6 | 98.7 |
| Loss on Ignition | % | 2.92 | 6.15 | 6.06 | 4.65 |
| Colour | | grey-black | grey-black | grey-black | grey-black |
| Odour | | rotting org. | rotting org. | rotting org. | rotting org. |
| Texture | | muddy | muddy | muddy | muddy |
| Arsenic | ug/g | 2.7 | 6.1 | 5.8 | 6.7 |
| Barium | ug/g | 89 | 167 | 153 | 93 |
| Cadmium | ug/g | 0.92 | <0.5 | <0.5 | 13 |
| Chromium | ug/g | 20 | 18 | 20 | 19 |
| Cobalt | ug/g | 5.4 | 6.9 | 7.5 | 6.9 |
| Copper | ug/g | 16 | 28 | 27 | 30 |
| Uranium | ug/g | 636 | 2060 | 2460 | 7820 |
| Iron | ug/g | 13800 | 17700 | 17400 | 15000 |
| Lead | ug/g | 1.8 | <2.0 | <2.0 | 8.0 |
| Manganese | ug/g | 129 | 304 | 276 | 150 |
| Mercury | ug/g | 0.03 | <0.5 | <0.1 | <0.5 |
| Nickel | ug/g | 44 | 20 | 21 | 26 |
| Vanadium | ug/g | 24 | 29 | 34 | 39 |
| Zinc | ug/g | 111 | 95 | 102 | 200 |

*NA = not available.

SOURCE: TABLE 2.3, TONES (1982)

are suitable for fish and invertebrates. However below this zone, dissolved oxygen levels were low and anerobic conditions existed in at least part of the hypolimnion (below 60 m). The entrances of the ore haul road and the waste haul road are the only shallow areas in the open pit that aquatic vegetation could colonize as the walls are essentially vertical (Tones, 1982).

During lake turnover in the fall (Figure 2c), the water column above the chemocline mixes and water quality was found to be relatively uniform above this zone. From the top of the chemocline down to the bottom of the pit, water quality remains essentially unchanged demonstrating the strong stability of these bottom layers.

There appears to be little mixing and minimal exchange between the chemocline and the upper zones. In general, major ions and contaminant (uranium, radium-226 and lead-210) levels in the monimolimnion are 5 to 10 times higher than levels observed above the hypolimnion; the specific conductivity is approximately 2,000 µmhos/cm as compared to 300-400 µmhos/cm at surface. The increase in specific conductivity in the bottom stratum was not found to be due to an unusual increase in any particular salt but rather it is attributed to a general increase in all the salts present throughout the flooded pit.

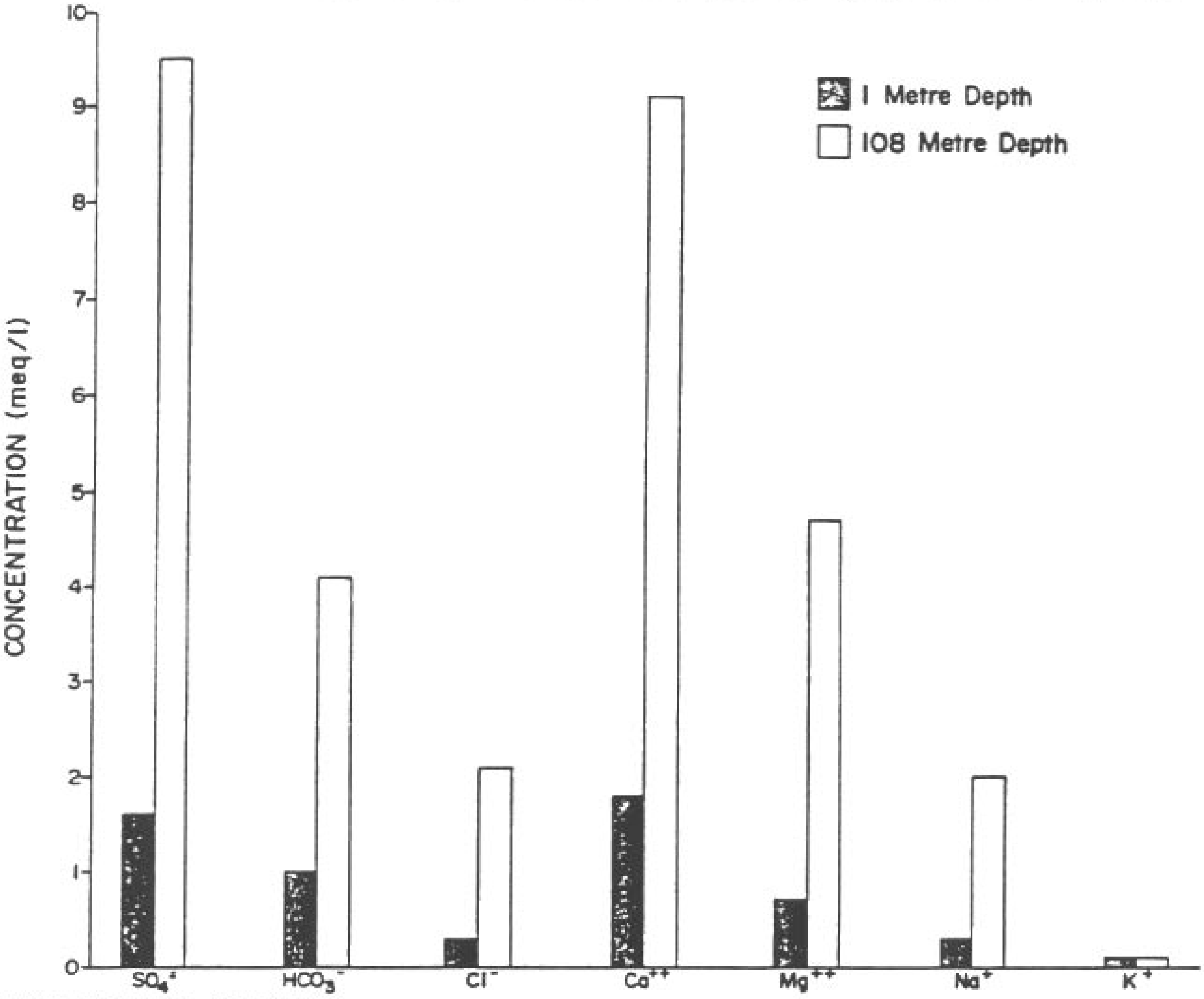
This is also illustrated graphically in Figures 3a, b, c.

Surface levels were relatively low; radium-226 in the surface water met the Saskatchewan Surface Water Quality Objective (SSWQO) of 3 pCi/L. Thorium isotopes were at or near detection limits at all depths. The mean concentration of uranium below the chemocline, 2,817 µg/L, would be toxic to aquatic organisms but most organisms are excluded from this region by the lack of oxygen.

Phosphate levels were an order of magnitude higher than background levels for lakes in the area and also an order of magnitude higher than the SSWQO. The fish processing plant has been assumed to be the major source of nutrients.

FIGURE 3a

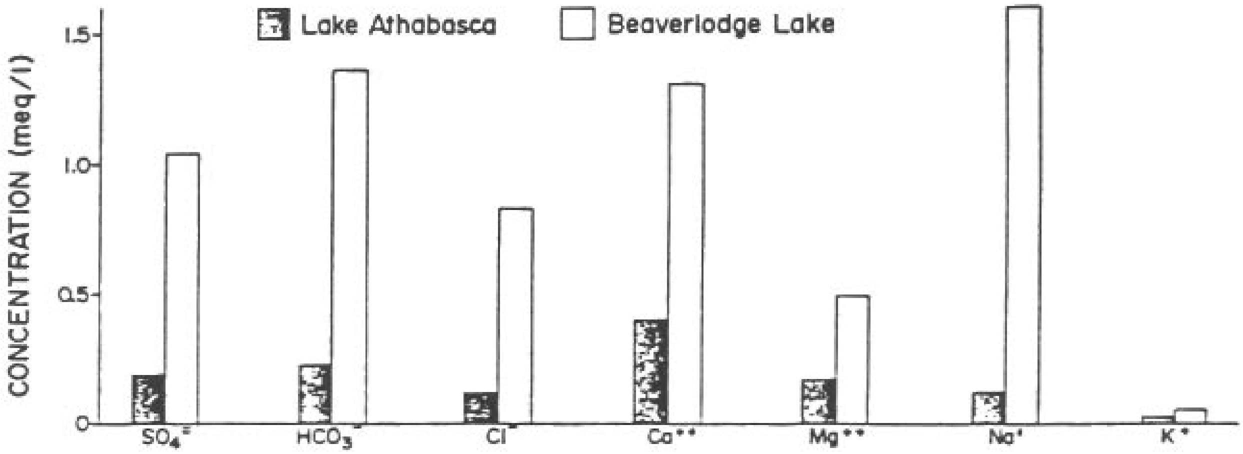
## DIFFERENCES IN MAJOR ION CONCENTRATION WITH DEPTH FOR FLOODED GUNNAR OPEN PIT, SEPTEMBER 20, 1981



SOURCE: FIGURE 2.6, TONES (1982)

FIGURE 3b

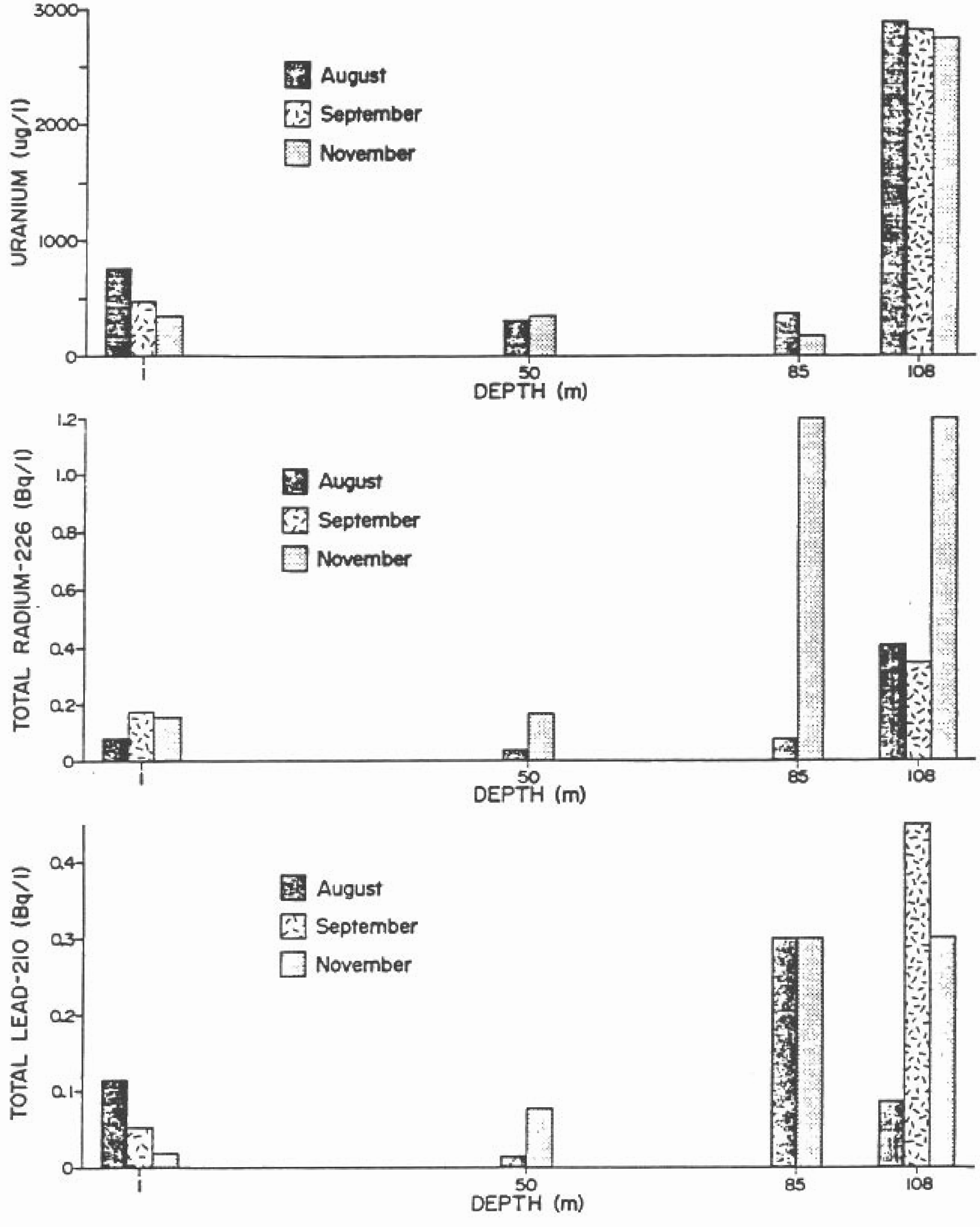
## MAJOR ION CONCENTRATIONS IN LAKE ATHABASCA AND BEAVERLODGE LAKE, 1981



SOURCE: FIGURE 2.7, TONES (1982)

FIGURE 3c

## CONCENTRATIONS OF URANIUM, RADIUM-226 AND LEAD-210 BY DEPTH FOR FLOODED GUNNAR OPEN PIT, 1981



SOURCE: FIGURE 2.8, TONES (1982)

Table 3

## WATER QUALITY OF SEEPAGE SAMPLES FROM THE GUNNAR SITE FROM LAKE ATHABASCA, AUGUST 1981

| | | Waste Rock Seepage | | Open Pit | | Lake |
|---|---|---|---|---|---|---|
| | Units | SP-1 | SP-3 | 1 m | 108 m | Athabasca |
| Bicarbonate | mg/L | 101 | 100 | 70 | 251 | 14 |
| Calcium | mg/L | 90 | 40 | 34 | 208 | 8 |
| Chloride | mg/L | 14 | 10 | 10 | 73 | 4.2 |
| Magnesium | mg/L | 36 | 12 | 10 | 43 | 2 |
| Potassium | mg/L | 7.7 | 5.0 | 2.8 | 7.4 | 1.1 |
| Sodium | mg/L | 23 | 11 | 6.1 | 47 | 2.8 |
| Sulphate | mg/L | 330 | 75 | 74 | 511 | 9.3 |
| Total Alkalinity | mg/L | 72 | 82 | 57 | 206 | 11 |
| Total Inorganic Carbon | mg/L | 15 | 18 | 15 | 50 | 7 |
| Total Organic Carbon | mg/L | 5 | 7 | 3 | 5 | 2 |
| Total Dissolved Solids | mg/L | 547 | 737 | 175 | 10.50 | 44 |
| Total Suspended Solids | mg/L | 12 | 20 | 2 | 2 | 3 |
| Total Kjeldahl Nitrogen | mg/L | 0.52 | 0.49 | 0.72 | 2.6 | 0.39 |
| Total Phosphate | mg/L | 0.20 | 0.20 | 0.58 | 0.80 | 0.13 |
| Total Lead-210 | Bq/L | 2.0 | 1.6 | 0.12 | 0.09 | <0.02 |
| Total Radium-226 | Bq/L | 0.16 | 0.30 | 0.09 | 0.40 | 0.05 |
| Uranium | ug/L | 18,000 | 26,800 | 708 | 2900 | 0.94 |
| Arsenic | ug/L | 0.8 | 13 | 1.6 | 2.6 | <0.5 |
| Cyanide | ug/L | 0.9 | <0.1 | <0.1 | <0.1 | <0.1 |
| Mercury | ug/L | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 |
| Selenium | mg/L | 0.002 | 0.005 | <0.001 | <0.001 | <0.001 |
| Cadmium | mg/L | 0.002 | 0.002 | 0.0018 | 0.0040 | 0.002 |
| Chromium | mg/L | 0.008 | 0.009 | 0.008 | 0.009 | 0.004 |
| Cobalt | mg/L | 0.015 | 0.018 | 0.002 | 0.004 | 0.002 |
| Copper | mg/L | 0.054 | 0.081 | 0.003 | 0.005 | 0.008 |
| Iron | mg/L | 0.65 | 0.74 | 0.044 | 0.13 | 0.057 |
| Lead | mg/L | 0.076 | 0.10 | 0.018 | 0.024 | 0.030 |
| Manganese | mg/L | 0.59 | 0.043 | 0.014 | 0.87 | 0.003 |
| Nickel | mg/L | 0.022 | 0.020 | 0.003 | 0.009 | 0.008 |
| Zinc | mg/L | 0.045 | 0.021 | 0.009 | 0.012 | 0.064 |
| Aluminum | mg/L | 1.7 | 1.8 | 0.12 | 0.41 | 0.28 |
| Barium | mg/L | 0.043 | 0.070 | 0.061 | 0.030 | 0.018 |
| Molybdenum | mg/L | 0.024 | 0.022 | <0.005 | <0.005 | <0.005 |

*The Lake Athabasca sample was a composite sample containing equal aliquots of water from 1 m below the surface, 1 m above the bottom, and mid-depth. The sampling location was approximately 400 m south-southeast of the Gunnar wharf (in St. Mary's Channel).

SOURCE: TABLE 2.6, TONES (1982)

## 3.0 Monitoring

The site contains a large waste rock pile beside the pit in addition to the waste disposed within the pit. The seepage from the exposed waste is heavily contaminated in comparison with pit water. Levels of uranium for example were more than 1 order of magnitude higher than levels in the pit. These data are provided in Table 3.

## 4.0 Principal Findings

The key findings of the study by Tones (1982) as they relate to utilization of pits for disposal, are as follows.

- Deep pit lakes are subject to thermal and chemical stratification.
- If waste materials are disposed at depth and contain high levels of salts, meromixis is likely to form.
- Chemical stratification can be very stable and the lack of vertical convection provides a barrier to contaminant release from materials stored below the chemocline.
- The flooded pit is a minor source of contaminant release, however, the waste dumps which are exposed on surface are a major source of contaminant release.

### Reference

Tones, P. 1982. *Limnological And Fisheries Investigation Of The Flooded Open Pit At The Gunnar Uranium Mine*, Saskatchewan Research Council, Publication No. C-805-10-E-82 February.

# CASE STUDY 10: CLUFF LAKE "D" PIT

## 1.0 Background Information

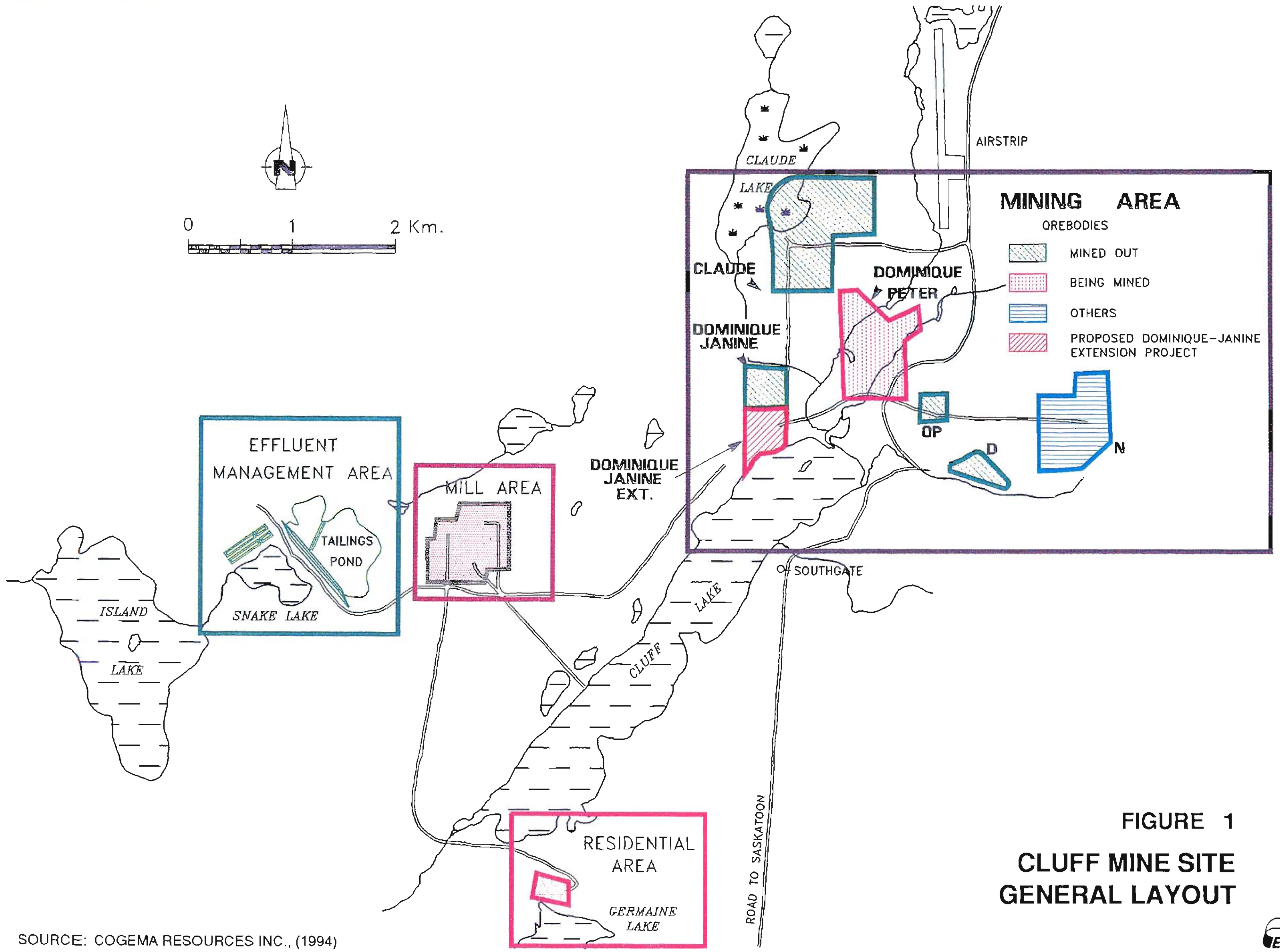
*Operating History*

The mining operation at Cluff Lake commenced in 1981 to recover uranium from a small, but high grade (average ore grade 3.5% $U_3O_8$) orebody.

"One of the recommendations of the Cluff Lake Board of Inquiry was that upon completion of the mining of the pit, the pit should be backfilled with waste rock from the mining operations. W.A. Meneley Consultants Ltd. were hired by Amok to evaluate the validity of backfilling...and recommended to the company that, *"the principal technical advantage of the revised scheme (i.e. not backfilling) is that it will provide for total runoff detention even under extreme storm conditions. The original proposal provided only very limited runoff detention. The revised scheme will also provide an opportunity to document the capability of the environment to prevent the migration of radionuclides and to measure the effectiveness of revegetation to limit sediment transport from abandoned minesites."* (Meneley, 1982). As a result of Meneley's report the pit was allowed to remain open". (Sask. Envir., 1993).

The ultimate dimensions of the Cluff "D" pit are 140 by 25 by 30 m (L,W,D). The dewatering systems were shut off in November 1982. "D" pit was decommissioned in the spring of 1983 by flooding with fresh water from Boulder Creek. The flooding was accidental, as Boulder Creek overtopped its banks and flowed into the pit, filling the pit to capacity in approximately 24 hours. Some waste rock containing less than 0.03% $U_3O_8$ (original cut-off grade) was pushed into the pit. At the present time, "D" pit contains 169,300 $m^3$ of water to a depth of 23 m.

There are two other open pit mines at Cluff Lake: the Claude pit which is inactive, partially flooded, and being backfilled for decommissioning; and the Dominique-Janine pit which is being mined with an extension of the open pit and a planned underground mine (Figure 1). Although this case study concerns "D" pit at Cluff Lake, the other two



SOURCE: COGEMA RESOURCES INC., (1994)

FIGURE 1

CLUFF MINE SITE
GENERAL LAYOUT

open pit mines are briefly reviewed as examples of pits proposed for subaqueous disposal of mine wastes.

*Claude Pit:*

The Claude pit is approximately circular (100 m diameter) and 90 to 100 m deep. A series of dams and cutoff walls separate Claude pit from Claude Lake. Plans are to place waste rock from the Dominique-Janine pit extension into Claude pit by end-dumping from the top of the south wall. The ramp into Claude pit collapsed in the late 1980's which has hindered access to the pit for water quality sampling and for waste disposal. The pit would be filled to 60% of its capacity and the waste rock would be submerged. Preparation for decommissioning Claude pit includes: monitoring of surface water and groundwater; determination of the appropriate final water level in the pit to control the connection to the adjoining lake; and ecological engineering studies for rehabilitation of the pit lake (Kalin, 1993).

*Dominique-Janine Pit:*

The Dominique-Janine pit and the Extension will be larger than "D" pit (Figure 2). The operation of this pit is described in Cogema (1994a and 1994b).

