

**ACID MINE DRAINAGE - STATUS OF
CHEMICAL TREATMENT
AND SLUDGE MANAGEMENT PRACTICES**

MEND Report 3.32.1

Prepared for

The Mine Environment Neutral Drainage (MEND) Program
Canadian Centre for Mineral and Energy Technology (CANMET)
SSC File No: 015SQ.23440-3-9140
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CANMET Scientific Authority: Karen Mailhiot
Work Funded by the Canada/Ontario Mineral Development Agreement

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FINAL DRAFT

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AND SLUDGE MANAGEMENT PRACTICES
VOLUME 2 - APPENDICES**

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EXECUTIVE SUMMARY

This manual has been developed to assist decision makers and others involved in the planning and evaluation of systems for the chemical treatment of acid mine drainage (AMD).

It addresses AMD chemical treatment at operating and decommissioned mine and mineral processing sites in Canada. Currently used chemical treatment processes and practices are summarized - including methods used to dispose of sludge.

In Canada, AMD chemical treatment is usually accomplished using proven and effective lime neutralization/precipitation technology. As such, the manual addresses concerns about the long term chemical stability of lime sludge. Alternate sludge disposal strategies are presented.

The pro's and con's, net present values, sludge production volumes, etc. are presented for three perpetual treatment strategies. The strategies range from the continued use of conventional lime treatment systems to the use of an enhanced high density sludge treatment system. Various sludge disposal options are also evaluated ranging from deposition in a tailings basin to the smelting of sludge.

The chemical treatment and sludge disposal case studies may be used as a guide for users in the planning or evaluations of AMD chemical treatment systems. Users are, however, cautioned that AMD chemical treatment criteria are site-specific and that their application will likely present special constraints and/or concerns.

RÉSUMÉ

Le présent manuel a pour but d'aider les décideurs et les responsables à planifier et à évaluer des systèmes de traitement chimique des effluents miniers acides (DMA).

Le document porte sur le traitement chimique des effluents aux installations minières et minéralurgiques abandonnées et en exploitation au Canada. On résume les méthodes de traitement chimique actuelles, y compris les méthodes d'élimination des boues.

Au Canada, on emploie généralement une technique efficace et éprouvée de neutralisation à la chaux et de précipitation. À ce sujet, le manuel traite des questions relatives à la stabilité chimique à long terme des boues qui renferment de la chaux. Les auteurs présentent également de nouvelles stratégies d'élimination des boues.

Le document examine trois stratégies de traitement continu en considérant notamment les avantages et les inconvénients, les valeurs actuelles nettes, les volumes de production des boues, etc. Les stratégies vont de l'emploi de systèmes traditionnels de traitement à la chaux à l'utilisation d'un système amélioré de traitement des boues à haute densité. Les auteurs évaluent également diverses possibilités d'élimination des boues, allant du confinement dans un bassin de résidus à la fonte des boues.

Les études de cas relatives au traitement chimique et à l'élimination des boues peuvent guider les utilisateurs dans la planification ou l'évaluation des systèmes de traitement chimique des effluents miniers acides. Les utilisateurs doivent toutefois savoir que les paramètres de traitement chimique peuvent varier d'un lieu à l'autre et que leur application imposera probablement des contraintes ou posera des problèmes particuliers.

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PART I

**CURRENT AMD CHEMICAL TREATMENT PRACTICES
AND ALTERNATE TECHNOLOGIES FOR
CHEMICAL TREATMENT**

1.0 INTRODUCTION

The Canadian mining industry continues to make technical advances regarding the prediction, control, prevention, and treatment of Acid Mine Drainage (AMD). This manual deals with the latter, focussing on AMD chemical treatment and sludge management practices.

AMD is characterized by a low pH, and elevated concentrations of contaminants including heavy metals. The principal objective in chemically treating AMD is to produce an effluent that can be recycled to the process or safely released to the receiving environment.

For the most part, AMD is treated using lime either in quicklime or hydrated lime form. In selected cases, other alkali may be employed for pH adjustment and other metallic salts for specific metals removal (e.g. iron salts for arsenic removal, barium salts for radium removal). Applications range from simple batch treatment of ponded acidic water to continuous treatment of large flows. Lime treatment produces an acceptable effluent and a gypsum/metal hydroxide/carbonate sludge by-product.

The mining industry has attained considerable experience in the operation and maintenance of AMD treatment systems using lime. Treatment systems now commonly operate efficiently in an automated mode. Current sludge management practices range from the direct discharge of low density sludges to tailings management areas to sludge densification and recycling.

1.1 SCOPE OF WORK

Closure planning and related research work has led to suggestions that the mining industry evaluate methods of improving, if possible, currently used AMD chemical treatment systems.

At mine sites where AMD can be eliminated through remedial works, it is expected that the AMD chemical treatment systems can be decommissioned shortly after mine closure. Questions have, however, been raised about the long term stability of the sludges produced during the active life of the mine and during post closure treatment.

Other AMD chemical treatment systems will need to continue to operate for perhaps hundreds of years following mine closure. Such long term treatment requirements are demanding given:

- the remote location of some sites;

- the sometimes large and fluctuating AMD flowrates that will require treatment;
- that at some sites, the cumulative volume of low density sludge produced could exceed the volume of impounded tailings;
- the requirement to set aside sufficient funding for long term AMD treatment; and
- that limited scientific work has been carried out on sludge chemical stability.

In response to the