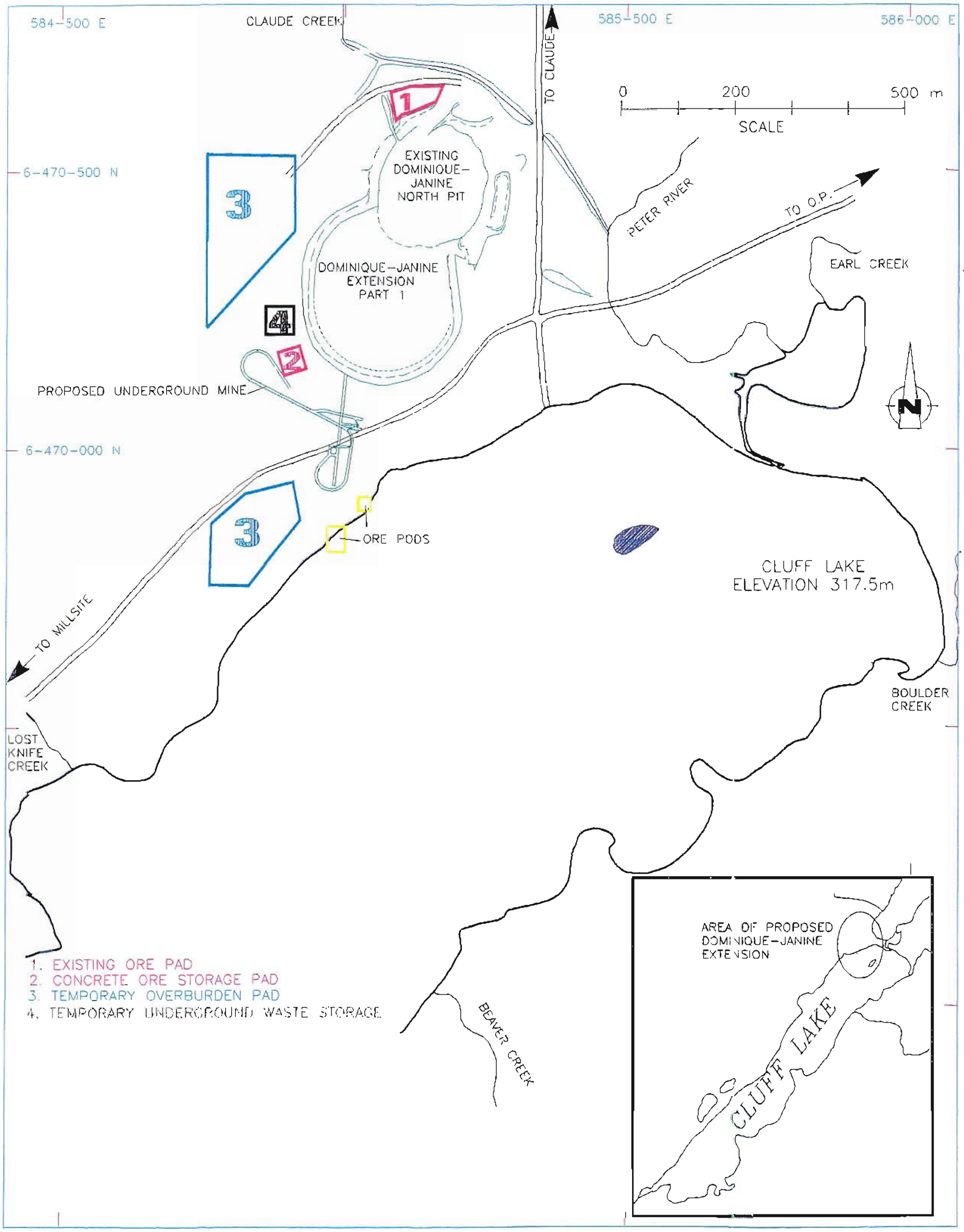
The open pit mining of the Extension will remove 678,000 m$^3$ of overburden and 2,256,000 m$^3$ of waste rock. The overburden is innocuous rock (glacial till) and will be stockpiled. All waste rock removed from the Dominique-Janine Extension can be disposed in the existing mined-out open pits by:

- dumping 410,000 m$^3$ of waste rock into the existing Dominique-Janine North pit which will be backfilled to an elevation of 316 m, (1 m below water level in Cluff Lake), and allowed to flood; and

- pushing (approximately 1,846,000 m$^3$) waste rock and special rock into the Claude pit from a platform constructed on the south side of the pit, and filling this pit to 60% of its volume below the bedrock elevation with subaqueous disposal of mine wastes.

FIGURE 2

# DOMINIQUE - JANINE PIT EXTENSION GENERAL ARRANGEMENT



SOURCE: COGEMA RESOURCES INC., (1994)

The waste rock will be sorted according to: special rocks (rocks with uranium content between 0.03 and 0.1% and strongly altered material, located within a 5 m zone around the orebody); and barren rock (all other waste rock). Only barren rock will go into Dominique-Janine North pit; the special rocks will go into Claude pit with the rest of the barren rock (Cogema 1994a).

The water level in Claude pit can be controlled by pumping water to the Mine Water Holding Pond, until it has been demonstrated that the water quality is acceptable for direct release to Claude Lake. The need to cover special rocks and barren rocks placed in Claude pit with a layer (0.5 m) of overburden will be assessed at the time of final decommissioning (Cogema 1994a, b).

*Mineralogy:*

Typical composition of the waste rock at Cluff Lake is shown in Table 1. The data were derived from ore assays at the mine site. The ore is relatively clean, since it contains low concentrations of arsenic and nickel minerals commonly associated with pitchblende mineralization. The predominant minerals are quartz and aluminum silicates with low levels of pyrite and arsenopyrite. The rock does not appear to be a potential source of acidity by sulphate production.

*Acidic Drainage:*

*"Cluff Mining has designed, installed and operated industrial scale waste rock leaching tests. Dominique-Janine North waste rock was tested as this material was selected to best represent the waste rock expected in the proposed Dominique-Janine Extension project.*

*Three experimental leach tests have been operating since 28 November 1992:*

*i) the dynamic leach test was designed to provide data from simulation of the leaching of submerged waste rock by Cluff Lake water during the operating phase of the proposed mine.*

## Table 1

## PHYSICAL AND CHEMICAL CHARACTERISTICS OF THE WASTE ROCK

| Physical | Specific Gravity | 2.72 |
|---|---|---|
| Major Components (µg/g) | $SiO_2$ | 671,000 |
| | Al | 30,000 |
| | Ca | 3,400 |
| | Fe | 26,000 |
| | Mg | 19,000 |
| | $CO_3$ | 3,100 |
| | K | 43,000 |
| | Na | 9,000 |
| Minor Components (µg/g) | As | 34 |
| | Bi | 9 |
| | Cu | 28 |
| | Mo | 32 |
| | Ni | 51 |
| | Zn | 104 |
| | S (total) | 1,860 |
| | $SO_4$ (free) | 160 |
| | U | 280 |
| Radionuclides (Bq/g) | $^{210}Pb$ | 3.0 |
| | $^{210}Po$ | 3.5 |
| | $^{226}Ra$ | 4.0 |
| | $^{230}Th$ | 4.0 |
| Acid-Base Accounting (g $CaCO_3$/kg) | AP | 6 |
| | NP | 18 |
| | NAG | -12 |

Source: Rowson, 1993.

Note: NAG = AP - NP, where: NAG - Net Acid Generation
AP - Acid Potential
NP - Neutralization Potential

ii) *the static leach test (was designed) to provide water quality data from submerged waste rock after mine operations cease, and*

iii) *the heap leach test (was designed) to provide, as a comparison, water quality data from leaching of surface stored waste rock.*

*All three tests have operated successfully, generating consistent, reliable data...The waste rock is not acid generating in any of the three tests.*

*It has been qualitatively demonstrated that submerged waste rock is much less chemically active then surface stored waste rock."* (Rowson, 1993).

## 2.0 Investigative Procedures

The flooded "D" pit has been routinely monitored since October, 1983 by the operator (formerly Amok Ltd., now Cogema). In March 1986, Amok Ltd. and Saskatchewan Environment and Resource Management initiated a study to:

1) determine the physical and chemical changes taking place in the water column;

2) identify the external influences, if any, affecting these changes; and

3) determine how these changes relate to arsenic concentrations and the Saskatchewan Surface Water Quality Objectives.

The pit water column has been sampled since 1986 with stratified samples routinely collected at depths of 5, 10, 15 and 20 m since 1992. Temperature profiles were taken in fall 1987 and 1988 to determine if turnover had occurred; the temperature data indicated the pit water had become well-mixed (i.e. constant temperature) and arsenic levels also suggested that mixing had taken place.

In 1988 the Saskatchewan Surface Water Quality Objectives were updated; the arsenic objective was increased to 0.05 mg/L from 0.01 mg/L and a new objective was specified for nickel. These changes significantly affected the assessment of "D" pit water quality as arsenic levels in surface layers (0 to 15 m) no longer exceeded the objective; however, nickel concentrations initially exceeded the new objective, but have since declined.

Cogema revisited "D" pit in 1992 to continue the pit water quality monitoring. Some contaminant levels in the top 10 m may exceed Surface Water Quality Objectives following spring runoff, rain storm events and full turnover; however most contaminant concentrations were declining below objectives over time.

## 3.0 Monitoring

The "D" pit monitoring data collected from 1982 to 1992 is described in Sask. Envir. (1993), and by Melville (1994). Terrestrial and Aquatic Environmental Managers Ltd. (TAEM) and SENES (1995) recently completed a Status of the Environment Report for the Cluff Lake Operation which summarizes the monitoring data collected for "D" pit from 1989 to 1994.

*Water Quality:*

Steady state conditions with respect to most constituents were established rapidly after flooding. Surface waters in the pit are characterized by neutral to slightly alkaline pH values (pH = 7.0 to pH = 8.0) at the middle of the pit. The pH has a tendency to decline with depth to pH = 6.5 to pH = 7.0 at the bottom. The waters possess moderate alkalinity reflecting the relative inertness of the host rock.

The concentrations of most metal ions and anionic constituents meet the Saskatchewan Surface Water Quality Objectives, the only exceptions being radium-226, arsenic, nickel and iron. The annual levels of arsenic, radium and uranium from 1983 to 1994 are summarized in Table 2. The annual average concentrations of parameters measured from 1989 to 1994 are shown in Table 3. Figures 3.1 to 3.10 show the concentrations by depth over this time period . The concentrations of these

Table 2

## MEAN ANNUAL CONTAMINANT LEVELS IN THE WATER COLUMN OF "D" PIT AT CLUFF LAKE (1983-1994)

| Year | Arsenic (mg/L) | | Radium-226 (Bq/L) | | Uranium (mg/L) | |
|---|---|---|---|---|---|---|
| | Number of Samples | Mean Value | Number of Samples | Number of Samples | Number of Samples | Mean Value |
| 1983 | 7 | 0.064 | 9 | 0.26 | 7 | 0.051 |
| 1984 | 11 | 0.078 | 11 | 0.29 | 6 | 0.250 |
| 1985 | 9 | 0.041 | 9 | 0.17 | 4 | 0.047 |
| 1986 | 13 | 0.014 | 14 | 0.09 | 10 | 0.049 |
| 1987 | 9 | 0.018 | 4 | 0.04 | 3 | 0.021 |
| 1988 | 5 | 0.019 | 4 | 0.04 | 5 | 0.038 |
| 1989 | 5 | 0.036 | 4 | 0.04 | 4 | 0.035 |
| 1990 | 4 | 0.019 | 4 | 0.03 | 4 | 0.027 |
| 1991 | 4 | 0.018 | 4 | 0.04 | 4 | 0.025 |
| 1992 | 9 | 0.022 | 9 | 0.03 | 9 | 0.072 |
| 1993 | 12 | 0.013 | 12 | 0.10 | 12 | 0.140 |
| 1994 | 12 | 0.011 | 12 | 0.03 | 12 | 0.087 |

Source: Adapted from Amok Ltd/Ltée, 1992.

Table 3

## WATER QUALITY SUMMARY FOR "D" PIT WATER, CLUFF LAKE

| Analyte | | | SWQO | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | Annual Average |
|---|---|---|---|---|---|---|---|---|---|---|
| pH | units | mean | 6.5-8.5 | 7.29 | 7.60 | 7.33 | 7.32 | 7.31 | 7.30 | 7.36 |
| | | S.D. | | 0.27 | 0.38 | 0.41 | 0.36 | 0.35 | 0.26 | 0.12 |
| | | number | | 4 | 4 | 4 | 9 | 12 | 12 | 6 |
| | | min. | | 7.08 | 7.06 | 6.77 | 6.78 | 6.67 | 7.02 | (1989) |
| | | max. | | 7.68 | 7.97 | 7.65 | 7.81 | 7.73 | 7.76 | (1990) |
| Sp. Cond. | (μmho/cm) | mean | | 177 | 193 | 175 | 158 | 169 | 185 | 176 |
| | | S.D. | | 26 | 14 | 6 | 44 | 43 | 9 | 12 |
| | | number | | 4 | 4 | 4 | 9 | 12 | 12 | 6 |
| | | min. | | 142 | 177 | 170 | 43 | 58 | 170 | (1992) |
| | | max. | | 198 | 210 | 184 | 188 | 212 | 199 | (1990) |
| TSS | (mg/L) | mean | | 2.3 | 1.8 | 1.0 | 2.2 | 2.9 | 2.2 | 2.1 |
| | | S.D. | | 1.3 | 0.5 | 0.0 | 1.8 | 3.7 | 1.4 | 0.6 |
| | | number | | 4 | 4 | 4 | 9 | 12 | 12 | 6 |
| | | min. | | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | (1991) |
| | | max. | | 4.0 | 2.0 | 1.0 | 6.0 | 14.0 | 4.0 | (1993) |
| Turbidity | (NTU) | mean | | 3.1 | 1.5 | 1.9 | 3.5 | 3.2 | 3.2 | 2.7 |
| | | S.D. | | 3.0 | 0.7 | 1.0 | 1.9 | 2.2 | 1.8 | 0.8 |
| | | number | | 4 | 4 | 4 | 9 | 12 | 12 | 6 |
| | | min. | | 1.2 | 0.9 | 0.7 | 0.8 | 0.8 | 0.8 | (1990) |
| | | max. | | 7.5 | 2.4 | 3.1 | 5.7 | 6.9 | 5.5 | (1992) |
| TDS | (mg/L) | mean | | 119 | 137 | 110 | 104 | 109 | 121 | 117 |
| | | S.D. | | 7 | 15 | 19 | 25 | 29 | 19 | 12 |
| | | number | | 3 | 4 | 4 | 9 | 12 | 12 | 6 |
| | | min. | | 112 | 125 | 92 | 41 | 38 | 84 | (1992) |
| | | max. | | 126 | 157 | 129 | 120 | 147 | 164 | (1990) |
| Total Alk. | (mg/L) | mean | | 71 | 73 | 68 | 62 | 63 | 73 | 68 |
| | | S.D. | | 6 | 5 | 6 | 18 | 18 | 4 | 5 |
| | | number | | 4 | 4 | 4 | 9 | 12 | 12 | 6 |
| | | min. | | 62 | 66 | 64 | 15 | 21 | 68 | (1992) |
| | | max. | | 75 | 78 | 76 | 73 | 84 | 80 | (1990) |

Table 3 (Cont'd)

## WATER QUALITY SUMMARY FOR "D" PIT WATER, CLUFF LAKE

| Analyte | | | SWQO | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | Annual Average |
|---|---|---|---|---|---|---|---|---|---|---|
| Total Hard. | (mg/L) | mean | | 84 | 88 | 86 | 75 | 78 | 88 | 83 |
| | | S.D. | | 6 | 4 | 8 | 22 | 21 | 6 | 5 |
| | | number | | 4 | 4 | 4 | 9 | 12 | 12 | 6 |
| | | min. | | 76 | 85 | 79 | 17 | 24 | 78 | (1992) |
| | | max. | | 89 | 92 | 98 | 88 | 94 | 94 | (1990) |
| $CO_3$ | (mg/) | mean | | 6.1 | 5.7 | 5.1 | 4.2 | 2.0 | 2.5 | 4.3 |
| | | S.D. | | 0.7 | 0.6 | 0.7 | 1.3 | 1.3 | 1.6 | 1.7 |
| | | number | | 3 | 4 | 3 | 9 | 24 | 23 | 6 |
| | | min. | | 5.6 | 4.9 | 4.6 | 0.8 | 1.0 | 1.0 | (1993) |
| | | max. | | 6.9 | 6.3 | 5.9 | 5.0 | 5.1 | 4.6 | (1989) |
| $HCO_3$ | | mean | | 87 | 89 | 82 | 76 | 77 | 89 | 83 |
| | | S.D. | | 8 | 7 | 7 | 21 | 22 | 5 | 6 |
| | | number | | 4 | 4 | 4 | 9 | 12 | 12 | 6 |
| | | min. | | 75 | 80 | 78 | 19 | 26 | 82 | (1992) |
| | | max. | | 92 | 95 | 93 | 89 | 102 | 98 | (1990) |
| $SO_4$ | (mg/L) | mean | | 9.9 | 7.4 | 7.0 | 7.2 | 7.8 | 9.1 | 8.1 |
| | | S.D. | | 2.0 | 0.4 | 0.9 | 2.3 | 2.6 | 0.7 | 1.2 |
| | | number | | 4 | 4 | 4 | 9 | 12 | 12 | 6 |
| | | min. | | 7.5 | 7.0 | 6.0 | 1.8 | 2.7 | 7.4 | (1991) |
| | | max. | | 12.0 | 8.0 | 7.9 | 9.6 | 10.0 | 9.8 | (1989) |
| Cl | (mg/L) | mean | 0.002 | 9 | | 5 | | | 5 | 6 |
| | | S.D. | | . | | . | | | . | 2 |
| | | number | | 1 | | 1 | | | 1 | 3 |
| | | min. | | 9 | | 5 | | | 5 | (1991) |
| | | max. | | 9 | | 5 | | | 5 | (1989) |

Table 3 (Cont'd)

## WATER QUALITY SUMMARY FOR "D" PIT WATER, CLUFF LAKE

| Analyte | | | SWQO | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | Annual Average |
|---|---|---|---|---|---|---|---|---|---|---|
| Ca | (mg/L) | mean | | 17 | 17 | 16 | 14 | 15 | 16 | 16 |
| | | S.D. | | 1 | 1 | 2 | 4 | 4 | 2 | 1 |
| | | number | | 4 | 4 | 4 | 9 | 12 | 12 | 6 |
| | | min. | | 16 | 16 | 15 | 4 | 5 | 13 | (1992) |
| | | max. | | 18 | 18 | 18 | 17 | 18 | 18 | (1989) |
| Mg | (mg/L) | mean | | 10 | 11 | 11 | 10 | 10 | 12 | 11 |
| | | S.D. | | 2 | 1 | 1 | 3 | 3 | 1 | 1 |
| | | number | | 4 | 4 | 4 | 9 | 12 | 12 | 6 |
| | | min. | | 8 | 11 | 10 | 2 | 3 | 10 | (1992) |
| | | max. | | 12 | 12 | 13 | 11 | 12 | 12 | (1994) |
| Na | (mg/L) | mean | | 4 | 4 | 3 | 3 | 4 | 4 | 4 |
| | | S.D. | | 0 | 0 | 0 | 1 | 1 | 1 | 0 |
| | | number | | 4 | 4 | 4 | 9 | 12 | 12 | 6 |
| | | min. | | 3 | 3 | 3 | 1 | 1 | 3 | (1992) |
| | | max. | | 4 | 4 | 4 | 4 | 5 | 5 | (1994) |
| Sums of Ions | (mg/) | mean | | 136 | 135 | 127 | 116 | 118 | 137 | 128 |
| | | S.D. | | 8 | 7 | 12 | 32 | 32 | 7 | 9 |
| | | number | | 4 | 4 | 4 | 9 | 12 | 12 | 6 |
| | | min. | | 125 | 126 | 119 | 30 | 40 | 127 | (1992) |
| | | max. | | 142 | 141 | 144 | 136 | 151 | 149 | (1994) |
| K | (mg/L) | mean | | 1.7 | 1.6 | 1.9 | 1.6 | 1.6 | 1.5 | 1.7 |
| | | S.D. | | 0.1 | 0.1 | 0.4 | 0.4 | 0.3 | 0.3 | 0.1 |
| | | number | | 4 | 4 | 4 | 9 | 12 | 12 | 6 |
| | | min. | | 1.6 | 1.5 | 1.4 | 1.4 | 1.1 | 1.2 | (1994) |
| | | max. | | 1.8 | 1.7 | 2.4 | 2.6 | 2.3 | 2.2 | (1991) |

Table 3 (Cont'd)

## WATER QUALITY SUMMARY FOR "D" PIT WATER, CLUFF LAKE

| Analyte | | | SWQO | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | Annual Average |
|---|---|---|---|---|---|---|---|---|---|---|
| As | (µg/L) | mean | 50.0 | 27.8 | 18.8 | 17.9 | 21.3 | 13.4 | 11.3 | 18.4 |
| | | S.D. | | 13.6 | 5.4 | 8.4 | 7.4 | 7.4 | 5.4 | 5.8 |
| | | number | | 4 | 4 | 4 | 9 | 12 | 12 | 6 |
| | | min. | | 16.0 | 12.0 | 7.5 | 15.0 | 3.0 | 2.2 | (1994) |
| | | max. | | 47.0 | 24.0 | 28.0 | 35.0 | 30.0 | 18.0 | (1989) |
| Cu | (mg/L) | mean | 0.01 | 0.005 | 0.005 | 0.005 | 0.004 | 0.004 | 0.003 | 0.004 |
| | | S.D. | | 0.002 | 0.003 | 0.003 | 0.002 | 0.003 | 0.002 | 0.000 |
| | | number | | 4 | 4 | 4 | 9 | 12 | 12 | 6 |
| | | min. | | 0.003 | 0.002 | 0.002 | 0.001 | 0.001 | 0.001 | (1994) |
| | | max. | | 0.007 | 0.008 | 0.008 | 0.008 | 0.010 | 0.007 | (1991) |
| Fe | (mg/L) | mean | 1.0 | 0.660 | 0.685 | 0.903 | 1.001 | 1.038 | 1.066 | 0.892 |
| | | S.D. | | 0.393 | 0.218 | 0.325 | 0.442 | 0.560 | 0.488 | 0.179 |
| | | number | | 4 | 4 | 4 | 9 | 12 | 12 | 6 |
| | | min. | | 0.350 | 0.360 | 0.540 | 0.530 | 0.420 | 0.240 | (1989) |
| | | max. | | 1.200 | 0.820 | 1.300 | 1.700 | 1.900 | 1.600 | (1994) |
| Ni | (mg/) | mean | 0.025 | 0.039 | 0.032 | 0.030 | 0.029 | 0.020 | 0.019 | 0.028 |
| | | S.D. | | 0.003 | 0.009 | 0.004 | 0.007 | 0.011 | 0.005 | 0.007 |
| | | number | | 4 | 4 | 4 | 9 | 12 | 12 | 6 |
| | | min. | | 0.034 | 0.020 | 0.024 | 0.020 | 0.007 | 0.009 | (1994) |
| | | max. | | 0.042 | 0.042 | 0.034 | 0.040 | 0.043 | 0.027 | (1989) |
| Pb | (mg/L) | mean | 0.02 | 0.005 | 0.013 | 0.005 | 0.007 | 0.006 | 0.005 | 0.007 |
| | | S.D. | | 0.000 | 0.017 | 0.000 | 0.004 | 0.002 | 0.001 | 0.003 |
| | | number | | 4 | 4 | 4 | 9 | 12 | 12 | 6 |
| | | min. | | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | (1989) |
| | | max. | | 0.005 | 0.038 | 0.005 | 0.017 | 0.010 | 0.007 | (1990) |

Table 3 (Cont'd)

## WATER QUALITY SUMMARY FOR "D" PIT WATER, CLUFF LAKE

| Analyte | | | SWQO | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | Annual Average |
|---|---|---|---|---|---|---|---|---|---|---|
| Zn | (mg/L) | mean | 0.05 | 0.011 | 0.013 | 0.013 | 0.072 | 0.019 | 0.038 | 0.028 |
| | | S.D. | | 0.009 | 0.009 | 0.005 | 0.165 | 0.016 | 0.063 | 0.024 |
| | | number | | 4 | 4 | 4 | 9 | 12 | 12 | 6 |
| | | min. | | 0.002 | 0.005 | 0.006 | 0.005 | 0.005 | 0.005 | (1989) |
| | | max. | | 0.022 | 0.025 | 0.018 | 0.510 | 0.046 | 0.220 | (1992) |
| Ra-226 | (Bq/L) | mean | 0.11 | 0.040 | 0.030 | 0.035 | 0.036 | 0.096 | 0.033 | 0.045 |
| | | S.D. | | 0.014 | 0.008 | 0.017 | 0.025 | 0.192 | 0.021 | 0.025 |
| | | number | | 4 | 4 | 4 | 9 | 12 | 12 | 6 |
| | | min. | | 0.030 | 0.020 | 0.020 | 0.010 | 0.010 | 0.010 | (1990) |
| | | max. | | 0.060 | 0.040 | 0.060 | 0.080 | 0.700 | 0.070 | (1993) |
| U | (µg/L) | mean | | 35.000 | 27.500 | 24.500 | 86.667 | 140.333 | 86.500 | 66.750 |
| | | S.D. | | 3.559 | 6.137 | 6.351 | 79.179 | 42.777 | 23.055 | 45.902 |
| | | number | | 4 | 4 | 4 | 9 | 12 | 12 | 6 |
| | | min. | | 31.000 | 20.000 | 16.000 | 23.000 | 66.000 | 53.000 | (1991) |
| | | max | | 38.000 | 35.000 | 31.000 | 231.000 | 218.000 | 136.000 | (1993) |

constituents suggest chemical stratification (chemical meromixis) with depth that seems to persist most of the year and suggests there is turnover in the fall to early winter period. The chemocline appears to be between 10 and 15 metres with relatively lower concentrations of the elements found near the surface and higher levels noted at greater depths. As shown in Figure 3.9, the total dissolved solids (TDS) concentration also has a tendency to increase with depth. The current concentration differences between top and bottom layers, however, are not believed to cause permanent meromixis based entirely on dissolved solids content.

Plots of metal (Figures 3.1 and 3.2) , Ra-226 (Figure 3.3) and uranium (Figure 3.4) concentrations demonstrate increasing concentrations with depth and suggest that pit sediments and/or settling of suspended solids over the non-stratified winter period might be major sources of contaminant loadings at depth in the "D" Pit. Nickel concentration-depth profiles (Figure 3.2) are unique in that nickel concentrations are greatest at a depth of 15 and lowest at a depth of 20 m, contrary to most other metals and radionuclides for which highest concentrations are noted at a depth of 20 m. This suggests that a source other than pit sediments might be driving nickel concentrations in the pit.

The development of permanent chemical stratification, as a result of combined temperature and concentration density (total dissolved solids) gradients, is not unexpected in colder climates.

## 4.0 Principal Findings

In the short time since the "D" pit was flooded, there has apparently been no recorded incidence of surface water discharge from the pit. Hence, the pit has not had a measurable impact on the surface waters in the area. "There is no evidence to suggest that the contaminants investigated are migrating into the surrounding groundwater regime" (Sask. Envir. 1993).

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Figure 3-1

**Plot of Arsenic Concentration vs. Time by Depth in D pit in Cluff Lake Area**

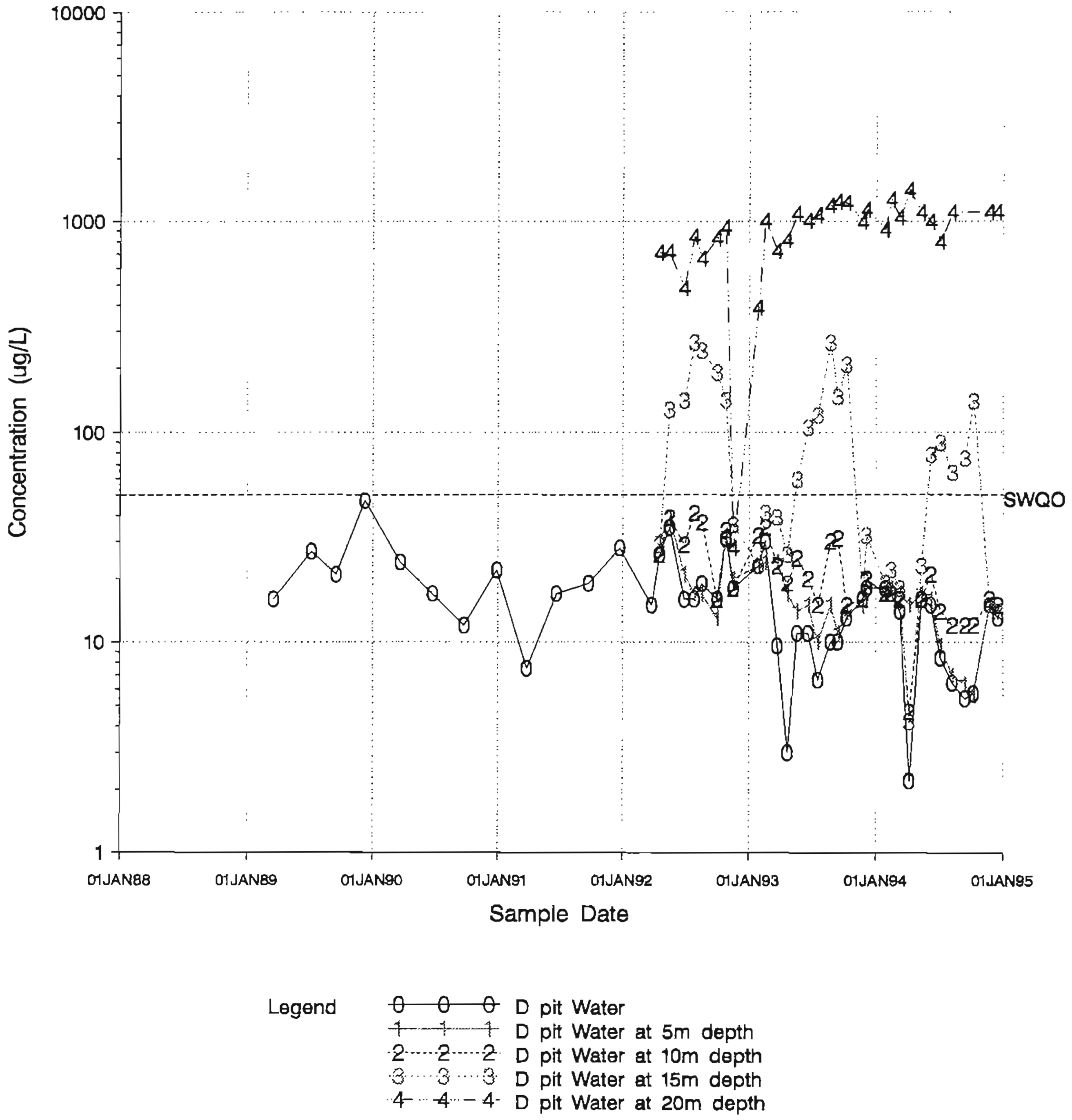
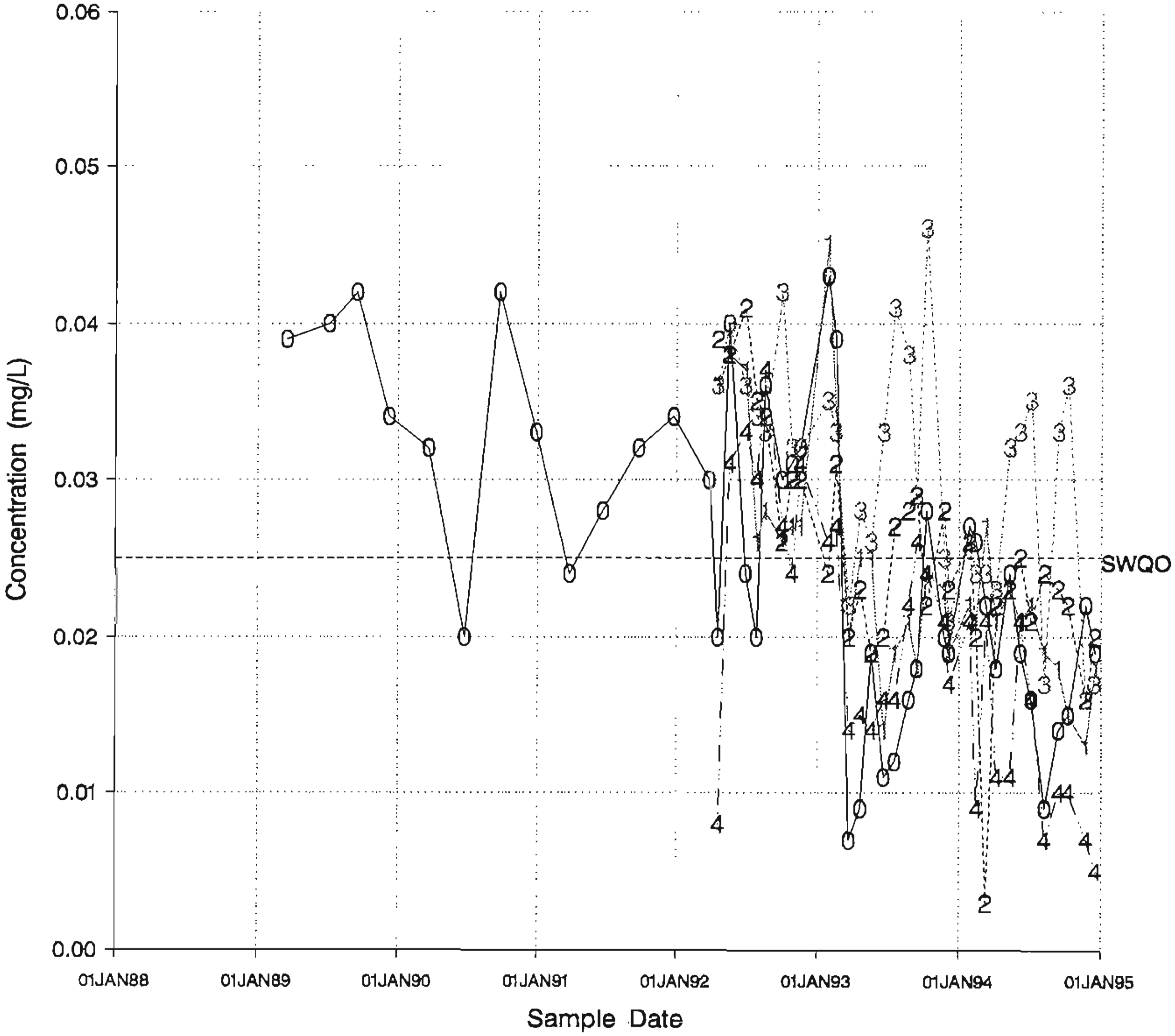


Figure 3-2

## Plot of Nickel Concentration vs. Time by Depth in D pit in Cluff Lake Area



Legend

0—0—0 D pit Water

1—1—1 D pit Water at 5m depth

2····2····2 D pit Water at 10m depth

3 ···3 ···3 D pit Water at 15m depth

4-·-4-·-4 D pit Water at 20m depth

**Figure 3-3**

**Plot of Ra-226 vs. Time by Depth in D pit in Cluff Lake Area**

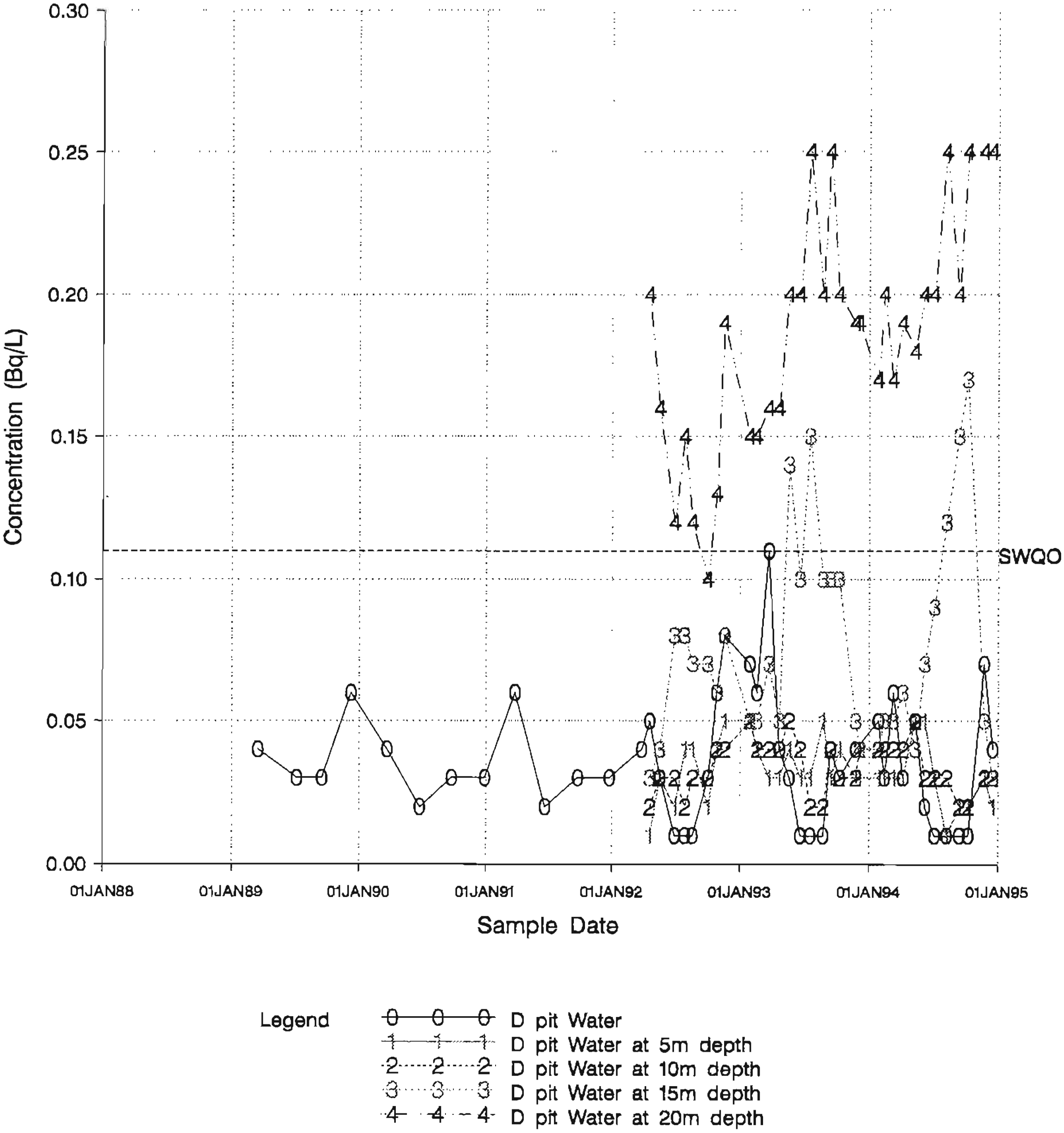


Figure 3-4

## Plot of Uranium Concentration vs. Time by Depth in D pit in Cluff Lake Area

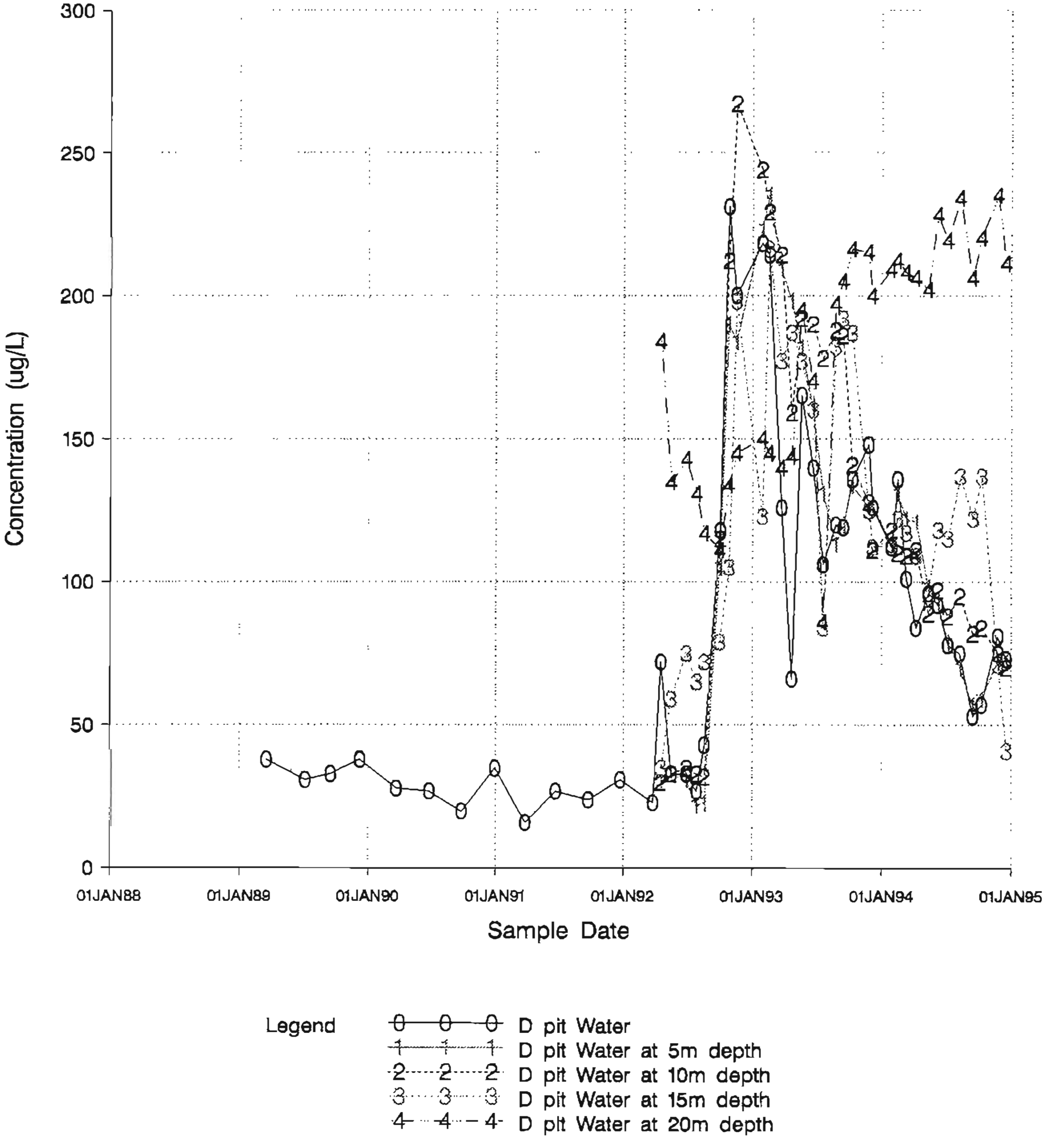


Figure 3 – 5

## Plot of pH Level vs. Time by Depth in D pit in Cluff Lake Area

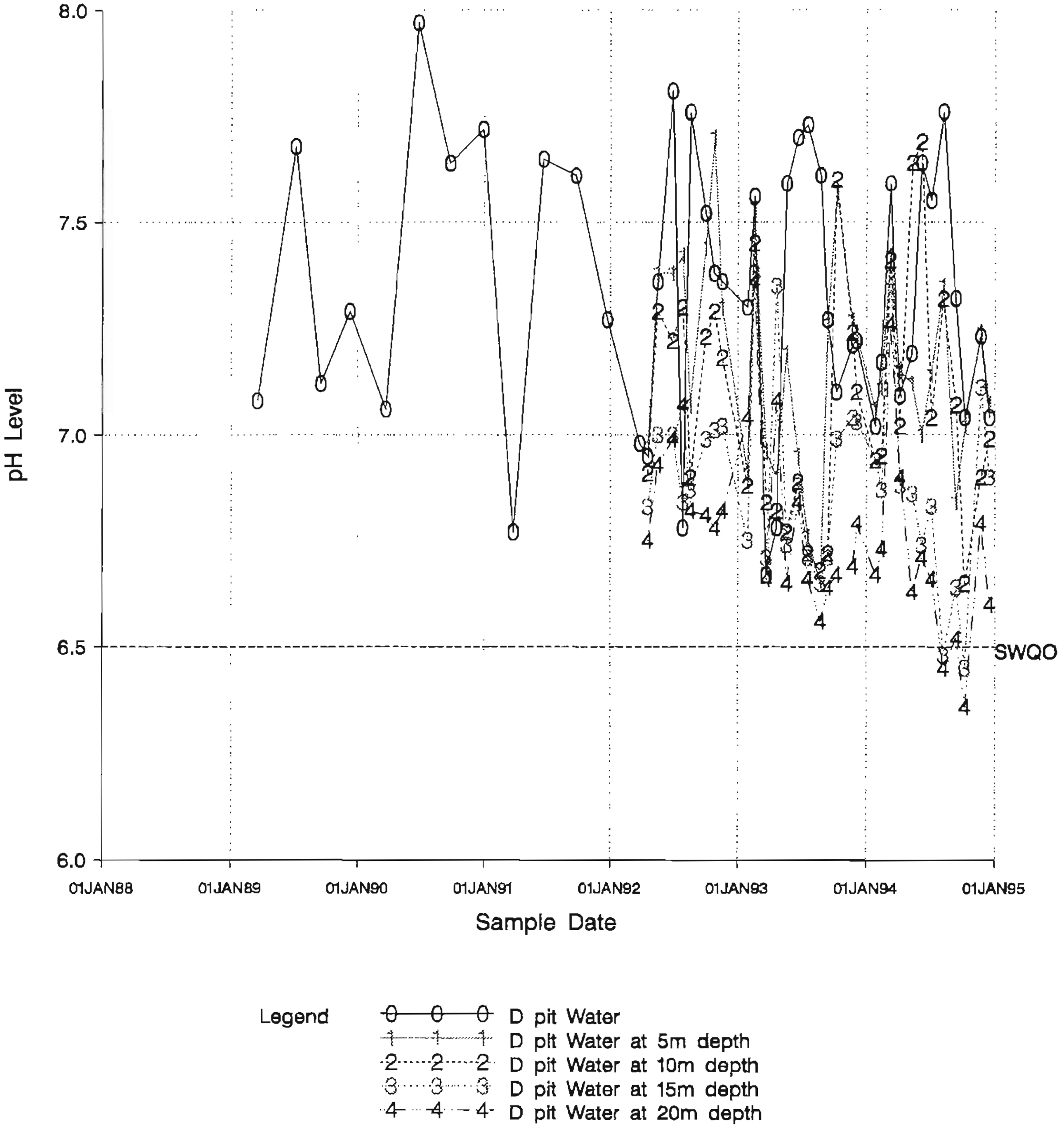


Figure 3-6

## Plot of Iron Concentration vs. Time by Depth in D pit in Cluff Lake Area

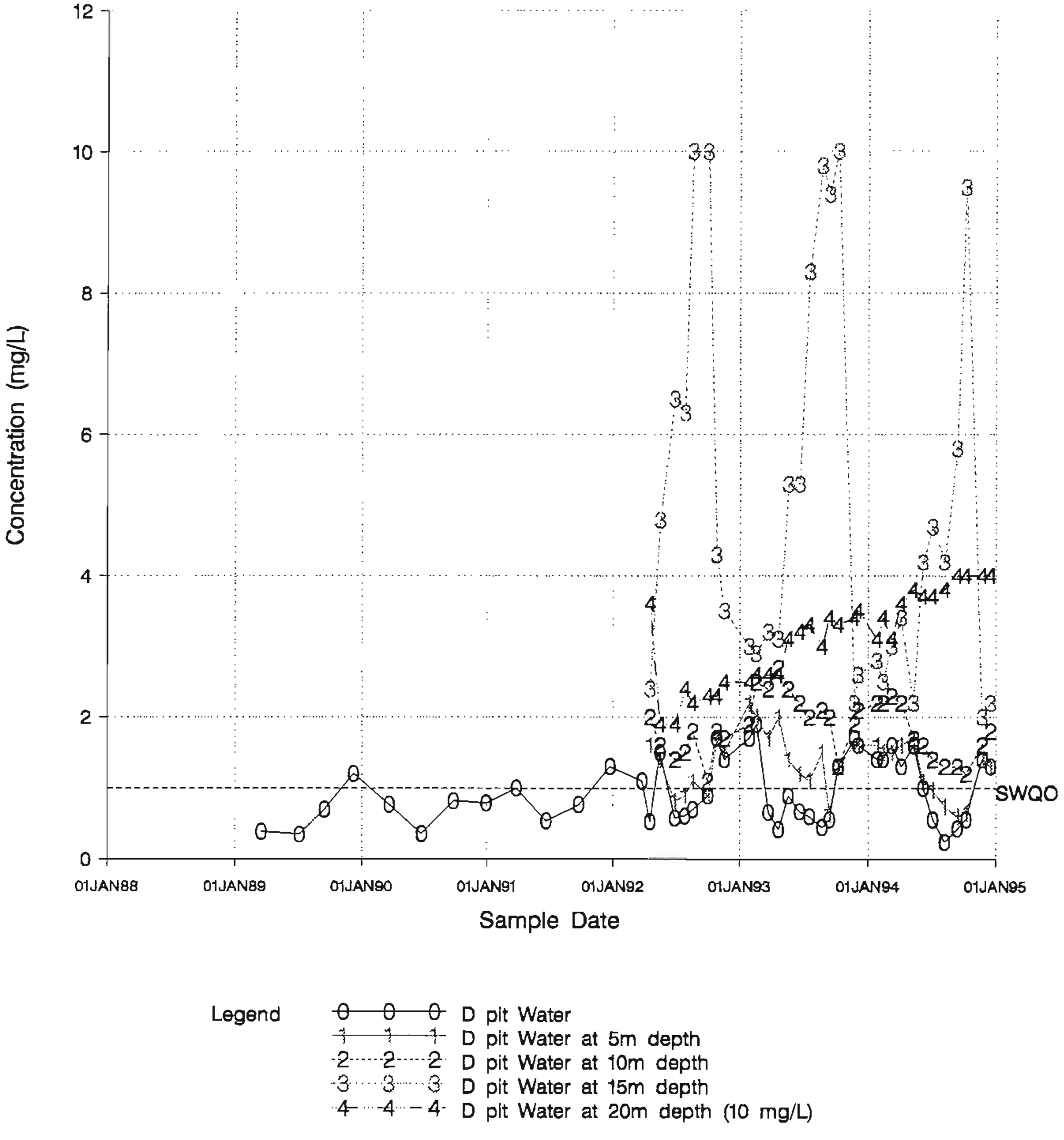


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Figure 3-7

## Plot of Lead Concentration vs. Time by Depth in D pit in Cluff Lake Area

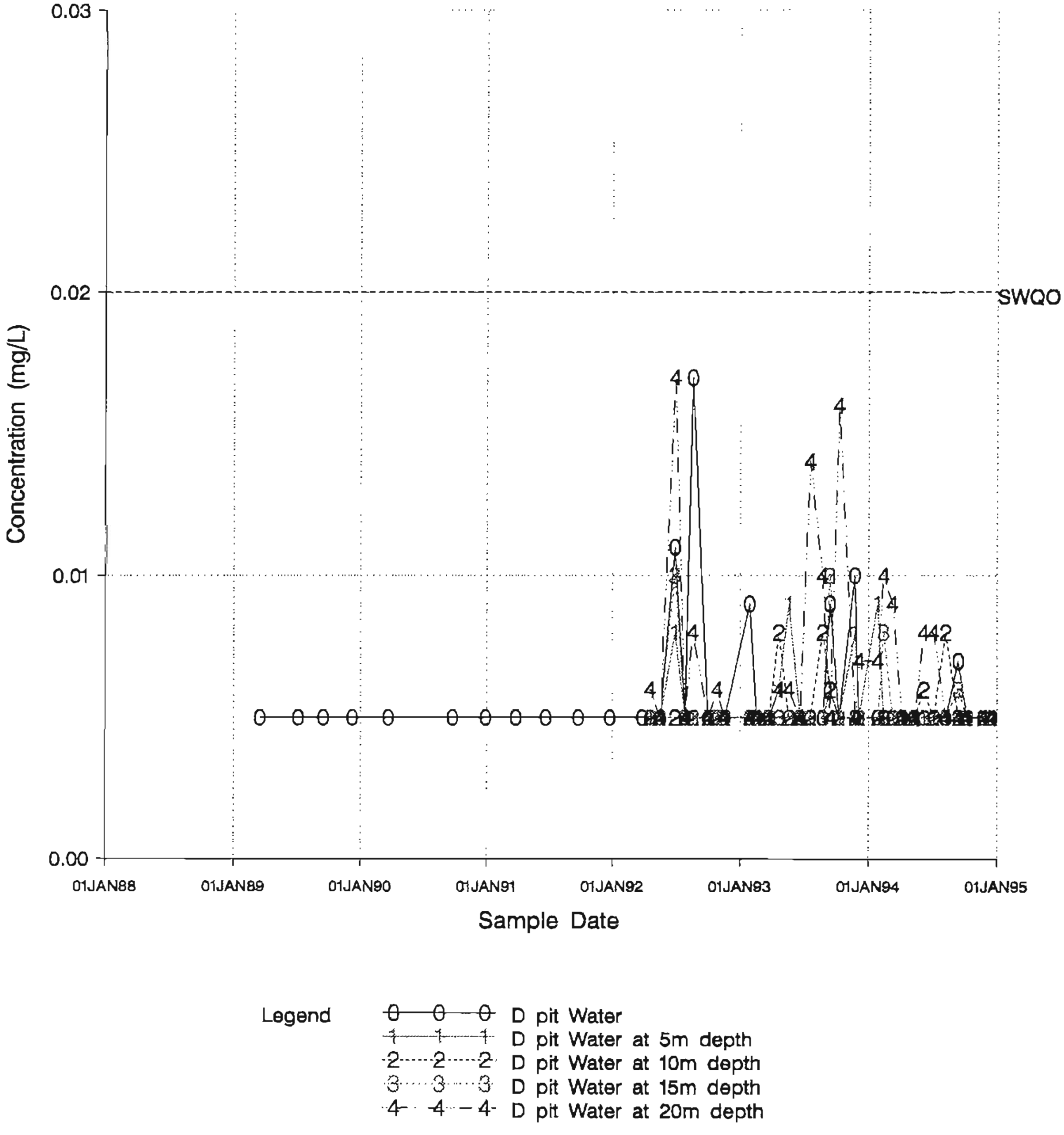

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Figure 3-8

## Plot of Zinc Concentration vs. Time by Depth in D pit in Cluff Lake Area

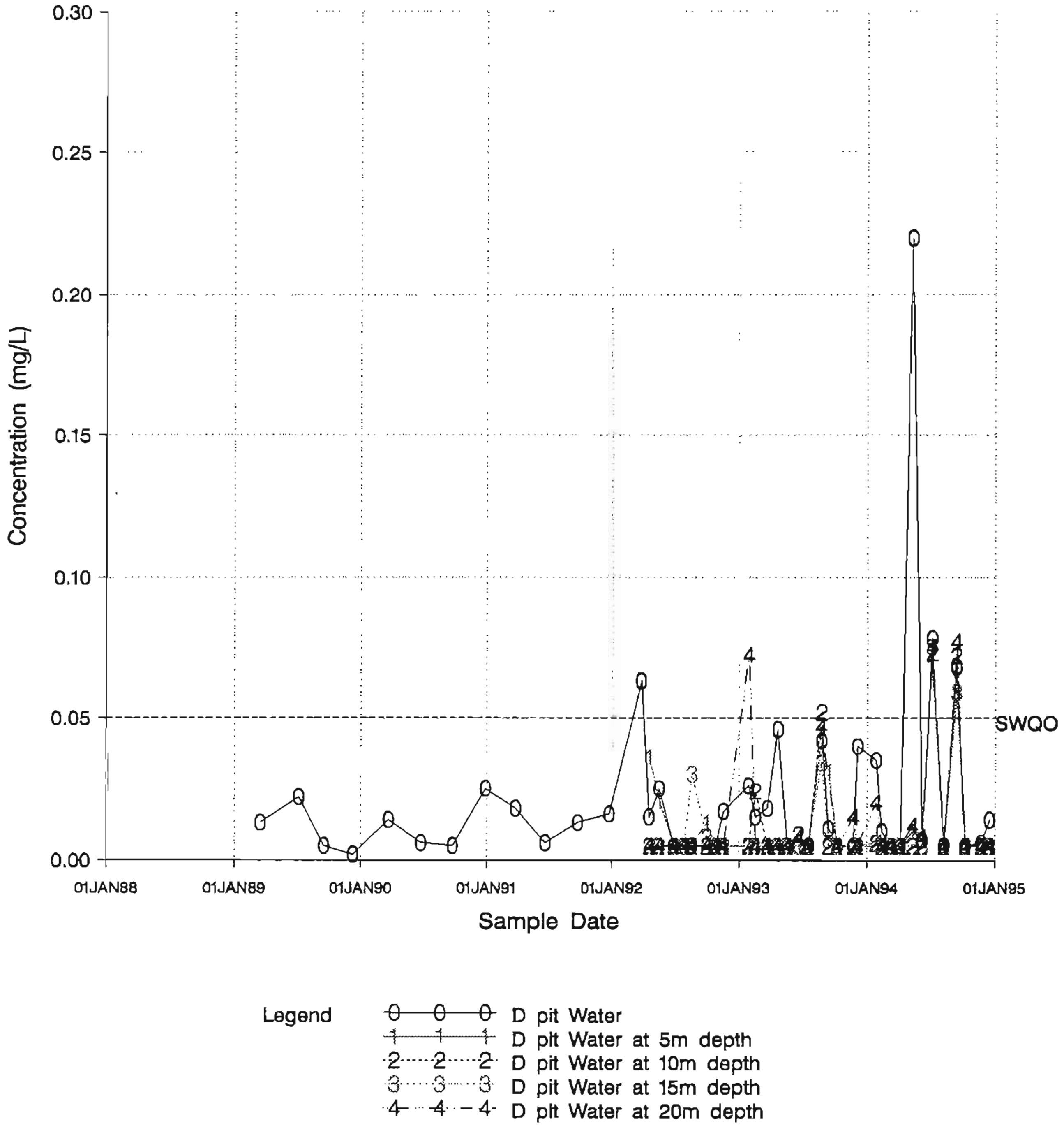

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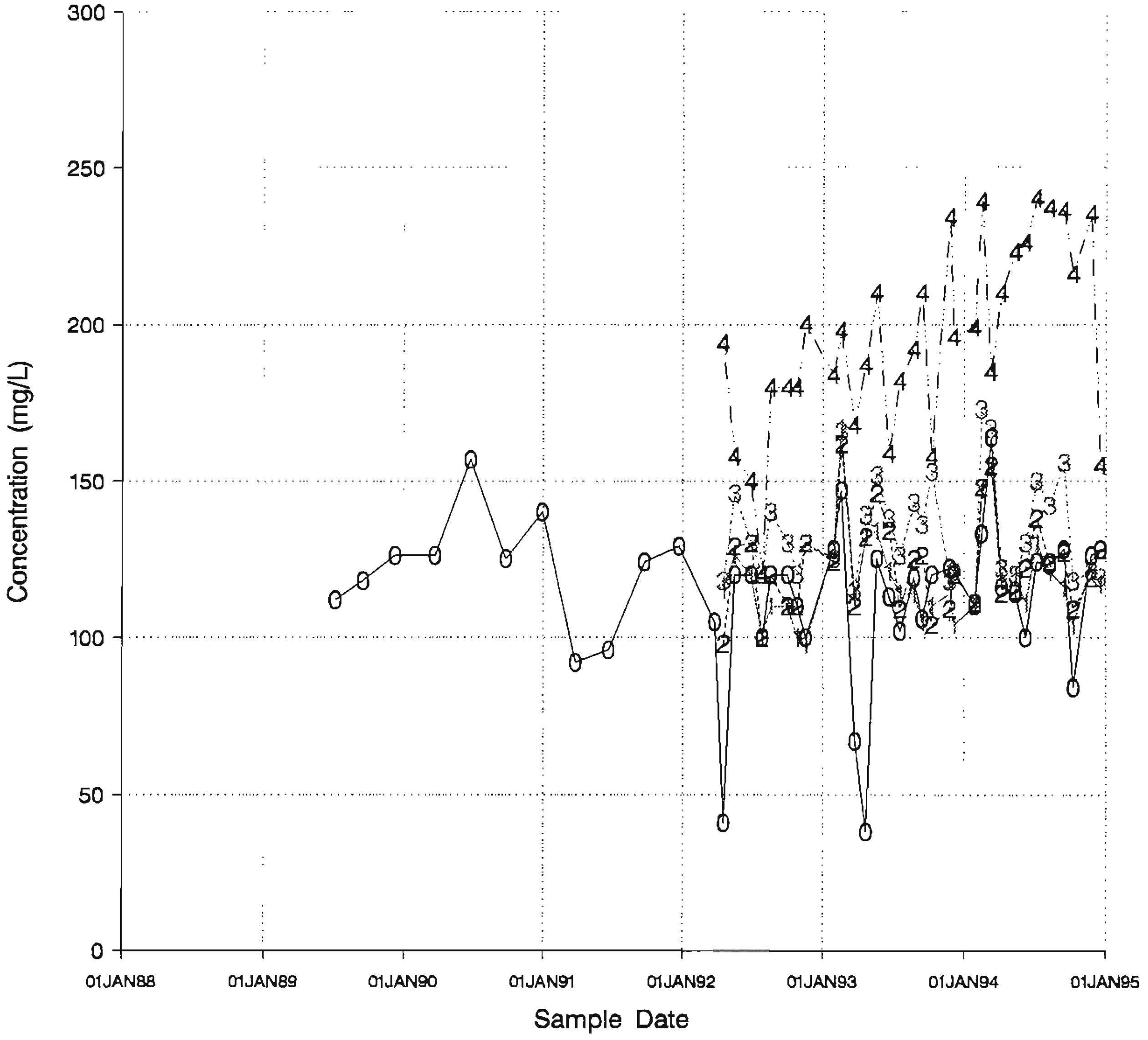
Figure 3-9

## Plot of Total Dissolved Solids vs. Time by Depth in D pit in Cluff Lake Area



| Legend | |
|---|---|
| 0 —— 0 —— 0 | D pit Water |
| 1 —— 1 —— 1 | D pit Water at 5m depth |
| 2 ····· 2 ····· 2 | D pit Water at 10m depth |
| 3 ····· 3 ····· 3 | D pit Water at 15m depth |
| 4 ·–· 4 ·–· 4 | D pit Water at 20m depth |

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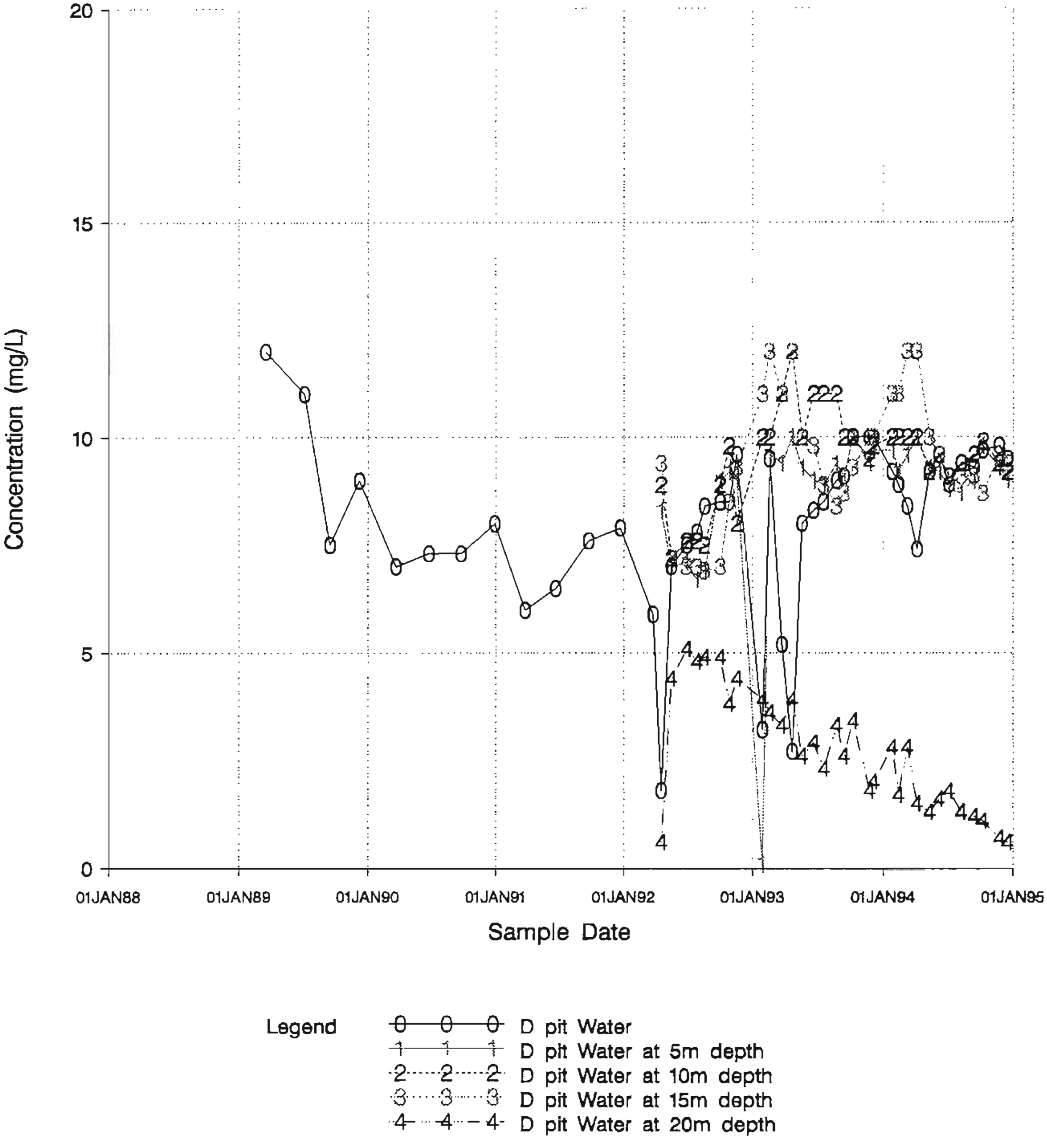
## Figure 3-10

## Plot of SO4 vs. Time by Depth in D pit in Cluff Lake Area



# CASE STUDY 11: DEILMANN

## 1.0 Background Information

The Key Lake Mine is an open pit uranium mining operation located in Northern Saskatchewan, approximately 70 km east-southeast of Cree Lake. The ore is contained within two deposits, the Deilmann and Gaertner ore bodies. Insufficient capacity exists within the existing surface tailings management facility to accommodate future tailings production. Cameco Corporation is currently reviewing various disposal options, one of which involves the conversion of the Deilmann pit into a full side-drain and under-drain permanent tailings management facility (TMF). The design objectives are similar to those described in Case Study 2 Rabbit Lake. A site plan is shown in Figure 1.

*Production History:*

The Key Lake Mine went into production in 1983. Mining of the Gaertner ore body ceased in 1987. Mining of the Deilmann ore body began in 1986 and is expected to continue until 1996. Milling of the Deilmann ore will continue for several additional years following completion of the mining.

Conventional open pit mining methods are employed; each stage of mining is done in 8 m benches. Ore (material>0.19% U30a) and special waste (material between 0.05 and 0.19% U30a) are transported to lined pads with water collection, while waste rock is placed on selected storage areas around the pit perimeter.

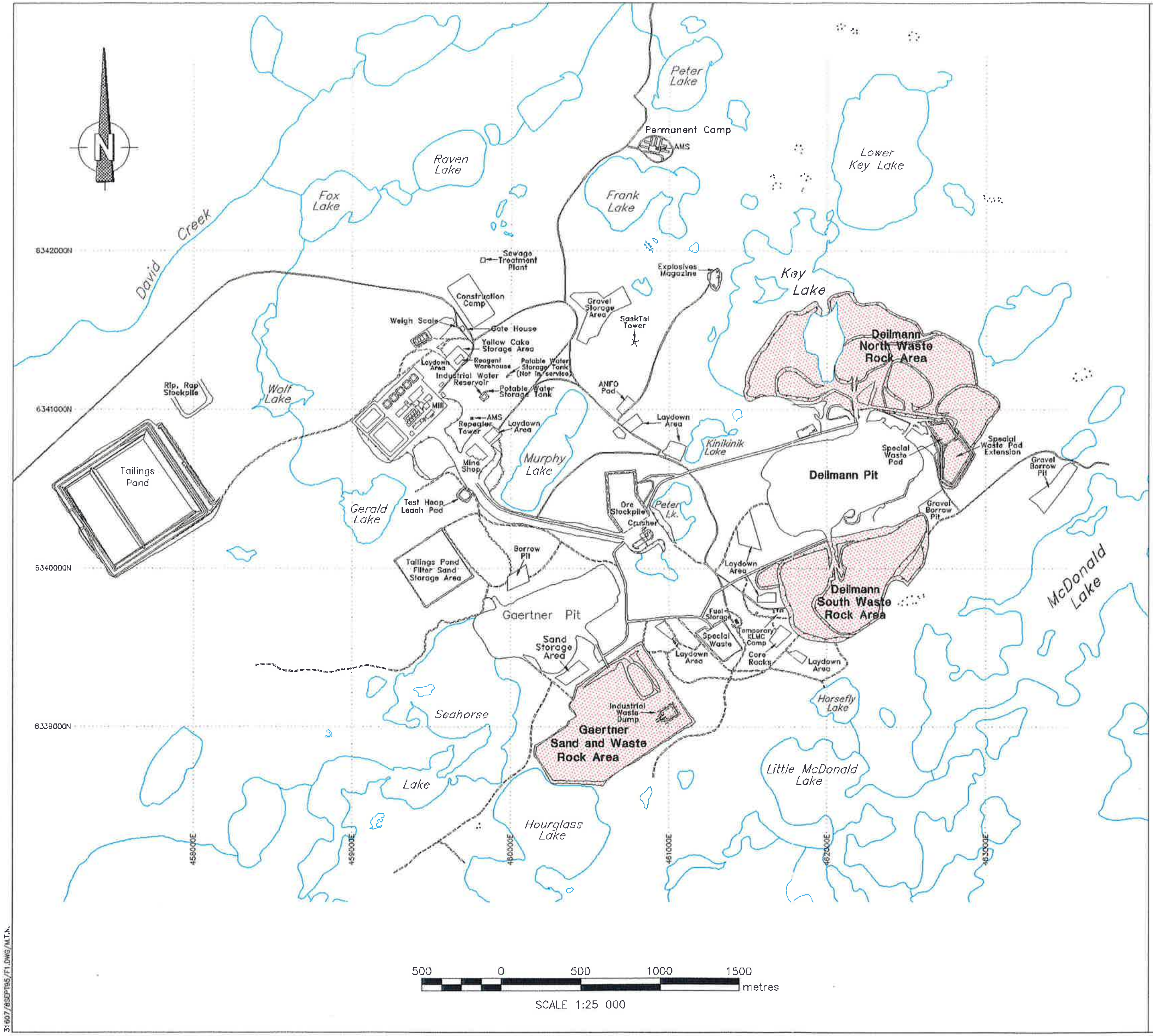
*Geology:*

The following description of the bedrock geology, quaternary geology, and mineralization were extracted from Cameco (1994).

The Key Lake ore bodies are located along the southeast rim of the Athabasca Basin. In the Key Lake area, sediments of the Athabasca Group of Helikian age unconformably overlie granitoid rocks of the Wolliston Domain which form part of the Churchill Structural Province of the Canadian Shield. The local stratigraphy is characterized by east-west and north-south striking fault zones.

# FIGURE 1

# KEY LAKE PROJECT
# SITE PLAN
# GENERAL ARRANGEMENT



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The majority of the uranium mineralization is hosted by the Athabasca Group sediments. However, basement-hosted ore which exists within the underlying gneissic rocks is known to extend for a depth of 30 m below the unconformity. Uraninite and coffinite are the predominant uranium minerals. An overprint of nickel-rich polymetallic mineralization is characteristic of the basement-hosted ore.

Unconsolidated quaternary deposits of glacial and periglacial deposits overlie the Athabasca sediments and basement rock windows. Glacial till in the form of ground moraines and drumlins form a 5 to 20 m thick cover. Glacial fluvial sediments are present in the form of eskers, kames, and outwash plains. Deposits of outwash sediments are known to exceed 80 m in thickness.

*Inventory of Waste Materials:*

Cameco (1995) estimates that 4 million m3 of additional storage capacity will be required to accommodate future tailings production and all special waste with a uranium-oxide content of 0.05 to 0.19%. Approximately 1.6 million tonnes of Key Lake ore will be processed between mid-1995 and the year 2000. An additional 0.3 million tonnes of waste will consist of chemical precipitates produced during milling. At a dry density of 0.65 *Vm3* this equates to approximately 3 million m3 of storage capacity. A total of approximately 2 million tonnes (1 million m3) of special waste basement rock and an additional 1.2 million m3 of segregated nickel-rich basement rock will require disposal in either the flooded Deilmann or Gaertner pits to minimize oxidation.

*Environmental Concerns:*

The generation of acid mine drainage is not considered a short term nor a long term problem. In fact, results of ABA (acid/base accounting) testing conducted by Steffen,

Robertson & Kirsten (1993) indicate that Key Lake tailings solids are slightly acid consuming with NP/AP (Neutralization Potential: Acid Producing Potential) ratios of 1.2 to 1.8.

Other environmental concerns relate to the radioactive nature of the waste materials. These include: exposure to gamma radiation; releases of radon gas; mobility of radioactive isotopes such as Ra-226 by leaching; and erosion of tailings by water and wind. Exposure to gamma radiation can be reduced to acceptable limits and the formation of radioactive dust eliminated by the placement of a soil or water cover. In addition, a water cover is an effective means of controlling radon emissions. The mobility of Ra-226 has been shown to be controlled by three phenomena: i) the agglomeration of finely suspended radium which settles to the bottom; ii) coprecipitation with supersaturated metal sulphates such as barium and calcium sulphates; and iii) adsorption into tailings solids.

The final concern is the mobility of potentially toxic elements such as arsenic and nickel. These elements, however, should remain relatively immobile as long as the tailings remain alkaline. In a non-acid generating system, the pH of the tailings pore water should remain above pH >8.0 and consequently, the existing arsenic, nickel hydroxide mineral complexes should remain stable.

## 2.0 Tailings Management Options

According to Cameco (1994), the chosen disposal concept must provide a safe storage of wastes by isolating these materials from the air, surface water, and groundwater. The present and future groundwater conditions are of fundamental importance when considering the storage of uranium tailings on or within natural bedrock formations. Furthermore, the disposal concept had to be considered a "walk away" situation without future management intervention by the operator and/or government.

In addition, changes to the ore-milling and tailings disposal practices were considered essential. Cameco (1994) summarized a series of affirmative action objectives, as suggested by Moffett (1991):

- Reduce the water content of the tailings by the maximum possible amount in the mill or in the TMF. The solids content of the tailings, prior to allowing for more than seasonal freezing, should be more than 52%.
- Achieve a stable moisture regime throughout the full depth of the tailings prior to decommissioning.
- Limit leachate generation from the above-ground tailings systems to the rate of infiltration. Long term infiltration should be less than 5% of the average annual precipitation.
- Limit the maximum long term flux from a pit disposal scheme, for all mechanisms (advection plus diffusion), to the equivalent of 5% infiltration through the plan area of the pit.
- Ensure that the thermal regime in the pit is stable within two to five years of decommissioning.

- Ensure that primary settlement is complete within two to five years of decommissioning.
- Derive primary protection from geological barriers, and site the TMF to obtain maximum protection from natural hydrogeological barriers.

The following tailings management facility (TMF) options were considered for the storage of future Key Lake tailings, special waste, and nickel-rich basement material:

- above ground storage within the existing TMF;
- above ground storage within a new facility constructed adjacent to the existing TMF;
- below ground storage beside the existing TMF which involves excavation of a new open pit;
- disposal in the Gaertner pit; and
- disposal in the Deilmann pit.

## 3.0 Selection of Preferred Waste Management Alternative

The first criterion was that all potential sites should be within an economical transport distance from the mill, and had to be of sufficient capacity. The remaining criteria were as follows:

- absence of ore;
- location and elevation of site relative to mill (controls pumping requirements);
- topography (controls facility design);
- geological and hydrogeological conditions (considers natural hydrologic barriers, structurally controlled seepage, foundation stability, aquifer delineation, and availability of borrow materials, etc.);
- hydrology and catchment areas (considers water balance parameters);
- property ownership; and
- decommissioning (considers ease of decommissioning, environmental impact, etc.).

During the selection procedure, each of the listed parameters were assessed using a performance scale ranging from 1 to 5 with 1 representing "Not Acceptable" and 5 rated as "Very Good". The most appropriate disposal option was not necessarily the one which recorded the highest score. The results of the rating process were used in conjunction with a sound knowledge of the area to select the most appropriate option.

## 4.0 Principal Findings

The final assessment as presented by Cameco (1994) is as follows.

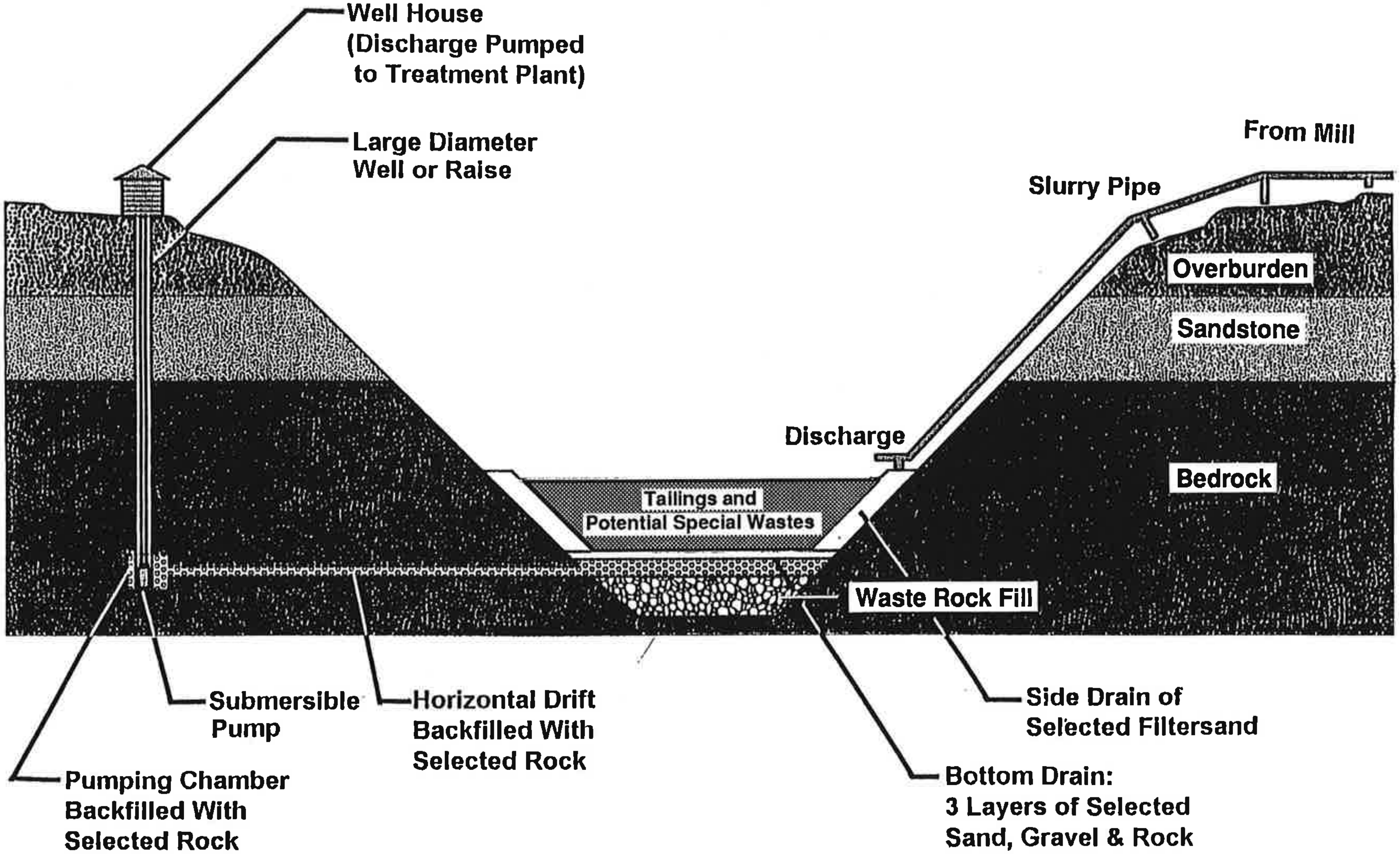
- Above ground storage within the existing TMF was rejected as a suitable option because of economic and possible environmental implications.
- Above ground storage within a new facility constructed adjacent to the existing TMF represented a viable, but less attractive alternative from an environmental and economic perspective.
- Below ground storage beside the existing TMF involves excavation of a new open pit which is not economically feasible but probably acceptable from an environmental perspective.
- Disposal in the Gaertner pit could have potential environmental and operational risks due to the hydrogeological conditions.
- Disposal in the Deilmann pit was deemed to have a very low long term environmental impact while providing economic storage of tailings.

The Deilmann pit was chosen as the best option because of the following reasons.

- The pit disposal concept within competent bedrock provides a stable containment facility which in turn ensures the long term stability of wastes.
- Greater than 99.9% of the groundwater flow will occur within the highly permeable sands which comprise the upper portion of the pit and consequently bypass the tailings mass deposited lower down in the pit.
- Submergence has proven to be the best available method of inhibiting oxidation and minimizing the long term leaching potential of the tailings constituents.
- With surface dimensions of approximately 1,300 m in length and 600 m in width and a maximum depth of 130 m, the capacity of the Deilmann pit far exceeds that required.

FIGURE 2

## PHASE 1 - SUBAERIAL DEPOSITION



SOURCE: FIGURE 1, CAMECO (1994)

A section showing the subaerial deposition of wastes is provided in Figure 2.

The design of the Deilmann pit TMF is based on the concept currently employed at the Rabbit Lake in-pit TMF which involves the subaerial deposition of tailings within a pervious surround (Case Study 2). The Rabbit Lake TMF design provides both excellent seepage control and overall tailings consolidation.

The pervious surround system consists of a highly permeable zone of crushed rock and sand surrounding the tailings. During placement of the tailings, this permeable zone provides a seepage path for the dissipation of excess porewater pressure and promotes consolidation of the tailings. The seepage collected during deposition is returned to the mill to be used as process water or for treatment.

A complete bottom and partial side-drain system will optimize consolidation of the tailings during deposition. The under-drain system will consist of a 6 m stratified layer of crushed rock, filter gravel and filter sand. The side-drain will consists of an 8 m thick layer of filter sand placed along the pit wall and extend for a height of up to 30 m above the under-drain. The leachate and inflowing groundwater will be pumped to the surface by a high-volume pump placed at the bottom of a vertical raise. A 2.5 by 2.5 m drift will connect the raise to the bottom of the pit.

Plans are to commence placement of tailings into the east end of the Deilmann pit in late 1995 while mining continues in the west end. The location of the tailings pipeline spigots will be rotated to ensure an even tailings distribution. The special waste will be either placed into the tailings using heavy equipment or milled to recover its uranium content.

Following completion of the disposal phase, the tailings will be covered with a two-metre sand/silt or till cover before it is flooded.

Following decommissioning, the ponded water will continue to be treated until water quality meets regulatory objectives. Monitoring of regional groundwater, the ponded water, and the tailings characteristics will be conducted to ensure that the TMF has a negligible impact on the surrounding environment

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Moffett, D. et al. 1991. *Enhancing Environmental Performance by Technological Improvements to Uranium Mill Processes.* A Report to Mines Pollution Control Branch - Saskatchewan Environmental and Public Safety.

Steffen, Robertson and Kirsten (Canada) Inc 1993. *Key Lake Waste Rock Characteristics.*

# CASE STUDY 12: THE BERKELEY PIT

## 1.0 Background

The Berkeley pit is a well-known example of a serious AMD problem in a flooding open pit. The mine site is part of a superfund site and numerous investigations have been and continue to be carried out at this location. This case study has been prepared by combining (e.g. quoting and/or paraphrasing) information from several key references provided by the Montana Bureau of Mines and Geology (Duaime, 1994).

*History:*

*"The Butte area has been mined almost continuously since 1880. Over a 110-year period, silver, gold, copper, zinc, lead and molybdenum have been mined in about 400 underground mines and several open pit mines. This mining activity has resulted in soil and water contamination and changes in the way ground and surface water flow in and near Butte. In 1985, the Silver Bow Creek site, which has been on the Superfund National Priorities List since December 1982, was expanded to include the Butte Area" (U.S. EPA, 1990) (Figure 1a).*

*"The Butte Mine Flooding Operable Unit (OU) part of the Silver Bow Creek/Butte Area National Priorities List (NPL) site is located in and near the cities of Butte and Walkerville, Montana. It consists of waters within the Berkeley pit, the underground mine workings hydraulically connected to the Berkeley pit, the associated alluvial and bedrock aquifers, and other contributing sources of inflow to the Berkeley pit/East Camp System (including surface runoff, leach pad and tailings slurry circuit overflows) and the Travona/West Camp System. The boundaries of the OU are approximately the Continental Divide to the east, Metro Storm Drain/Silver Bow Creek to the south, Missoula Gulch to the west, and the Yankee Doodle Tailings Pond watershed drainage system to the north. The OU is within the Butte mining district in the upper Silver Bow Creek drainage, and covers about 23 square miles"* (60 km$^2$) (U.S. EPA 1994).

*"With the suspension of active mining in 1982 in the Berkeley pit and underground mines, the pumps were turned off and the underground mines began to flood. Once water levels reached the bottom of the pit (November, 1983), it began to fill. The*

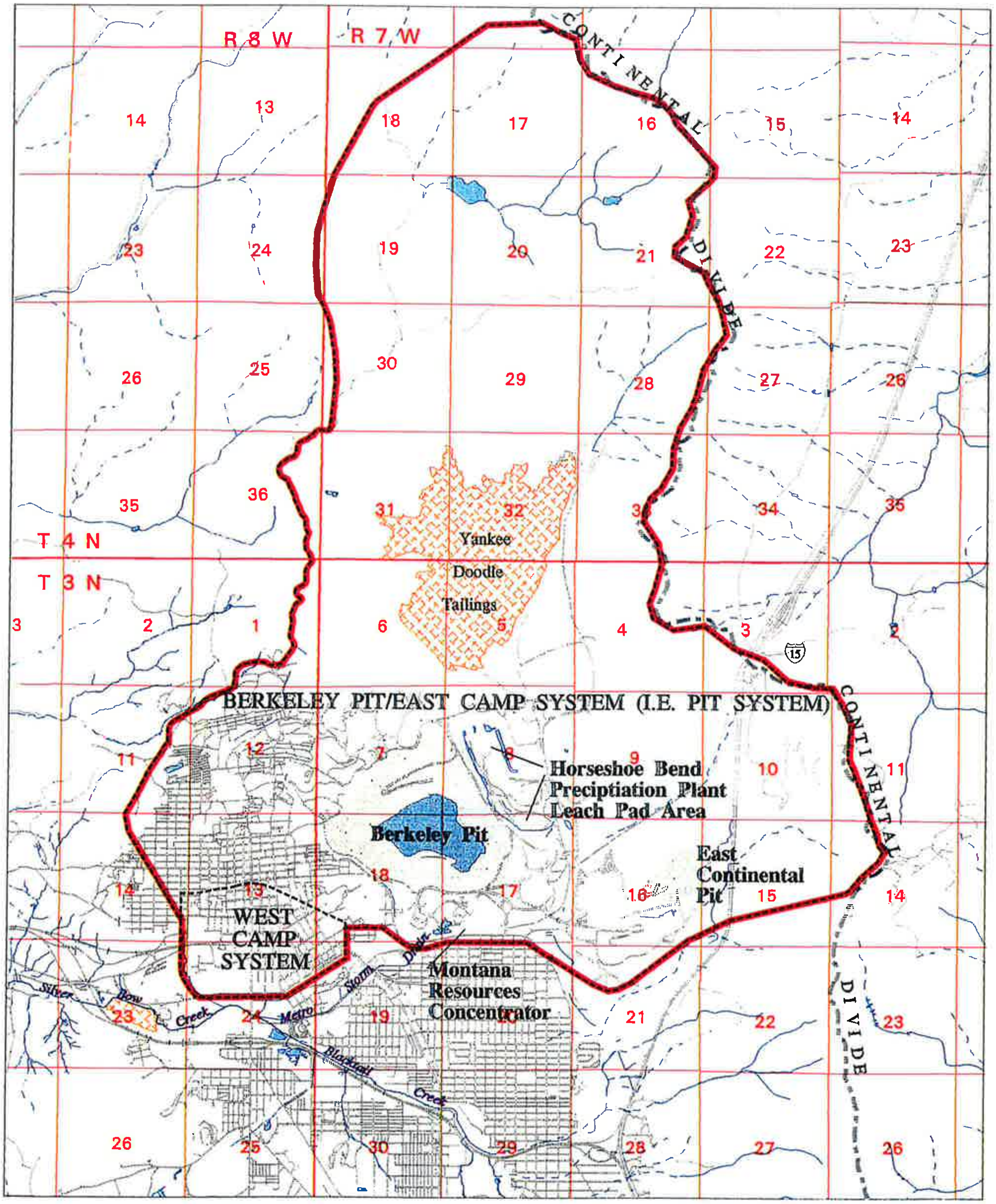


FIGURE 1a

BUTTE, MONTANA
AND SURROUNDING AREA
MINE FLOODING OPERABLE UNIT

SOURCE: USEPA (1994)

*water levels in the West Camp are currently higher than those in the East Camp, with water in the Berkeley pit lower than the water levels elsewhere in the area. This causes water to flow into the pit (see Figure 1b)"* (U.S. EPA, 1990).

*"The Berkeley pit is 1,780 feet (543 m) deep, encompassing an area of 675 acres (2.7 km$^2$) and currently has a volume of 26 billion gallons (98 billion litres) of contaminated water. This system also encompasses more than 3,000 miles (4,828 km) of underground mine workings. The West Camp System is located in the southwest corner of the OU and includes the Travona, Emma, and Ophir mines and their associated underground workings. These two systems are separated by bulkheads installed in the late 1950s and are considered to be separate hydrologic systems; however, the bulkheads may be leaking, thereby allowing water to flow from the West Camp System to the Pit System"* (U.S. EPA 1994).

The leach pads area (low-grade ore and waste rock) is located northeast of the Berkeley pit and covers an area of 775 acres (3 km$^3$). An acid leaching solution percolates through the pads, leaching copper from the ore, and is collected for extraction of the dissolved copper (U.S. EPA 1994).

A major seepage area originates in the Horseshoe Bend area, located northwest of the Precipitation Plant (Figure 1a). A portion of the acidic Horseshoe Bend water is mixed with the leaching solution, and returned to the leach pads area or discharged to the tailings pond. The remaining acidic seepage from Horseshoe Bend is discharged into the Berkeley pit (U.S. EPA 1994).

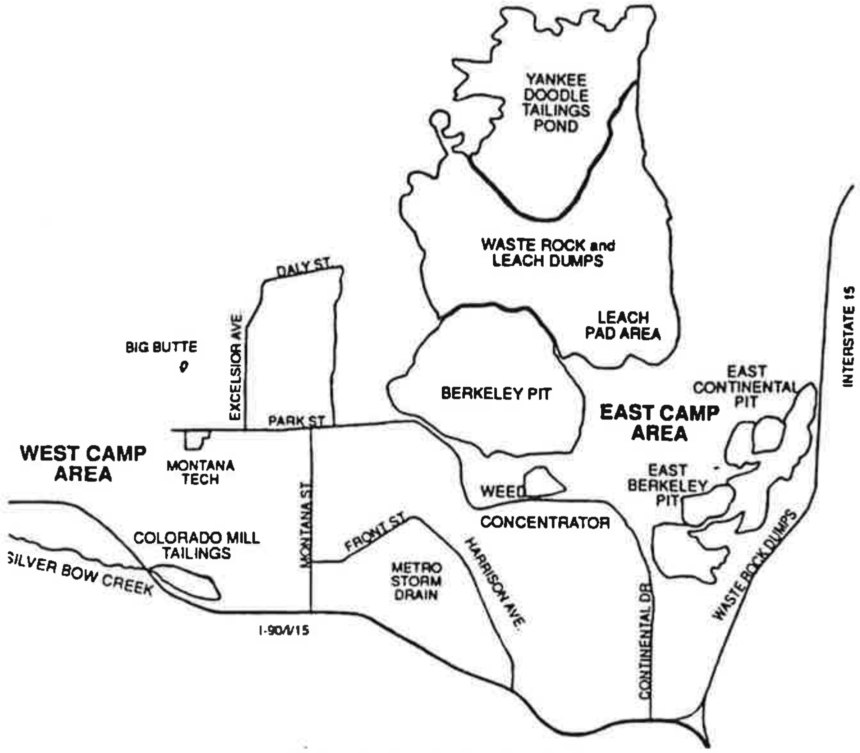
*Hydrogeology:*

*"The principal geologic rock units within the Butte Mine Flooding OU are the alluvium and the bedrock. The alluvium is a sedimentary deposit consisting of unconsolidated and discontinuous layers of sand, silt, clay, and gravel. The alluvium thickness east of the pit ranges from 130 feet (40 m) near the leach pads to 600 feet (183 m) or more southeast of the Berkeley pit. Underlying the alluvium is igneous bedrock consisting primarily of quartz monzonite. The upper 100 to 200 feet (30 to 60 m) of the bedrock is weathered (oxidized and decomposed) to a clayey material interspersed with rock fragments"* (U.S. EPA 1994).

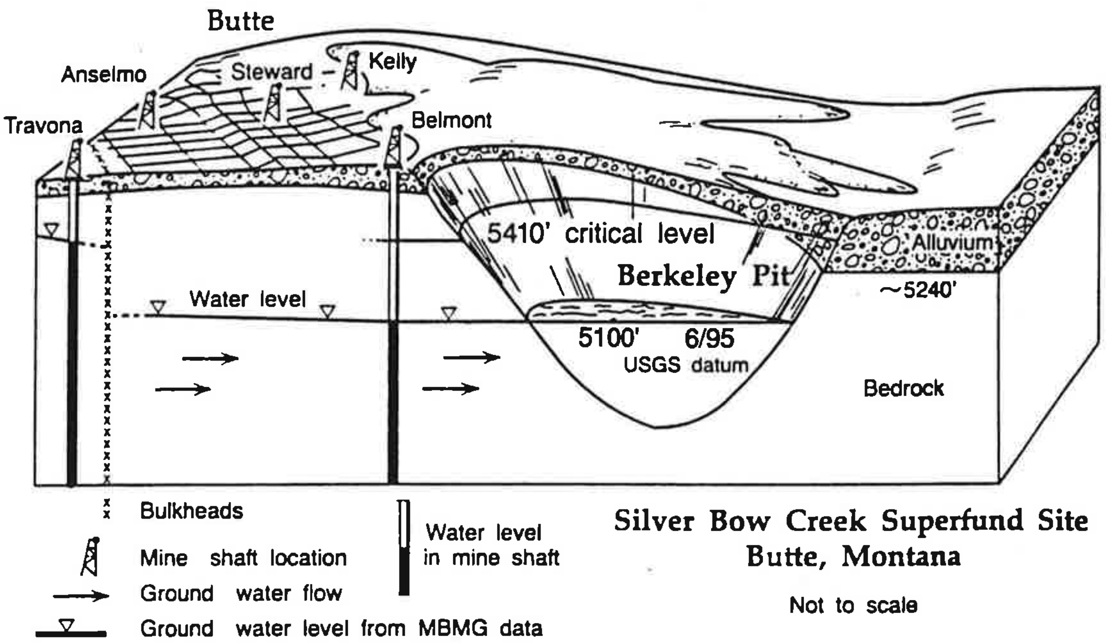
*"The two main aquifers in the area are the bedrock, which underlies the entire OU, and the alluvium, which was deposited over the bedrock in valleys and drainages.*

## FIGURE 1b

# SITE LOCATION MAP AND CONCEPTUAL MODEL ILLUSTRATION



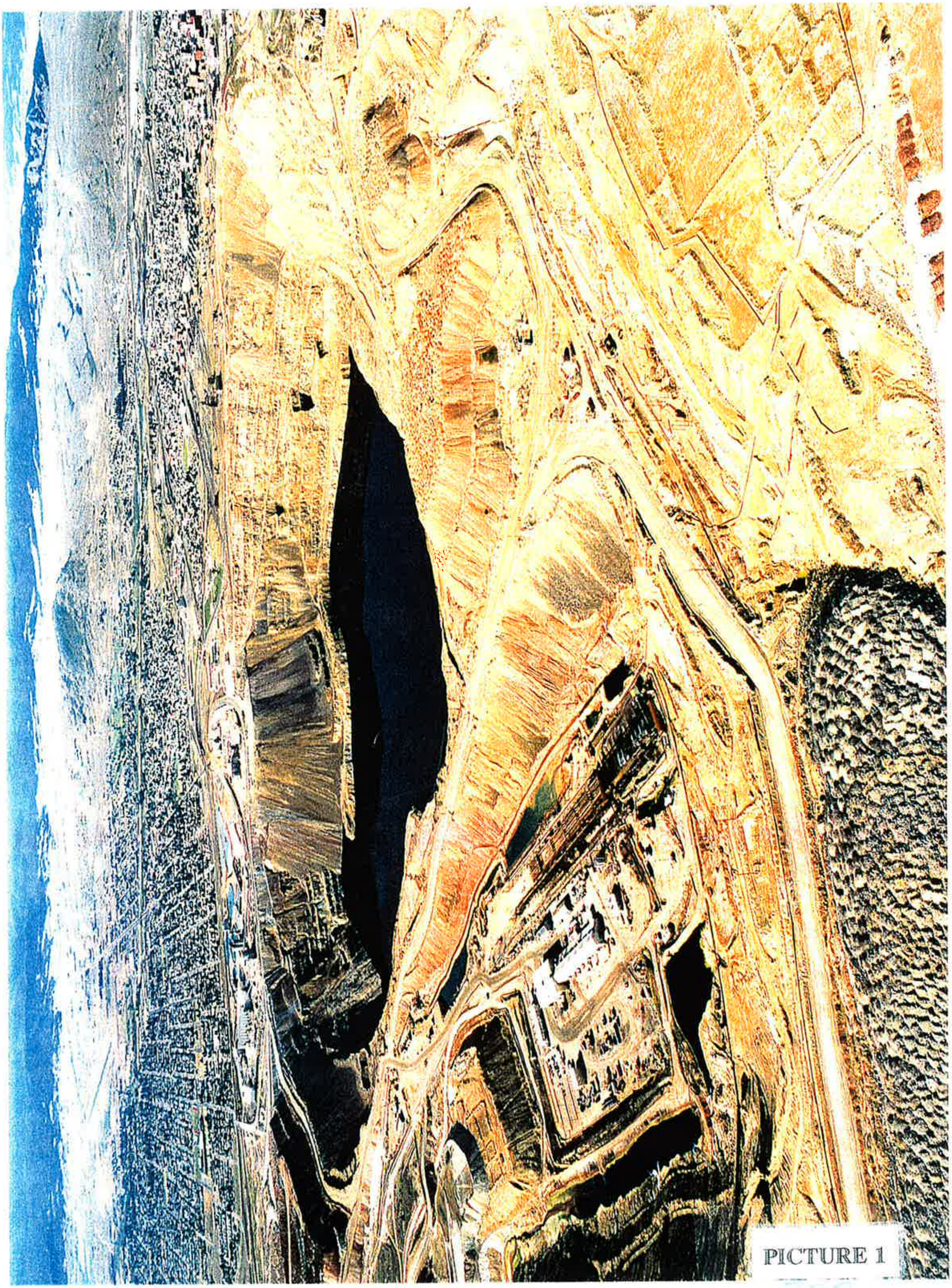
SITE LOCATION MAP



**NOTE:** illustrates the relationship of ground water beneath the Butte Area to the Berkeley Pit and the 5,410-foot critical elevation (USGS datum). Relative water levels are shown to indicate the separation of the East Camp and the West Camp. The data used for water levels in this figure are from the Montana Bureau of Mines and Geology (MGMG).

Conceptual Model of Water Levels Below the Surface

SOURCE: USEPA (1994)



PICTURE 1

PICTURE 2

*Groundwater in the bedrock occurs in fractures, joints, and mine workings. Currently, groundwater levels in the surrounding bedrock aquifer are higher than the water level in the Berkeley pit, resulting in radial flow of groundwater from the bedrock toward the pit"* (U.S. EPA 1994).

There are no wastes reported to have been (intentionally) deposited in the pit; however, there would be release of contamination from any exposed residual mineralization. This source could be significant since the Berkeley pit is a terraced open pit mine over a mile across and 1,780 feet deep (1,609 m across, 543 m deep). Sonderegger et al. (1987) observed mass-wasting of the sides of the pit into the water during a water sampling program. The mining operations were suspended in 1982 for economic reasons; the copper ore has not been mined-out. The waste rock and sub-ore piles on surface above the pit are currently technically leached to recover copper. None of the references reviewed suggested these wastes could be disposed in the pit at some time in the near future. The decommissioning investigations are primarily concerned with treating the pit water to ensure any future overflow into the surrounding alluvial strata would not impact on potential drinking water aquifers.

An article by Baum and Knox (undated) suggests the flooding Berkeley pit and the surrounding landscape will likely be decommissioned in its current configuration as there are plans to transform the entire Butte Mining area into a national historic park. The challenge is to make the environment safe without altering the city's historic mining character.

### *Acidic Drainage:*

The Berkeley pit is filling with water originating from the surrounding bedrock and alluvial aquifers and also from surface inflows. The water depth is currently over 800 feet (244 m). The water accumulating in the Berkeley pit is highly acidic and contains high concentration of metals (Table 1).

Major ions (calcium, potassium, magnesium, aluminum chloride, sulphate) and total suspended solids increase with depth. Trace metals (lead, cadmium, copper, manganese, zinc) also increase with depth and are present in concentrations above federal drinking water standards.

Table 1

## COMPOSITION OF BERKELEY PIT WATER AT VARIOUS DATES AND DEPTHS FROM SURFACE

| | **Nov. 84 62 ft.*** | **Jun. 85 100 ft.** | **Oct. 86 200 ft.** | **Oct. 87 216 ft.** | **May 91 225 ft.** | **Oct. 92 200 ft.** | **Gold Book** | **Drinking Standard** |
|---|---|---|---|---|---|---|---|---|
| Al | 142 | 172 | 192 | 193 | 288 | 304.5 | 0.087 | |
| As | 0.2 | 0.43 | 0.04 | 1.2 | 0.83 | 0.43 | 0.05 | 0.05 |
| Cd | 1.54 | 1.62 | 1.74 | 1.76 | 1.57 | 2.00 | 0.0023 | 0.01 |
| Ca | 477 | 435 | 457 | 479 | 492 | 525.1 | | |
| Co | -- | -- | 1.05 | 1.19 | 1.80 | -- | | |
| Cu | 164 | 229 | 204 | 202 | 191 | 215.1 | 0.042 | 1 |
| Fe | 256 | 451 | 918 | 1,010 | 1,088 | 1,112 | 1 | 0.3 |
| K | 4.4 | 8.8 | 24.3 | 18.7 | 20 | 19.9 | | |
| Mg | 236 | 261 | 291 | 279 | 418 | 517 | | |
| Mn | 106 | 116 | 144 | 161 | 182 | 225.5 | 0.05 | 0.05 |
| Ni | -- | -- | 0.91 | 0.99 | 1.05 | 0.91 | | |
| Na | 61.7 | 60 | 65.8 | 70.5 | 68 | 107.1 | | |
| Pb | -- | -- | -- | 0.66 | 0.08 | <0.13 | 0.01 | 0.05 |
| Zn | 255 | 329 | 460 | 494 | 552 | 636.6 | 0.23 | |
| $SiO_2$ | | | | | | 51.24 | | |
| $Cl^-$ | 12.3 | 8.3 | -- | 21.8 | 10.9 | -- | | 250 |
| $F^-$ | -- | -- | 8.4 | 19.2 | -- | -- | | 4 |
| Sulphate | 4,410 | 5,550 | -- | 6,940 | 8,010 | 7,700 | | 250 |
| pH | 2.78 | 2.48 | -- | 3.15 | 2.84 | 2.69 | | 6.8-8.5 |
| Eh, mv | -- | -- | -- | 463 | 650 | 621 | | |

Source: Huang and Liu 1993.

Notes:

* Composite of 50 and 75 foot samples (Duaime 1995).

EPA Gold Book: Quality Criteria for Water, 1986 and revision 1991; Some metal concentrations are computed based on the hardness of 250 mg/L for aquatic life; manganese level was taken from the criteria for human life (Huang and Liu, 1993).

*"The source of the contamination is AMD from the bedrock in the mine workings, waste rock dumps, and leach pads. Presently, because all bedrock groundwater flow in the area is toward the Berkeley pit, contaminated mine water is being contained...However, if water levels continue to rise uncontrolled and exceed an elevation of 5,410 ft (1,649 m), the hydraulic gradient could change and contaminated water could begin to flow into the surrounding alluvial groundwater and eventually to Silver Bow Creek. To prevent this from occurring, the U.S. EPA and the State of Montana determined that the water level in the OU must not rise above the following levels"* (U.S. EPA, 1990, 1994):

- East Camp - 5,410 feet (1,649 m);
- West Camp - 5,435 feet (1,657 m), (USGS datum).

*"These water levels are based on extensive monitoring of water levels in both the alluvial and bedrock groundwater systems by the Montana Bureau of Mines and Geology (MBMG) and the Montana Department of Health and Environmental Sciences (MDHES). The East Camp level represents the lowest alluvial groundwater elevation in the area*" (U.S. EPA 1994).

*"The PRPs (Potentially Responsible Parties) who signed the Administrative Order on Consent at this superfund site have agreed not to allow the water (at any specified monitoring location) in the East Camp system to exceed the stipulated level. If the water does exceed this level, they are subject to $25,000 per-day stipulated penalties*" (U.S. EPA 1990).

## 2.0 Investigative Procedures

*"The general objectives of the RI/FS (Remedial Investigation/Feasibility Study) are to identify the nature and extent of contamination associated with mine flooding and evaluate remedial alternatives. The specific goals are to mitigate the impact of mine water discharge on Silver Bow Creek and the adjacent alluvial aquifer and to maintain flow toward the pit and thereby contain the contaminated bedrock groundwater in the Berkeley pit for ultimate treatment. Specific remedial response objectives to meet these goals are to control the rate of mine flooding and to design and implement an appropriate remedy to ensure that discharges of mine water to Silver Bow Creek or the adjacent alluvial aquifer meet applicable state and federal water quality standards"* (U.S EPA 1990).

*"The U.S. EPA (1990) directed the PRPs to undertake the following tasks during the Remedial Investigation portion of the RI/FS:*

- ***Inflow Control Investigation:*** *Monitor significant amounts of water entering the pit ("inflows") so that alternatives to control inflow can be evaluated. If inflows can be controlled, treatment of the pit water potentially could be deferred.*

- ***Surface Water Investigation:*** *Monitor the flow and quality of water in the Silver Bow Creek/Butte Area at the approximate location where treated mine water discharge would enter the creek. This will provide the data necessary to determine if discharges to Silver Bow Creek meet state water quality limits.*

- ***Syndicate Pit Evaluation:*** *Evaluate existing data to determine the amount of inflow to the Syndicate Pit system from storm water runoff from upper Missoula Gulch. Storm water entering the Syndicate Pit eventually reaches the Berkeley Pit through the mine workings. If this flow is significant and can be controlled, treatment of the Berkeley Pit water potentially could be deferred.*

- ***Butte Disturbed Soils Investigation:*** *Review currently available data and relevant literature to determine whether water percolating through disturbed soils and solid waste piles contributes significantly to mine flooding. This study will evaluate whether clay barriers that prevent water seepage ("caps") are appropriate for controlling this inflow. Caps could extend the time available to develop treatment alternatives for the water in the pit.*

- ***Assessment of Tailings Dam Safety:*** *Review a previous safety evaluation of the Yankee Doodle Tailings Pond Dam to determine safety given the current condition of the dam. If the dam failed, a large amount of water would immediately enter the pit, thereby potentially reducing the amount of time available for action.*

- ***Bedrock Groundwater Monitoring:*** *Use existing shafts and install wells to monitor water quality and water levels in the bedrock. Resulting data would be used to develop a critical water action level* *and to monitor whether water levels rise more quickly than anticipated.*

- ***Leach Pad Area Alluvial Investigation:*** *Install monitoring wells to evaluate whether the leach pads are a current source of contamination to the alluvial groundwater system and Silver Bow Creek.*
- ***Private Well Inventory:*** *Identify and possibly monitor all existing private and municipal shallow wells to provide additional information on alluvial water levels and water quality.*

- ***Neutralization Investigation:*** *Sample pit water and conduct studies to determine the feasibility of neutralizing the pit water by disposing of mine tailings in the pit.*

*If the need for treatment is postponed (as indicated in some of the tasks above), innovative treatment technologies might be developed that will treat the water more completely and efficiently"* (U.S. EPA 1990).

## 3.0 Water Quality Investigations

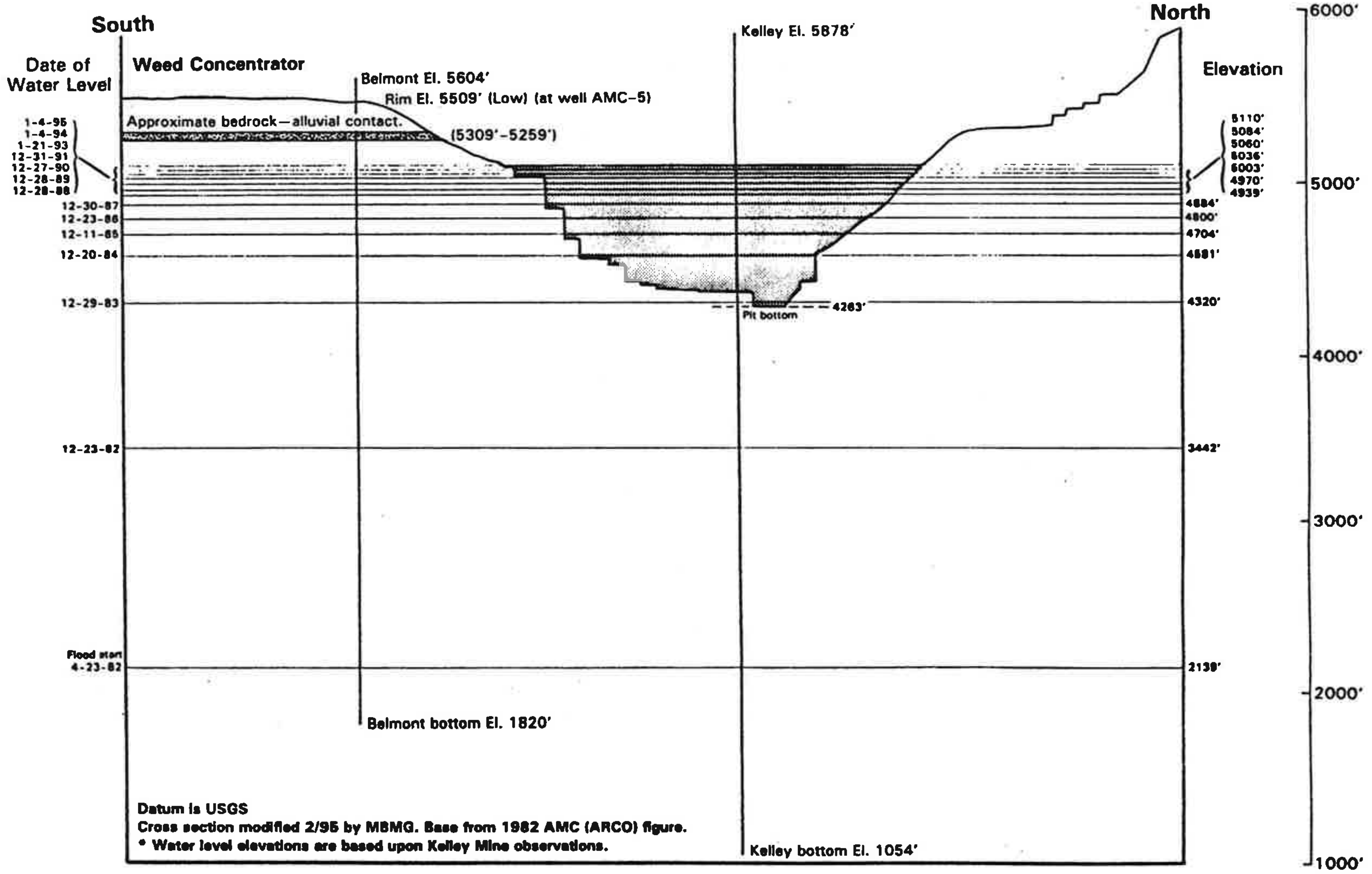
*"The Anaconda Minerals Company (AMC) suspended their pumping of underground mine water in April 1982. Prior to this suspension of pumpage, AMC pumped an average of 5,000 gallons per minute from the 3,900 foot level of the Kelley Mine. Water levels reached the bottom of the Berkeley pit during November 1983. Figure 1.c is cross-section of the pit which shows yearly water-level elevations as measured in the Kelley mineshaft. Water levels have risen over 2,800 feet* (853 m) *(in the dewatered underground mine system since the cessation of pumping in 1982 (MBMG, 1995). As a result of this water level rise, water in the Berkeley pit is over 825 feet* (251 m) *deep*" (Duaime 1995; Duaime et al. 1993).

*Monitoring:*

*"In April 1983, the Montana Bureau of Mines and Geology (MBMG) began participating in monitoring and sampling activities associated with the Butte Mine Flooding Monitoring Program initiated by the AMC in 1982, pursuant to agreements with the Montana Department of State Lands...The Montana Department of Health and Environmental Sciences (MDHES) entered into a*

FIGURE 1c

## BERKELEY PIT CROSS-SECTION SHOWING YEARLY WATER-LEVEL ELEVATIONS



Datum is USGS
Cross section modified 2/95 by MBMG. Base from 1982 AMC (ARCO) figure.
* Water level elevations are based upon Kelley Mine observations.

SOURCE: DUAIME et al (1995)

*Memorandum of Agreement with the (MBMG) and Montana Tech to continue monitoring activities which supplement data collected by AMC and to provide technical assistance to the U.S. EPA, and their contractors, and MDHES in addition to AMC, ARCO and other involved parties"* (Duaime et al. 1993).

*"Currently the MBMG's monitoring network consists of over 100 monitoring wells (eight of which are equipped with continuous recorders) and seven mine shafts, three surface water gauging stations (maintained by the U.S. Geological Survey through a cooperative program with the MBMG), and the major surface water input into the Berkeley pit, which is equipped with a flume and continuous recorder. To date, the MBMG has collected over 500 water quality analyses from mine shafts, alluvial wells, bedrock wells, the Berkeley pit, surface waters draining into the Berkeley Pit, and surface waters within the Butte Basin"* (Duaime et al. 1993).

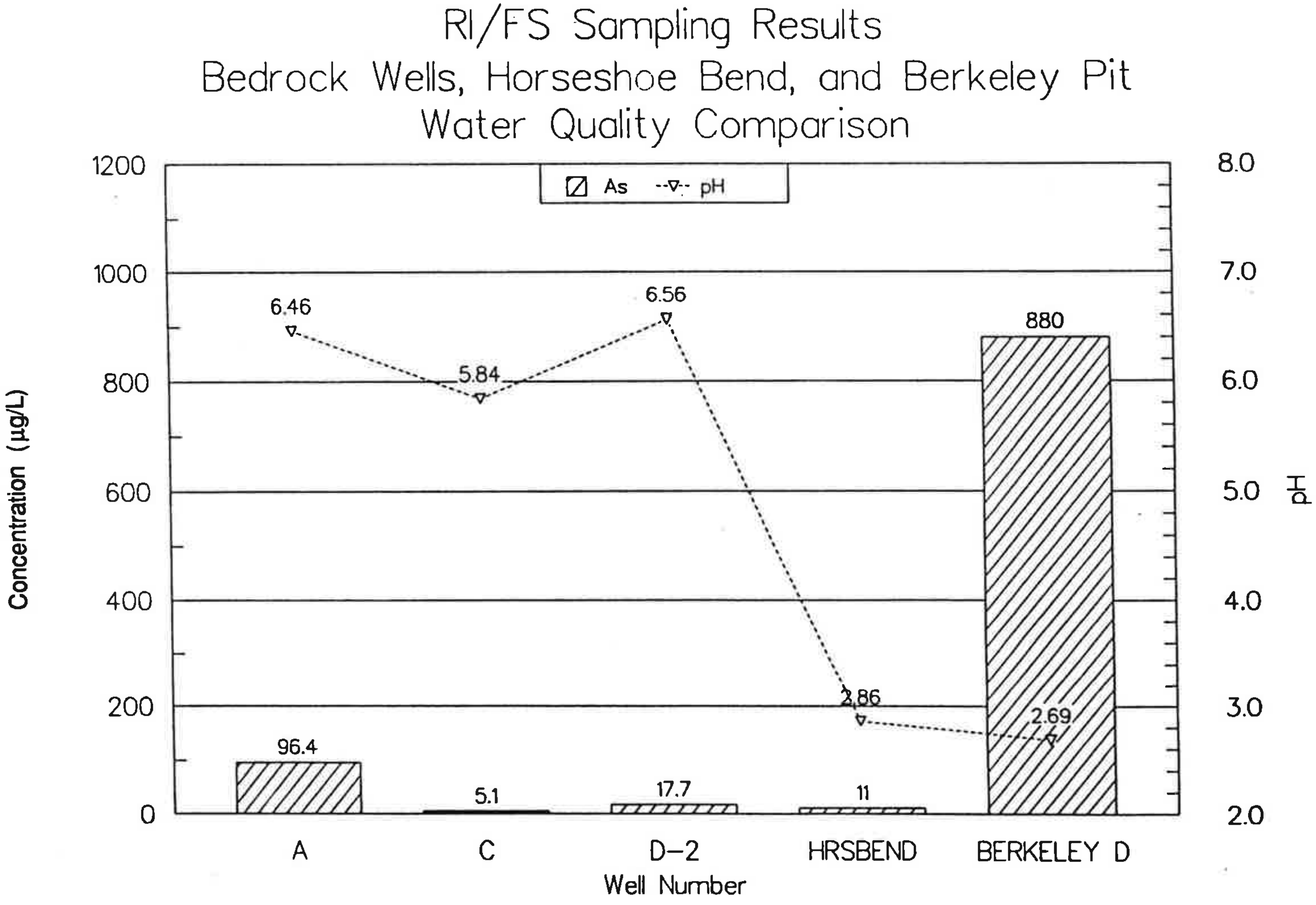
*"Figures 2, 3 and 4 show results of water quality sampling undertaken as part of the ongoing MBMG and Superfund investigations. These figures show arsenic, copper, zinc and pH comparisons for three bedrock wells, (A, C and D-2), the Horseshoe Bend drainage (surface drainage into the pit), and a 400 foot (122 m) deep sample from the Berkeley pit. From these figures it is apparent that water quality in the bedrock wells immediately surrounding the Berkeley pit, to the east and southeast, is of good quality. Metal concentrations in the bedrock wells are several orders of magnitude below those found in both the Horseshoe Bend and Berkeley pit water samples. Arsenic values in the Berkeley pit are far higher than those found in any of the other samples. The water quality data for wells surrounding the Berkeley pit is of good quality, which suggests that no degradation of bedrock water quality is occurring as a result of the flooding of mine workings"* (Duaime et al. 1993).

*"The MBMG has periodically collected water quality samples from the Berkeley pit since 1984. Water samples collected in 1984 and 1985 were collected...from within the helicopter while it hovered above the water surface; therefore measurements of the sample-depth below the water surface are, at best, approximate. Figures 5 and 6 show water quality comparison for pH, arsenic, copper and zinc for five pit sampling events,...and at various depths*" (Duaime et al. 1993).

*"Berkeley pit water quality is considerably worse than that found in any of the underground mines...Concentrations appear to have increased somewhat over time in Berkeley pit water samples, whereas the underground mine waters have shown the opposite trend*" (Duaime et al. 1993).

**FIGURE 2**

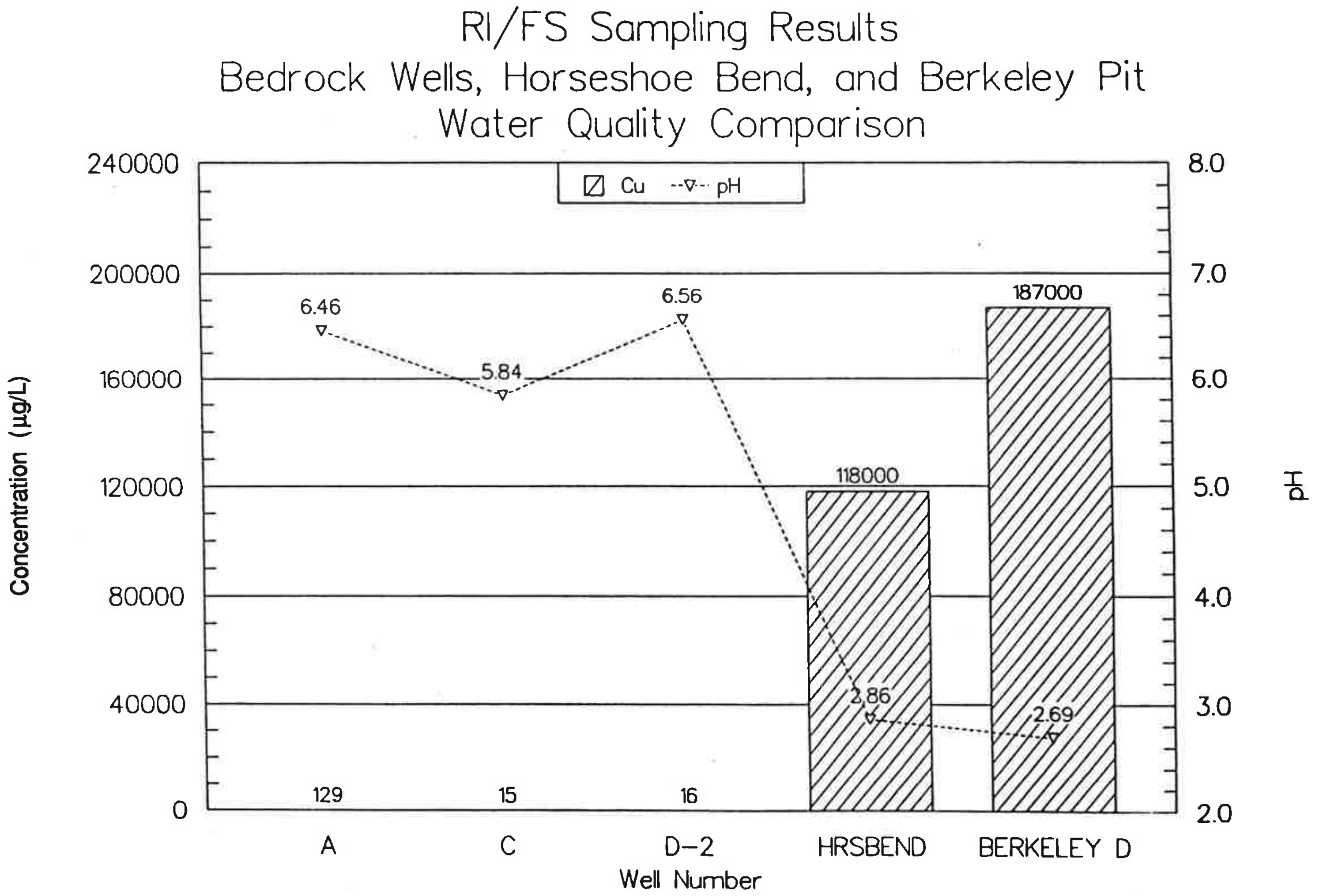
**ARSENIC AND pH COMPARISONS**
**( BERKELEY PIT SAMPLE - 400 ft. BELOW WATER SURFACE)**



SOURCE: DUAIME et al (1993)

FIGURE 3

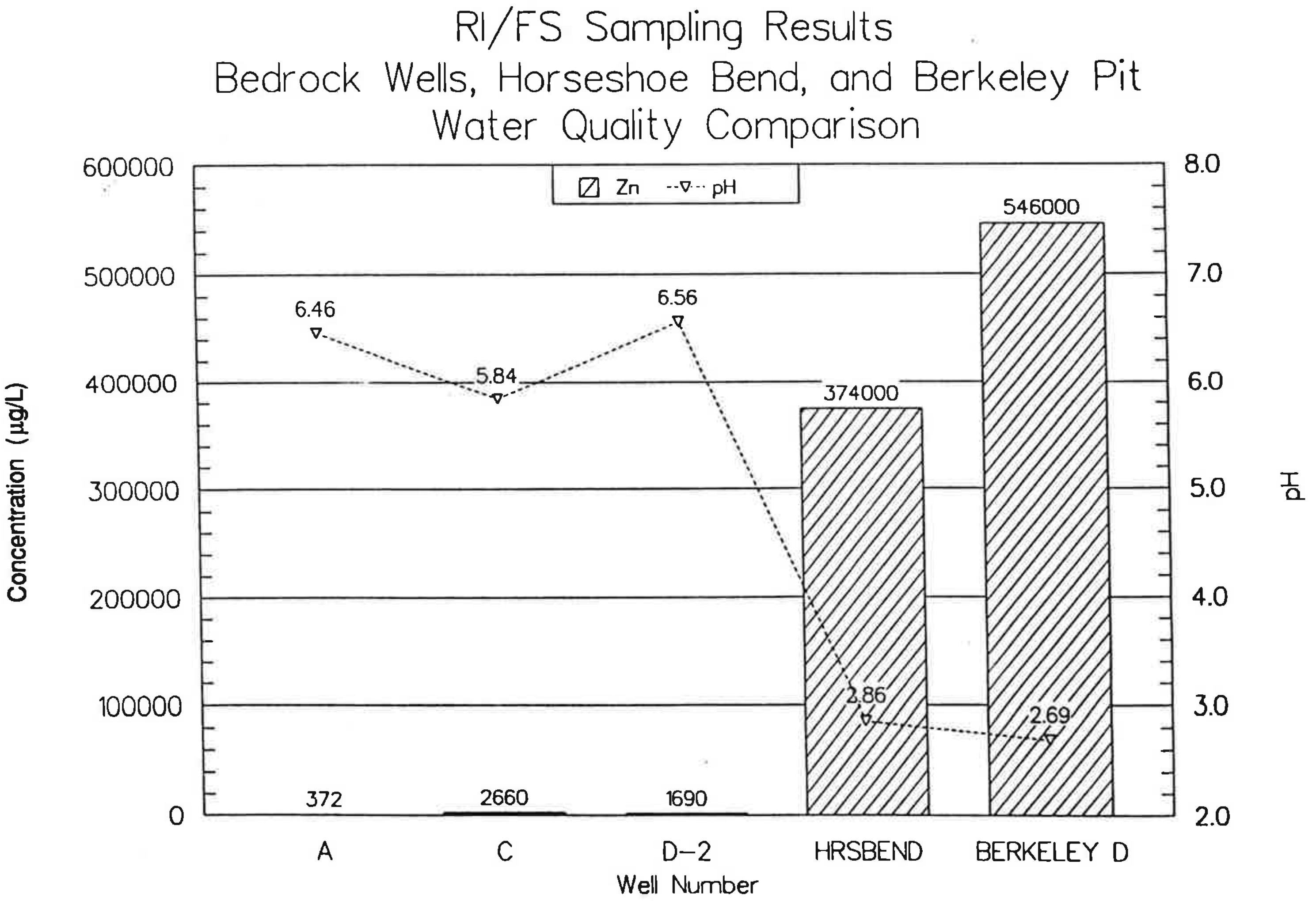
## COPPER AND pH COMPARISONS
## ( BERKELEY PIT SAMPLE - 400 ft. BELOW WATER SURFACE)



SOURCE: DUAIME et al (1993)

**FIGURE 4**

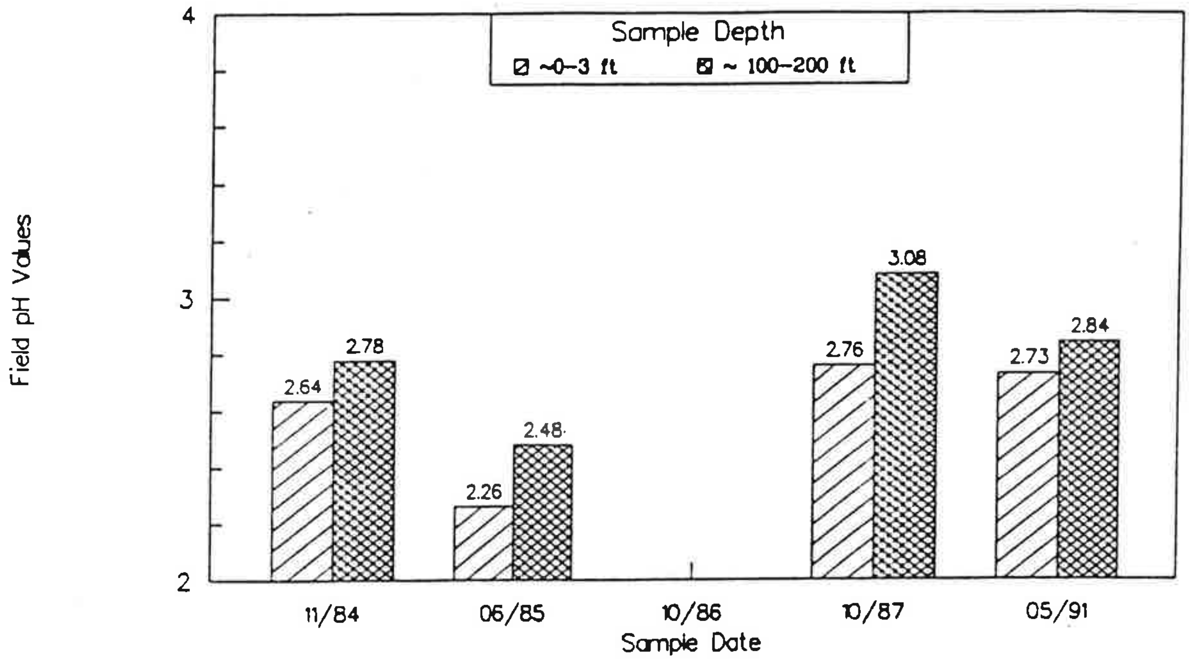
## ZINC AND pH COMPARISONS
## ( BERKELEY PIT SAMPLE - 400 ft. BELOW WATER SURFACE)



SOURCE: DUAIME et al (1993)

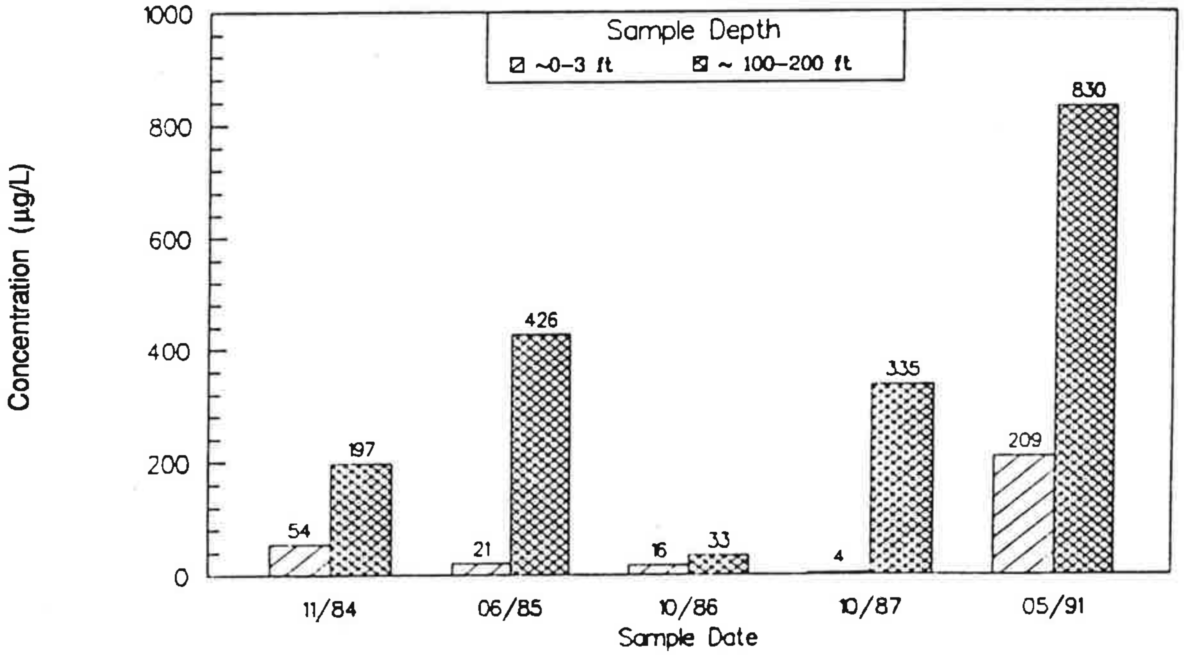
## FIGURE 5

## BERKELEY PIT pH AND ARSENIC COMPARISONS



BERKELEY PIT

pH Comparisons



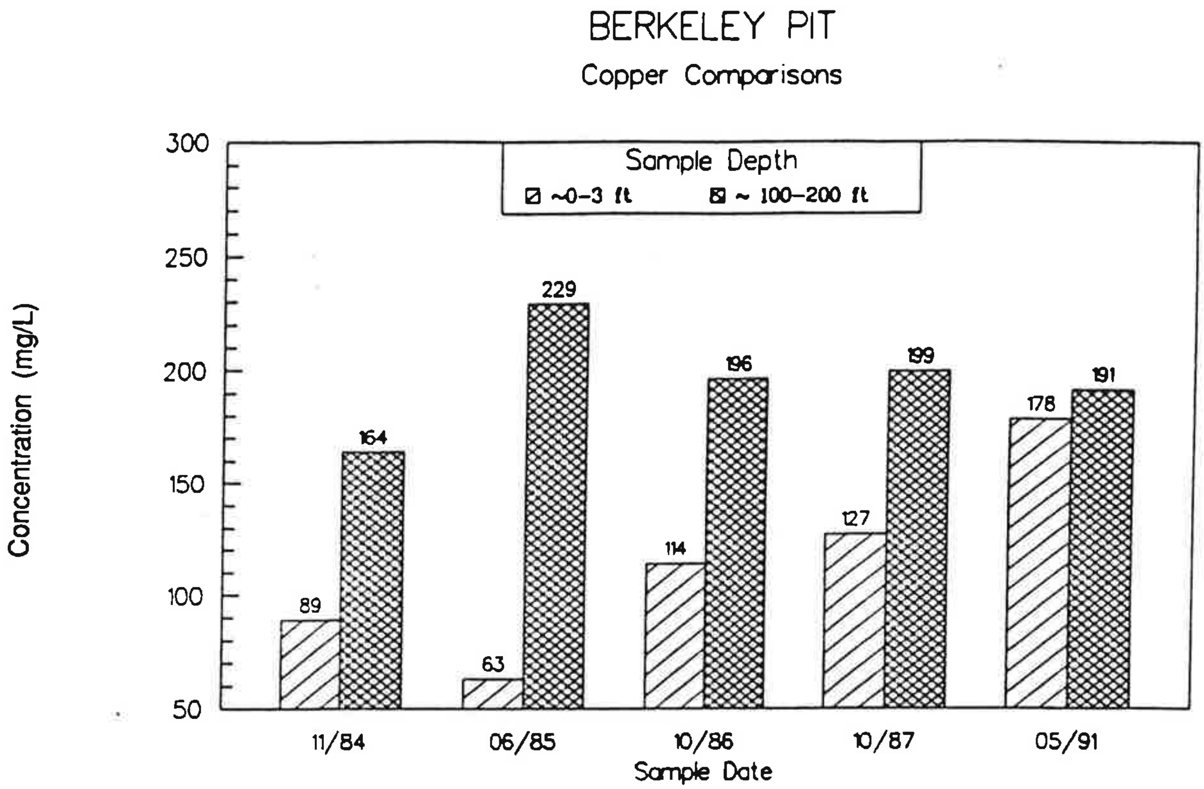
BERKELEY PIT

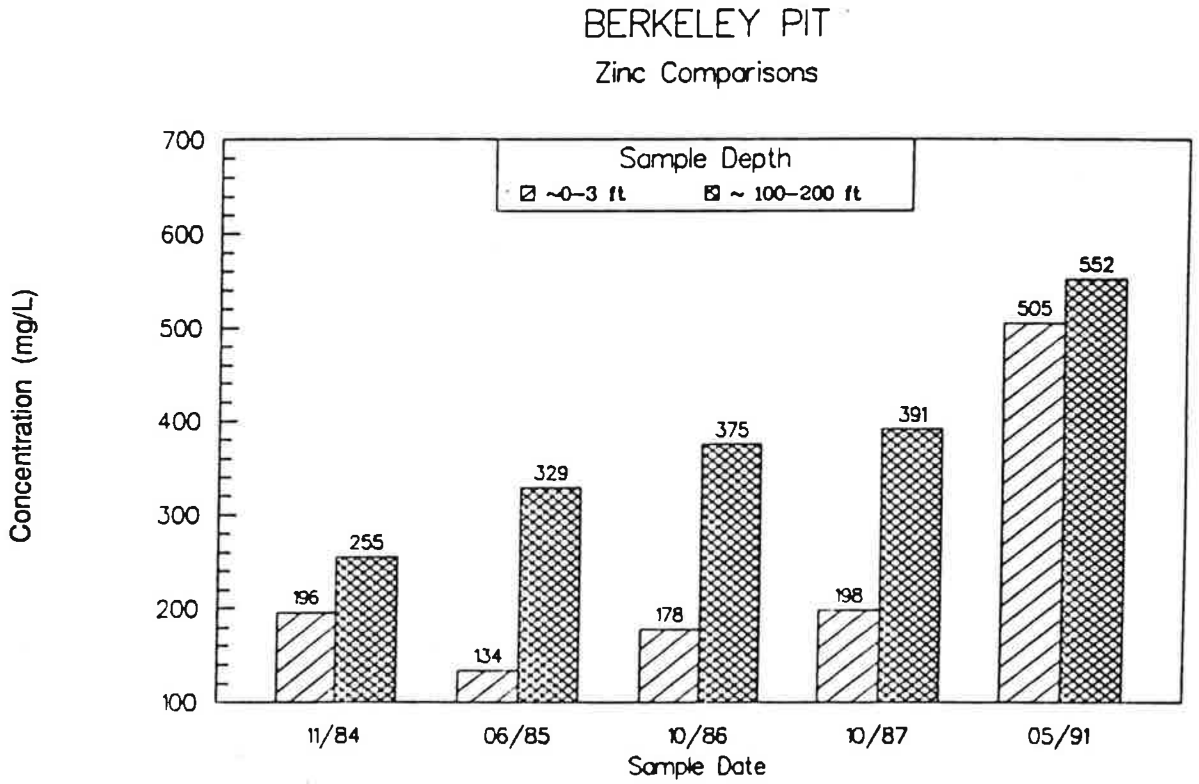
Arsenic Comparisons

SOURCE: DUAIME et al (1993)

FIGURE 6

## BERKELEY PIT COPPER AND ZINC COMPARISONS





SOURCE: DUAIME et al (1993)

*"Initial concentrations of trace metals in the underground mines were considerably above EPA recommended drinking water standards. Over time a gradual decrease in concentrations has occurred as water levels and pH increased in the mine waters. However, concentrations of a number of analytes still exceed standards, with one exception being copper concentrations, which are currently below standards*" (Duaime et al. 1993).

*Treatment Investigations:*

Like all acid mine drainage, the major contribution of the contaminants is due to the reactions associated with oxidation of sulphides. Most of water flows through ore deposits, or mine workings, or waste rock dumps before discharging into the Berkeley pit. Water samples taken from the surrounding area are all acidic and contain heavy metals (Table 2).

The chemistry of the Berkeley pit water was studied by Huang and Liu (1993) of Montana Tech (Department of Metallurgical Engineering) for evaluating treatment options. The chemistry study is based mostly on the reports from Davis and Ashenberg (1989) and water samples taken by MBMG in 1991 and 1992 for this treatability study. (Draft data from MBMG is presented in Tables 3a, b, c and d).

*"In general, the deep water (31 metres below the surface) representing the bulk water has relatively uniform metal concentrations The shallow water (0-10 metres) is more acidic and has much lower metal concentrations, except ferric ion and redox potential which are both higher. Near the surface, atmospheric oxygen causes iron to be oxidized from ferrous to ferric which mostly forms a solid hydroxide, such as FeOOH or Fe(OH)$_3$. As the solid particles form, they tend to adsorb or co-precipitate other metals. Eventually, the particles sink, resulting in low metal concentrations at surface. Winter freezing may also contribute to lowering the surface metal concentrations*" (Huang and Liu 1993).

Table 2

## COMPOSITION OF THE BERKELEY PIT WATER AND WATER SAMPLES FROM SURROUNDING AREA

| | **Alluvial Well** | **Bedrock Wells** | **Kelley Mine (deep)** | **Kelley Mine (surface)** | **Horseshoe Bend** | **Berkeley Pit** |
|---|---|---|---|---|---|---|
| Al | | | 204 | 2.15 | 282.5 | 304.5 |
| As | 0.008 | 0.039 | 17 | 1.42 | <0.24 | 0.43 |
| Cd | 0.226 | 0.002 | | 0.152 | 2.17 | 2.00 |
| Ca | | | 615 | 435 | 477.9 | 525.1 |
| Cu | 4.55 | 0.053 | | 0.169 | 91.15 | 215.1 |
| Fe | 0.096 | 14.6 | 4,484 | 364 | 324.6 | 1,112 |
| K | | | | 31.4 | 8.69 | 19.9 |
| Mg | | | 790 | 152 | 453 | 517 |
| Mn | 0.83 | 3.1 | 384.5 | 64 | 168.6 | 225.5 |
| Ni | | | | 0.14 | -- | 0.91 |
| Na | | | | 38 | 76.62 | 107.7 |
| Pb | | | | 0.005 | <0.13 | <0.13 |
| Zn | 22.96 | 1.57 | 801.5 | 153 | 354.59 | 636.6 |
| $SiO_2$ | | | | 38.8 | 55.09 | 51.24 |
| $Cl^-$ | | | | 50.5 | | -- |
| $F^-$ | | | | 4.7 | | -- |
| Sulphate | | | | 2,598 | | 7,700 |
| pH | 5.5 | 6.28 | 3.3-3.7 | 5.44 | 3.23 | 2.69 |
| Eh, mv | | | 490 | | 691 | 621 |

Source: Huang and Liu, 1993.

Notes:

Provided by Montana Bureau of Mines and Geology:
- Alluvial well water: Average from 3 wells, taken from February to May 91
- Bedrock well water: Average from 3 wells, taken in May 91
- Kelley mine (surface water): about 800 ft. from land surface, taken October 92

Provided by Metanetix
- Kelley mine (deep water): 3,500 ft. from land surface, taken in July 93.

Provided by Montana Tech.
- Horseshoe Bend Water: Surface water flows to the Berkeley pit, taken January 93
- Berkeley pit water: 200 ft. below surface, taken October 92.

## TABLE 3a

BERKELEY PIT PROFILE 03/03/92
THROUGH ICE AT PLATFORM JM/FS

SUBJECT TO REVIEW

Date (MMDDYY) : 030392

| TIME | TEMP deg C | pH | SC mS/cm | TDS | DO %SAT | DO mg/l | REDOX mV | DEPTH meters | BATT volts |
|---|---|---|---|---|---|---|---|---|---|
| 110426 | 1.00 | 2.67 | 2.80 | 1.80 | 70.90 | 8.13 | 511.00 | 0.00 | 12.00 |
| 110507 | 0.93 | 2.72 | 2.80 | 1.80 | 50.10 | 5.76 | 510.00 | 0.00 | 12.00 |
| 110715 | 0.92 | 2.72 | 2.90 | 1.90 | 41.90 | 4.81 | 510.00 | 0.00 | 12.00 |
| 110807 | 0.89 | 2.71 | 3.00 | 1.90 | 40.10 | 4.61 | 510.00 | 0.00 | 12.00 |
| 110947 | 1.51 | 2.32 | 7.40 | 4.70 | 20.50 | 2.28 | 516.00 | 0.90 | 12.00 |
| 111047 | 2.29 | 2.28 | 8.10 | 5.20 | 5.50 | 0.59 | 512.00 | 3.60 | 12.00 |
| 111123 | 4.83 | 2.25 | 8.40 | 5.40 | 4.60 | 0.46 | 467.00 | 6.40 | 12.00 |
| 111157 | 5.82 | 2.26 | 8.70 | 5.50 | 4.10 | 0.40 | 454.00 | 8.60 | 12.00 |
| 111215 | 5.80 | 2.26 | 8.60 | 5.50 | 3.80 | 0.38 | 454.00 | 8.60 | 12.00 |
| 111256 | 6.56 | 2.31 | 8.70 | 5.60 | 3.50 | 0.34 | 450.00 | 10.80 | 12.00 |
| 111308 | 6.49 | 2.33 | 8.70 | 5.60 | 3.40 | 0.33 | 448.00 | 10.80 | 12.00 |
| 111345 | 6.74 | 2.30 | 8.80 | 5.60 | 3.30 | 0.32 | 450.00 | 13.00 | 12.00 |
| 111418 | 6.84 | 2.30 | 8.80 | 5.60 | 3.40 | 0.32 | 450.00 | 15.40 | 12.00 |
| 111459 | 6.86 | 2.30 | 8.80 | 5.60 | 3.50 | 0.33 | 450.00 | 18.10 | 12.00 |
| 111533 | 6.86 | 2.29 | 8.80 | 5.70 | 3.50 | 0.33 | 451.00 | 20.80 | 12.00 |
| 111603 | 6.86 | 2.31 | 8.80 | 5.70 | 3.40 | 0.33 | 450.00 | 23.10 | 12.00 |
| 111627 | 6.87 | 2.28 | 8.80 | 5.70 | 3.40 | 0.32 | 452.00 | 26.60 | 12.00 |
| 111718 | 6.89 | 2.31 | 8.80 | 5.60 | 3.00 | 0.29 | 450.00 | 30.10 | 12.00 |
| 111754 | 6.87 | 2.30 | 8.80 | 5.70 | 2.80 | 0.27 | 451.00 | 33.30 | 12.00 |
| 111832 | 6.86 | 2.32 | 8.90 | 5.70 | 2.80 | 0.27 | 449.00 | 36.10 | 12.00 |
| 111910 | 6.85 | 2.30 | 8.90 | 5.70 | 2.80 | 0.27 | 451.00 | 39.10 | 12.00 |
| 111940 | 6.86 | 2.31 | 8.90 | 5.70 | 2.70 | 0.26 | 450.00 | 42.20 | 12.00 |
| 112021 | 6.92 | 2.31 | 8.90 | 5.70 | 2.40 | 0.23 | 449.00 | 46.00 | 12.00 |
| 112111 | 6.91 | 2.31 | 8.90 | 5.70 | 2.40 | 0.23 | 450.00 | 49.00 | 12.00 |
| 112156 | 6.91 | 2.32 | 8.90 | 5.70 | 2.20 | 0.21 | 450.00 | 51.50 | 12.00 |
| 112231 | 6.91 | 2.30 | 8.90 | 5.70 | 2.20 | 0.21 | 451.00 | 53.90 | 12.00 |
| 112319 | 6.91 | 2.32 | 8.90 | 5.70 | 2.10 | 0.20 | 449.00 | 56.20 | 12.00 |
| 112350 | 6.91 | 2.35 | 8.90 | 5.70 | 1.90 | 0.18 | 447.00 | 58.10 | 12.00 |
| 112435 | 6.91 | 2.35 | 8.90 | 5.70 | 1.90 | 0.18 | 447.00 | 59.60 | 12.00 |
| 112508 | 6.91 | 2.35 | 8.90 | 5.70 | 1.90 | 0.18 | 447.00 | 61.30 | 12.00 |
| 112548 | 6.92 | 2.35 | 8.90 | 5.70 | 1.70 | 0.17 | 447.00 | 64.10 | 12.00 |
| 112623 | 6.92 | 2.35 | 8.90 | 5.70 | 1.80 | 0.17 | 447.00 | 64.10 | 12.00 |
| 112720 | 6.91 | 2.36 | 8.90 | 5.70 | 1.70 | 0.17 | 447.00 | 66.10 | 12.00 |
| 112808 | 6.91 | 2.36 | 8.90 | 5.70 | 1.70 | 0.17 | 447.00 | 68.50 | 12.00 |
| 112849 | 6.91 | 2.35 | 8.90 | 5.70 | 1.70 | 0.17 | 447.00 | 71.50 | 12.00 |
| 112923 | 6.91 | 2.36 | 8.90 | 5.70 | 1.70 | 0.16 | 447.00 | 73.80 | 12.00 |
| 112959 | 6.92 | 2.35 | 8.90 | 5.70 | 1.60 | 0.15 | 448.00 | 76.40 | 12.00 |
| 113056 | 6.92 | 2.32 | 8.90 | 5.70 | 1.40 | 0.14 | 450.00 | 78.70 | 12.00 |
| 113141 | 6.92 | 2.38 | 8.90 | 5.70 | 1.40 | 0.14 | 446.00 | 79.30 | 12.00 |
| 113154 | 6.92 | 2.37 | 8.90 | 5.70 | 1.40 | 0.14 | 447.00 | 79.30 | 12.00 |
| 113239 | 6.92 | 2.37 | 8.90 | 5.70 | 1.40 | 0.13 | 446.00 | 78.50 | 12.00 |
| 113316 | 6.92 | 2.37 | 8.90 | 5.70 | 1.40 | 0.13 | 446.00 | 76.70 | 12.00 |
| 113353 | 6.92 | 2.36 | 8.90 | 5.70 | 1.30 | 0.12 | 447.00 | 74.80 | 12.00 |
| 113424 | 6.92 | 2.38 | 8.90 | 5.70 | 1.20 | 0.12 | 446.00 | 72.60 | 12.00 |
| 113456 | 6.91 | 2.37 | 8.90 | 5.70 | 1.30 | 0.12 | 447.00 | 70.00 | 12.00 |
| 113527 | 6.91 | 2.37 | 8.90 | 5.70 | 1.30 | 0.12 | 446.00 | 66.80 | 12.00 |
| 113606 | 6.91 | 2.36 | 8.90 | 5.70 | 1.20 | 0.11 | 447.00 | 63.70 | 12.00 |
| 113649 | 6.91 | 2.37 | 8.90 | 5.70 | 1.10 | 0.11 | 446.00 | 60.50 | 12.00 |
| 113731 | 6.91 | 2.37 | 8.90 | 5.70 | 1.20 | 0.11 | 446.00 | 57.10 | 12.00 |
| 113815 | 6.91 | 2.37 | 8.90 | 5.70 | 1.00 | 0.10 | 447.00 | 53.50 | 12.00 |
| 113918 | 6.89 | 2.36 | 8.90 | 5.70 | 1.10 | 0.11 | 447.00 | 49.20 | 12.00 |
| 113955 | 6.91 | 2.36 | 8.90 | 5.70 | 1.10 | 0.11 | 447.00 | 46.30 | 12.00 |
| 114059 | 6.87 | 2.36 | 8.90 | 5.70 | 1.00 | 0.10 | 447.00 | 43.30 | 12.00 |
| 114139 | 6.89 | 2.36 | 8.90 | 5.70 | 1.10 | 0.11 | 448.00 | 43.30 | 12.00 |
| 114212 | 6.86 | 2.37 | 8.90 | 5.70 | 1.10 | 0.10 | 447.00 | 40.20 | 12.00 |
| 114249 | 6.86 | 2.36 | 8.90 | 5.70 | 0.90 | 0.09 | 447.00 | 37.20 | 12.00 |
| 114351 | 6.87 | 2.35 | 8.90 | 5.70 | 0.80 | 0.08 | 449.00 | 34.10 | 12.00 |
| 114425 | 6.87 | 2.37 | 8.90 | 5.70 | 0.90 | 0.08 | 447.00 | 30.80 | 12.00 |
| 114521 | 6.88 | 2.36 | 8.90 | 5.70 | 0.90 | 0.09 | 447.00 | 28.30 | 12.00 |
| 114641 | 6.87 | 2.36 | 8.90 | 5.70 | 0.90 | 0.09 | 448.00 | 25.80 | 12.00 |
| 114751 | 6.86 | 2.36 | 8.90 | 5.70 | 0.80 | 0.08 | 448.00 | 23.40 | 12.00 |
| 114850 | 6.86 | 2.36 | 8.90 | 5.70 | 0.80 | 0.08 | 447.00 | 19.80 | 12.00 |
| 114922 | 6.87 | 2.36 | 8.90 | 5.70 | 0.90 | 0.09 | 448.00 | 19.80 | 12.00 |
| 115015 | 6.86 | 2.36 | 8.90 | 5.70 | 0.90 | 0.09 | 448.00 | 17.10 | 12.00 |
| 115049 | 6.83 | 2.35 | 8.90 | 5.70 | 0.80 | 0.08 | 448.00 | 15.40 | 12.00 |
| 115115 | 6.72 | 2.37 | 8.90 | 5.70 | 0.80 | 0.08 | 448.00 | 12.70 | 12.00 |
| 115150 | 6.12 | 2.34 | 8.80 | 5.70 | 0.70 | 0.07 | 450.00 | 9.00 | 12.00 |
| 115228 | 4.99 | 2.33 | 8.80 | 5.60 | 0.80 | 0.08 | 464.00 | 6.10 | 12.00 |
| 115315 | 2.84 | 2.36 | 8.40 | 5.30 | 0.60 | 0.07 | 505.00 | 3.20 | 12.00 |
| 115432 | 0.65 | 2.58 | 4.90 | 3.10 | 16.80 | 1.92 | 509.00 | 0.20 | 12.00 |

SUBJECT TO REVIEW

# TABLE 3b

SUBJECT TO REVIEW

DRAFT

**BERKELEY PIT PROFILE**
**MBMG**

**Date (MMDDYY) : 090591**

| TIME | TEMP deg C | pH units | SC mS/cm | TDS Kmg/l | DO %Sat | DO mg/l | REDOX mv | DEPTH meters | BATT |
|---|---|---|---|---|---|---|---|---|---|
| 143423 | 23.91 | 2.46 | 7.24 | 4.63 | 52.6 | 3.52 | 541 | .2 | 11.8 |
| 143726 | 23.71 | 2.42 | 7.31 | 4.68 | 60.8 | 4.09 | 561 | .2 | 11.8 |
| 143805 | 23.01 | 2.41 | 7.37 | 4.72 | 63.7 | 4.34 | 563 | .3 | 11.8 |
| 143827 | 21.96 | 2.41 | 7.42 | 4.75 | 57.6 | 4 | 566 | .3 | 11.8 |
| 145008 | 19.85 | 2.34 | 7.48 | 4.79 | 49.9 | 3.61 | 565 | .5 | 11.8 |
| 145058 | 17.14 | 2.36 | 7.61 | 4.87 | 41.2 | 3.15 | 561 | 2.4 | 11.8 |
| 145138 | 16.16 | 2.37 | 7.63 | 4.88 | 14.6 | 1.14 | 440 | 4 | 11.8 |
| 145215 | 10.36 | 2.45 | 8.14 | 5.21 | 8.3 | .74 | 384 | 6 | 11.8 |
| 145304 | 7.66 | 2.44 | 8.22 | 5.26 | 6.3 | .59 | 377 | 7.8 | 11.8 |
| 145348 | 6.91 | 2.43 | 8.15 | 5.22 | 6.2 | .6 | 377 | 9.5 | 11.8 |
| 145430 | 6.63 | 2.42 | 8.03 | 5.14 | 6.2 | .6 | 377 | 11.3 | 11.8 |
| 145501 | 6.53 | 2.4 | 8.04 | 5.15 | 6.5 | .63 | 377 | 13.2 | 11.8 |
| 145542 | 6.65 | 2.38 | 8.03 | 5.14 | 6 | .58 | 378 | 15.1 | 11.8 |
| 145622 | 6.76 | 2.37 | 8.03 | 5.14 | 6 | .57 | 378 | 16.9 | 11.8 |
| 145650 | 6.62 | 2.36 | 8.05 | 5.15 | 5.8 | .56 | 378 | 18.3 | 11.8 |
| 145720 | 6.66 | 2.35 | 8.04 | 5.15 | 5.8 | .56 | 378 | 20.4 | 11.8 |
| 145733 | 6.64 | 2.35 | 8.06 | 5.16 | 5.5 | .53 | 378 | 20.4 | 11.8 |
| 145809 | 6.57 | 2.34 | 8.11 | 5.19 | 5.7 | .55 | 378 | 22.2 | 11.8 |
| 145842 | 6.58 | 2.33 | 8.06 | 5.16 | 5.4 | .53 | 379 | 24 | 11.8 |
| 145922 | 6.6 | 2.33 | 8.05 | 5.15 | 5.4 | .52 | 378 | 25.7 | 11.8 |
| 145947 | 6.52 | 2.33 | 8.09 | 5.18 | 5.5 | .53 | 378 | 27.1 | 11.8 |
| 150051 | 6.49 | 2.32 | 8.11 | 5.19 | 4.7 | .46 | 379 | 29 | 11.8 |
| 150123 | 6.5 | 2.32 | 8.1 | 5.18 | 4.9 | .47 | 379 | 30.8 | 11.8 |
| 150159 | 6.51 | 2.32 | 8.11 | 5.19 | 4.8 | .46 | 379 | 32.3 | 11.8 |
| 150252 | 6.52 | 2.31 | 8.11 | 5.19 | 4.5 | .44 | 379 | 32.7 | 11.8 |
| 150320 | 6.56 | 2.32 | 8.13 | 5.2 | 4.1 | .4 | 379 | 32.7 | 11.8 |
| 150442 | 6.39 | 2.31 | 8.14 | 5.21 | 4.8 | .47 | 379 | 31.7 | 11.8 |
| 150503 | 6.38 | 2.31 | 8.09 | 5.18 | 5.2 | .5 | 379 | 30 | 11.8 |
| 150534 | 6.37 | 2.31 | 8.14 | 5.21 | 5.2 | .51 | 379 | 28.2 | 11.8 |
| 150604 | 6.34 | 2.3 | 8.15 | 5.21 | 5.6 | .54 | 379 | 25.2 | 11.8 |
| 150628 | 6.34 | 2.3 | 8.11 | 5.19 | 5.3 | .51 | 379 | 22.1 | 11.8 |
| 150654 | 6.29 | 2.3 | 8.13 | 5.2 | 5.9 | .58 | 379 | 19.5 | 11.8 |
| 150718 | 6.29 | 2.3 | 8.12 | 5.2 | 5.3 | .52 | 379 | 17.2 | 11.8 |
| 150737 | 6.3 | 2.3 | 8.08 | 5.17 | 4.6 | .45 | 379 | 17.2 | 11.8 |
| 150811 | 6.24 | 2.3 | 8.1 | 5.18 | 5.1 | .5 | 379 | 15 | 11.8 |
| 150839 | 6.15 | 2.3 | 8.1 | 5.18 | 5.8 | .57 | 380 | 12.6 | 11.8 |
| 150906 | 6.24 | 2.3 | 8.08 | 5.17 | 5.3 | .52 | 381 | 10.5 | 11.8 |
| 150934 | 7.14 | 2.27 | 8.07 | 5.16 | 5.5 | .53 | 383 | 8.4 | 11.8 |
| 151046 | 12.12 | 2.25 | 7.76 | 4.97 | 5.3 | .45 | 404 | 5.9 | 11.8 |
| 151129 | 16.41 | 2.21 | 7.48 | 4.78 | 27.4 | 2.13 | 550 | 3.4 | 11.8 |
| 151202 | 17.03 | 2.23 | 7.54 | 4.82 | 43.3 | 3.32 | 579 | 1.5 | 11.8 |
| 151228 | 23.54 | 2.27 | 7.49 | 4.79 | 49.7 | 3.35 | 569 | 1 | 11.8 |

151228 23.54 2.27 7.49 4.79 49.7 3.35 569 1.0 11.8
Recovery finished at 090691 084611

DRAFT

## TABLE 3c

BERKELY PIT HYDROLAB PROFILE
5/23/91 BY JM/PS
MONTANA BUREAU OF MINES AND GEOLOGY

SUBJECT TO REVIEW

Date (MMDDYY) : 052391

| Time HHMMS | Temp degC | pH units | SpCond mS/cm | Salin ppt | DO %Sat | DO mg/l | Redox mV | Depth meters | Batt volts | Depth bel Surface (meters) |
|---|---|---|---|---|---|---|---|---|---|---|
| 104353 | 14.32 | 2.58 | 7.17 | 4.00 | 84.30 | 6.88 | 567.00 | .80 | 12.10 | -.80 |
| 104421 | 13.08 | 2.56 | 7.13 | 4.00 | 75.00 | 6.29 | 574.00 | 2.00 | 12.00 | -2.00 |
| 104444 | 12.26 | 2.58 | 7.12 | 4.00 | 55.00 | 4.69 | 581.00 | 2.70 | 12.10 | -2.70 |
| 104514 | 9.05 | 2.62 | 7.62 | 4.30 | 12.20 | 1.12 | 461.00 | 3.20 | 12.00 | -3.20 |
| 104624 | 8.35 | 2.62 | 7.67 | 4.30 | 3.50 | .33 | 446.00 | 4.20 | 12.00 | -4.20 |
| 104649 | 6.77 | 2.60 | 8.04 | 4.50 | 2.50 | .24 | 425.00 | 5.60 | 12.10 | -5.60 |
| 104711 | 6.02 | 2.61 | 8.14 | 4.60 | 2.00 | .20 | 419.00 | 6.90 | 12.00 | -6.90 |
| 104744 | 6.02 | 2.64 | 8.13 | 4.50 | 1.60 | .16 | 415.00 | 8.10 | 12.10 | -8.10 |
| 104808 | 6.00 | 2.64 | 8.13 | 4.50 | 1.50 | .15 | 415.00 | 9.10 | 12.00 | -9.10 |
| 104830 | 5.88 | 2.62 | 8.17 | 4.60 | 1.60 | .16 | 415.00 | 10.70 | 12.00 | -10.70 |
| 104852 | 5.91 | 2.62 | 8.15 | 4.60 | 1.50 | .15 | 415.00 | 12.10 | 12.00 | -12.10 |
| 104913 | 5.90 | 2.61 | 8.09 | 4.50 | 1.60 | .16 | 416.00 | 13.70 | 12.00 | -13.70 |
| 104952 | 5.96 | 2.61 | 8.18 | 4.60 | 1.80 | .18 | 415.00 | 15.30 | 12.10 | -15.30 |
| 105020 | 5.94 | 2.61 | 8.17 | 4.60 | 1.80 | .17 | 415.00 | 16.70 | 12.00 | -16.70 |
| 105046 | 5.91 | 2.60 | 8.13 | 4.60 | 1.60 | .16 | 416.00 | 18.40 | 12.10 | -18.40 |
| 105118 | 5.94 | 2.60 | 8.14 | 4.60 | 1.60 | .16 | 416.00 | 19.60 | 12.00 | -19.60 |
| 105141 | 5.93 | 2.60 | 8.16 | 4.60 | 1.60 | .15 | 416.00 | 21.10 | 12.00 | -21.10 |
| 105215 | 5.92 | 2.60 | 8.16 | 4.60 | 1.40 | .14 | 415.00 | 23.00 | 12.00 | -23.00 |
| 105308 | 6.02 | 2.60 | 8.18 | 4.60 | 1.40 | .14 | 415.00 | 24.60 | 12.00 | -24.60 |
| 105354 | 5.89 | 2.60 | 8.19 | 4.60 | 1.20 | .12 | 415.00 | 26.30 | 12.00 | -26.30 |
| 105420 | 5.85 | 2.59 | 8.14 | 4.60 | 1.40 | .14 | 416.00 | 28.00 | 12.10 | -28.00 |
| 105446 | 5.86 | 2.59 | 8.25 | 4.60 | 1.20 | .12 | 416.00 | 29.60 | 12.00 | -29.60 |
| 105523 | 5.87 | 2.59 | 8.22 | 4.60 | 1.10 | .11 | 416.00 | 31.20 | 12.10 | -31.20 |
| 105553 | 5.86 | 2.59 | 8.20 | 4.60 | 1.10 | .11 | 416.00 | 32.90 | 12.10 | -32.90 |
| 105618 | 5.86 | 2.59 | 8.18 | 4.60 | 1.10 | .11 | 416.00 | 34.70 | 12.10 | -34.70 |
| 105652 | 5.84 | 2.59 | 8.19 | 4.60 | 1.10 | .11 | 416.00 | 36.40 | 12.10 | -36.40 |
| 105725 | 5.86 | 2.59 | 8.25 | 4.60 | 1.00 | .10 | 415.00 | 38.20 | 12.10 | -38.20 |
| 105748 | 5.83 | 2.59 | 8.27 | 4.60 | 1.10 | .11 | 416.00 | 39.50 | 12.10 | -39.50 |
| 105847 | 5.87 | 2.59 | 8.20 | 4.60 | .80 | .08 | 416.00 | 41.00 | 12.00 | -41.00 |
| 105925 | 5.85 | 2.59 | 8.23 | 4.60 | .90 | .09 | 416.00 | 41.10 | 12.00 | -41.10 |
| 110039 | 5.88 | 2.59 | 8.16 | 4.60 | .90 | .09 | 415.00 | 42.50 | 12.10 | -42.50 |
| 110110 | 5.79 | 2.59 | 8.24 | 4.60 | .90 | .09 | 416.00 | 44.10 | 12.10 | -44.10 |
| 110146 | 5.79 | 2.59 | 8.24 | 4.60 | .80 | .08 | 416.00 | 46.70 | 12.10 | -46.70 |
| 110223 | 5.81 | 2.59 | 8.27 | 4.60 | .70 | .07 | 416.00 | 48.00 | 12.00 | -48.00 |
| 110229 | 5.82 | 2.59 | 8.19 | 4.60 | .70 | .07 | 416.00 | 48.00 | 12.10 | -48.00 |
| 110308 | 5.81 | 2.59 | 8.32 | 4.70 | .80 | .07 | 416.00 | 49.40 | 12.00 | -49.40 |
| 110341 | 5.76 | 2.59 | 8.23 | 4.60 | .80 | .08 | 416.00 | 51.30 | 12.00 | -51.30 |
| 110425 | 5.78 | 2.59 | 8.25 | 4.60 | .80 | .08 | 416.00 | 52.80 | 12.10 | -52.80 |
| 110456 | 5.76 | 2.58 | 8.26 | 4.60 | .80 | .08 | 416.00 | 54.30 | 12.10 | -54.30 |
| 110512 | 5.76 | 2.59 | 8.26 | 4.60 | .80 | .08 | 416.00 | 54.30 | 12.00 | -54.30 |
| 110553 | 5.76 | 2.59 | 8.27 | 4.60 | .70 | .07 | 416.00 | 56.00 | 12.00 | -56.00 |
| 110629 | 5.75 | 2.59 | 8.35 | 4.70 | .80 | .08 | 416.00 | 57.40 | 12.10 | -57.40 |
| 110702 | 5.74 | 2.59 | 8.20 | 4.60 | .70 | .07 | 416.00 | 59.10 | 12.10 | -59.10 |
| 110737 | 5.77 | 2.59 | 8.31 | 4.70 | .70 | .07 | 416.00 | 61.10 | 12.10 | -61.10 |
| 110805 | 5.78 | 2.59 | 8.26 | 4.60 | .60 | .06 | 416.00 | 62.80 | 12.00 | -62.80 |
| 110834 | 5.78 | 2.59 | 8.25 | 4.60 | .70 | .07 | 416.00 | 64.80 | 12.10 | -64.80 |
| 110923 | 5.83 | 2.59 | 8.32 | 4.70 | .70 | .07 | 416.00 | 67.10 | 12.00 | -67.10 |
| 110952 | 5.80 | 2.59 | 8.27 | 4.60 | .70 | .07 | 416.00 | 68.80 | 12.10 | -68.80 |
| 111035 | 5.84 | 2.59 | 8.29 | 4.60 | .70 | .07 | 416.00 | 70.70 | 12.10 | -70.70 |
| 111119 | 5.85 | 2.59 | 8.28 | 4.60 | .60 | .06 | 416.00 | 72.30 | 12.10 | -72.30 |
| 111202 | 5.87 | 2.59 | 8.31 | 4.70 | .70 | .07 | 416.00 | 73.80 | 12.10 | -73.80 |
| 111242 | 5.87 | 2.59 | 8.29 | 4.60 | .60 | .06 | 416.00 | 75.60 | 12.10 | -75.60 |
| 111245 | 5.87 | 2.59 | 8.26 | 4.60 | .60 | .06 | 416.00 | 75.60 | 12.10 | -75.60 |
| 111318 | 5.89 | 2.59 | 8.34 | 4.70 | .60 | .06 | 416.00 | 77.30 | 12.10 | -77.30 |
| 111408 | 5.89 | 2.59 | 8.31 | 4.70 | .70 | .07 | 416.00 | 79.60 | 12.00 | -79.60 |
| 111443 | 5.89 | 2.59 | 8.30 | 4.70 | .60 | .06 | 416.00 | 81.50 | 12.10 | -81.50 |
| 111526 | 5.90 | 2.59 | 8.34 | 4.70 | .60 | .06 | 416.00 | 83.20 | 12.10 | -83.20 |
| 111646 | 5.95 | 2.48 | 8.24 | 4.60 | .60 | .06 | 422.00 | 84.50 | 12.10 | -84.50 |
| 111730 | 5.97 | 2.58 | 8.27 | 4.60 | .70 | .07 | 416.00 | 84.50 | 12.10 | -84.50 |
| 111738 | 5.97 | 2.58 | 8.31 | 4.70 | .60 | .06 | 416.00 | 84.40 | 12.10 | -84.40 |
| 111749 | 5.97 | 2.59 | 8.32 | 4.70 | .50 | .05 | 415.00 | 84.50 | 12.10 | -84.50 |
| 111811 | 5.97 | 2.58 | 8.34 | 4.70 | .50 | .05 | 416.00 | 84.50 | 12.10 | -84.50 |

## TABLE 3d

**BERKELY PIT HYDROLAB PROFILE**
**5/21/91 BY CANNONIE**
**MONTANA BUREAU OF MINES AND GEOLOGY**

SUBJECT TO REVIEW

DRAFT

**Date (MMDDYY) : 052191**

| Time HHMMSS | Temp degC | pH units | SpCond mS/cm | Salin ppt | DO %Sat | DO mg/l | Redox mV | Depth meters | Batt volts |
|---|---|---|---|---|---|---|---|---|---|
| 114142 | 5.84 | 3.18 | 8.07 | 4.50 | 2.50 | .29 | 417.00 | 16.00 | 12.20 |
| 114203 | 5.78 | 3.13 | 8.09 | 4.50 | 2.10 | .25 | 418.00 | 15.70 | 12.20 |
| 114847 | 5.72 | 3.23 | 8.13 | 4.60 | 3.90 | .45 | 418.00 | 30.90 | 12.20 |
| 114906 | 5.70 | 3.19 | 8.11 | 4.50 | 3.10 | .35 | 418.00 | 30.80 | 12.20 |
| 115325 | 5.79 | 3.64 | 8.15 | 4.60 | 6.20 | .71 | 418.00 | 46.60 | 12.20 |
| 115344 | 5.80 | 3.55 | 8.15 | 4.60 | 4.30 | .50 | 418.00 | 46.40 | 12.20 |
| 115722 | 5.85 | 4.30 | 8.14 | 4.60 | 5.70 | .65 | 418.00 | 61.70 | 12.20 |
| 115816 | 5.84 | 3.85 | 8.18 | 4.60 | 2.90 | .34 | 418.00 | 61.50 | 12.20 |
| 120400 | 5.89 | 3.62 | 8.16 | 4.60 | 3.80 | .43 | 418.00 | 77.50 | 12.20 |
| 120420 | 5.89 | 3.54 | 8.18 | 4.60 | 3.30 | .38 | 417.00 | 77.70 | 12.20 |
| 120745 | 5.99 | 3.99 | 8.22 | 4.60 | 4.80 | .55 | 417.00 | 92.10 | 12.20 |
| 120805 | 5.98 | 3.85 | 8.26 | 4.60 | 3.50 | .40 | 417.00 | 92.10 | 12.20 |
| 121550 | 6.08 | 3.19 | 8.28 | 4.60 | 6.50 | .75 | 417.00 | 107.30 | 12.20 |
| 121609 | 6.08 | 3.15 | 8.22 | 4.60 | 5.00 | .56 | 416.00 | 107.40 | 12.20 |
| 122230 | 6.08 | 3.26 | 8.19 | 4.60 | 2.60 | .29 | 416.00 | ###.# | 12.20 |
| 125247 | 6.07 | 2.69 | 8.13 | 4.60 | .50 | .06 | 417.00 | ###.# | 12.20 |
| 130035 | 6.08 | 2.68 | 8.21 | 4.60 | .70 | .08 | 416.00 | ###.# | 12.20 |
| 132404 | 6.07 | 2.67 | 8.27 | 4.60 | .20 | .03 | 417.00 | ###.# | 12.20 |
| 134043 | 6.07 | 2.67 | 8.32 | 4.70 | .50 | .05 | 417.00 | ###.# | 12.20 |
| 134403 | 6.08 | 2.67 | 8.29 | 4.60 | .50 | .06 | 417.00 | ###.# | 12.20 |
| 134638 | 6.07 | 2.67 | 8.39 | 4.70 | .30 | .03 | 417.00 | ###.# | 12.20 |
| 134753 | 6.08 | 2.67 | 8.24 | 4.60 | .30 | .03 | 416.00 | ###.# | 12.20 |
| 134950 | 6.08 | 2.67 | 8.27 | 4.60 | .40 | .05 | 417.00 | ###.# | 12.20 |
| 135716 | 6.08 | 2.67 | 8.25 | 4.60 | .60 | .07 | 417.00 | ###.# | 12.20 |
| 140527 | 6.08 | 2.67 | 8.28 | 4.60 | .40 | .04 | 416.00 | ###.# | 12.20 |
| 141134 | 6.08 | 2.67 | 8.33 | 4.70 | .30 | .04 | 417.00 | ###.# | 12.20 |
| 142216 | 6.08 | 2.67 | 8.33 | 4.70 | .50 | .06 | 417.00 | ###.# | 12.20 |
| 142527 | 6.08 | 2.67 | 8.33 | 4.70 | .50 | .06 | 417.00 | ###.# | 12.20 |
| 143133 | 6.08 | 2.67 | 8.33 | 4.70 | .60 | .06 | 417.00 | ###.# | 12.20 |
| 143513 | 6.08 | 2.67 | 8.32 | 4.70 | .50 | .05 | 416.00 | ###.# | 12.20 |
| 144251 | 6.08 | 2.67 | 8.32 | 4.70 | .60 | .07 | 417.00 | ###.# | 12.20 |
| 154045 | 12.51 | 2.49 | 7.05 | 3.90 | 69.70 | 6.85 | 605.00 | 1.30 | 12.00 |
| 154456 | 13.02 | 2.47 | 7.07 | 3.90 | 78.80 | 7.66 | 612.00 | 1.40 | 11.90 |
| 155104 | 13.03 | 2.47 | 7.08 | 3.90 | 78.70 | 7.65 | 611.00 | 1.50 | 11.90 |
| 155544 | 12.97 | 2.46 | 7.08 | 3.90 | 79.30 | 7.71 | 615.00 | 1.50 | 11.80 |
| 160344 | 12.94 | 2.49 | 7.09 | 3.90 | 77.20 | 7.51 | 621.00 | 1.50 | 12.00 |
| 160548 | 12.85 | 2.50 | 7.09 | 3.90 | 75.00 | 7.32 | 623.00 | 1.50 | 12.00 |
| 162706 | 12.44 | 2.52 | 7.10 | 3.90 | 67.10 | 6.60 | 622.00 | 1.60 | 12.10 |
| 163413 | 12.60 | 2.48 | 7.08 | 3.90 | 72.40 | 7.10 | 626.00 | 1.50 | 12.00 |
| 164242 | 12.79 | 2.50 | 7.08 | 3.90 | 67.90 | 6.63 | 624.00 | 1.60 | 11.80 |
| 165057 | 13.43 | 2.49 | 7.07 | 3.90 | 79.10 | 7.62 | 609.00 | 1.60 | 12.00 |
| 165510 | 13.84 | 2.48 | 7.07 | 3.90 | 81.20 | 7.75 | 607.00 | 1.50 | 11.80 |
| 170022 | 13.74 | 2.48 | 7.07 | 3.90 | 79.00 | 7.56 | 607.00 | 1.60 | 11.90 |
| 170144 | 13.67 | 2.48 | 7.07 | 3.90 | 80.10 | 7.67 | 605.00 | 1.40 | 11.80 |
| 170542 | 13.56 | 2.48 | 7.07 | 3.90 | 77.60 | 7.45 | 602.00 | 1.60 | 11.80 |
| 170946 | 13.57 | 2.48 | 7.07 | 3.90 | 79.20 | 7.60 | 603.00 | 1.40 | 12.00 |

DRAFT

SUBJECT TO REVIEW

The Montana Bureau of Mines and Geology, Montana Tech, began their depth-sequential sampling program in 1987. This field investigation is reported by Sonderegger et al. (1987). The sampling was conducted for a nonprofit organization (The Headwaters Research Institute) to evaluate whether metals could be recovered from pit waters. This program is briefly described below as the sampling constraints (e.g. access to the pit, cost, etc.) may be of interest to investigators studying flooded open pit mines.

*"The sampling crew, equipment, and a double-hulled fiberglass boat were airlifted into the Berkeley pit by helicopter. Samples were obtained utilizing a battery-driven, peristaltic pump with an inline filter on the discharge end of the tubing. They tried to locate the pit's deepest point using a large sash weight attached to a nylon rope. Although the calculated depth of water was 525 feet (160 metres), they could not locate any point deeper than about 400 feet (122 metres) in 1987. Filling of the pit by mass-wasting of its sides was observed while sampling. Polyvinyl tubing was taped to the rope starting 10 feet (3 metres) above the bottom of the weight. Samples were collected in 110-feet (34-metres) increments starting at a depth of 0.5 foot (0.2 metre). Two additional samples, filtered and unfiltered, were collected from a depth of 390 feet (119 metres), in order to evaluate whether suspended sediment existed above the pit bottom"* (Sonderegger et al. 1987).

The analytical results for these samples are presented in Table 4. Other sampling results (conducted by the Montana Bureau of Mines and Geology and Department of State Lands) using a helicopter and bailer are presented in Table 5 for comparison. The pH, conductivity and redox potential were not measured as these instruments could not be carried into the pit. A pH of 2.5 to 3 was estimated from measured concentrations. The oxidation reduction potential (pe) of the water was calculated utilizing the ratio of arsenic (III) to arsenic (V) [total arsenic less arsenic (III)]. Sonderegger et al. (1987) explained that the data showed that the water in the pit is fairly oxidized and that the metal concentrations in the water will be limited mainly by the pH of the pit water. As a result of their study, Sonderegger et al. (1987) concluded that the proposed discharge of the high pH, coarse concentrator waste stream into the pit may lead to reduced metal concentrations. The alkaline concentrator discharge stream (water and tailings) from the mine had occasionally been directed into the pit and was being discharged during their sampling program.

## TABLE 4

## BERKELEY PIT SAMPLES, OCTOBER 17, 1986 (mg/L)

| Depth (ft.) | 0.5 | 110 | 220 | 330 | 390 | 390* |
|---|---|---|---|---|---|---|
| Temp (°C) | --- | --- | --- | --- | --- | --- |
| pH | --- | --- | --- | --- | --- | --- |
| Ca | 425 | 457 | 450 | 457 | 456 | 455 |
| Mg | 149 | 250 | 291 | 310 | 310 | 313 |
| Na | 59.3 | 64.7 | 65.8 | 66.5 | 65.4 | 65.8 |
| K | 12.9 | 19.5 | 24.3 | 26.2 | 26.2 | 27.8 |
| $SiO_2$ | 78.9 | 104 | 108 | 109 | 111 | 110 |
| Fe | 177 | 685 | 918 | 1,010 | 1,020 | 1,060 |
| Mn | 64 | 122 | 144 | 154 | 156 | 160 |
| Al | 91.6 | 171 | 192 | 201 | 203 | 209 |
| Ag | 0.019 | 0.032 | 0.037 | 0.043 | 0.043 | 0.043 |
| B | 0.15 | 0.25 | 0.33 | 0.39 | 0.40 | 0.28 |
| Cd | 1.0 | 1.62 | 1.74 | 1.80 | 1.69 | 1.70 |
| Cu | 114 | 196 | 204 | 214 | 213 | 209 |
| Li | 0.16 | 0.23 | 0.25 | 0.27 | 0.26 | 0.26 |
| Mo | 0.14 | 0.21 | 0.23 | 0.28 | 0.25 | 0.26 |
| Ni | 0.46 | 0.79 | 0.91 | 0.97 | 0.95 | 0.99 |
| $PO_4$ as P | <.1 | 0.5 | 0.5 | 0.5 | 1.1 | 1.4 |
| Sr | 0.86 | 1.03 | 1.02 | 1.02 | 1.00 | 0.99 |
| Ti | 0.01 | 0.015 | 0.022 | 0.014 | 0.027 | 0.062 |
| V | 0.029 | 0.22 | 0.27 | 0.31 | 0.31 | 0.31 |
| Zn | 178 | 375 | 460 | 472 | 477 | 492 |
| Zr | <.004 | 0.023 | 0.049 | 0.062 | 0.062 | 0.065 |
| As (total) | 0.016 | 0.033 | 0.041 | 0.050 | 0.123 | 0.188 |
| As (III)** | <.001 | 0.0023 | 0.005 | 0.0053 | 0.0043 | 0.0047 |
| Co | 0.57 | 0.94 | 1.05 | 1.06 | 1.07 | 1.07 |
| Cr | 0.004 | 0.042 | 0.050 | 0.055 | 0.047 | 0.048 |
| pe*** | >7.1 | 7.06 | 6.92 | 6.96 | 7.22 | --- |

* unfiltered sample

** acidified with 1/2% nitric acid and analyzed within 24 hours; all other determinations upon an aliquot further acidified to 1% (by volume) nitric acid

*** calculated from arsenic concentrations

SOURCE: SONDEREGGER et al (1987)

## TABLE 5
## EARLIER BERKELEY PIT SAMPLES (mg/L)

| Date | 6/18/85 | 6/18/85 | 11/21/84 | 11/21/84* |
|---|---|---|---|---|
| Depth (ft.) | 1.0 | 100 (approx.) | 1.0 | 62 (approx.) |
| Temp (°C) | 10.2 | 10.4 | 5.6 | 6.5 |
| pH | 2.26 | 2.48 | 2.64 | 2.78 |
| Ca | 412 | 435 | 455 | 447 |
| Mg | 148 | 261 | 204 | 236 |
| Na | 64.8 | 60.3 | 63.2 | 61.7 |
| K | 7.9 | 8.8 | 4.9 | 4.4 |
| $SiO_2$ | 85.6 | 100 | 83.6 | 87.6 |
| Fe | 114 | 451 | 214 | 256 |
| Mn | 68.1 | 116 | 87.5 | 106 |
| Al | 86 | 172 | 120 | 142 |
| Ag | 0.033 | 0.043 | 0.017 | 0.030 |
| B | 0.10 | 0.15 | 0.11 | 0.20 |
| Cd | 1.00 | 1.62 | 1.23 | 1.54 |
| Cu | 63 | 229 | 89.6 | 164 |
| Li | 0.11 | 0.15 | 0.10 | 0.12 |
| Mo | 0.07 | 0.20 | 0.17 | 0.31 |
| Ni | 0.47 | 0.83 | 0.63 | 0.85 |
| $PO_4$ as P | <.1 | <.1 | 0.1 | <.1 |
| Sr | 0.97 | 0.90 | 0.86 | 0.88 |
| Ti | 0.076 | 0.082 | 0.079 | 0.094 |
| V | 0.031 | 0.168 | 0.028 | 0.066 |
| Zn | 134 | 329 | 196 | 255 |
| Zr | 0.031 | 0.047 | 0.019 | 0.035 |
| As (total) | 0.021 | 0.426 | 0.054 | 0.197 |
| Co | 0.064 | 1.17 | 0.085 | 0.98 |
| Cr | 0.048 | 0.092 | 0.061 | 0.097 |
| Cl | 12.3 | 8.3 | 12 | 12.3 |
| $SO_4$ | 3,200 | 5,550 | 3,707 | 4,410 |
| $NO_3$ as N | 0.16 | 0.23 | 0.20 | 0.12 |
| F | 3.7 | 13.6 | 4.2 | 5.8 |
| Br | <.1 | <.1 | <.1 | <.1 |
| Pb | --- | --- | 0.17 | 0.16 |

* Composite of 50 and 75 foot samples

SOURCE: SONDEREGGER et al (1987)

## 4.0 Principal Findings

The investigations and studies of the Berkeley pit continue. The water level in the pit continues to rise and the current pit water volume approaches 26 billion gallons (98 billion litres) of acidic water. Efforts continue on development of remediation options; most treatment options appear to be aimed at neutralization (i.e. lime addition) (Duaime 1994).

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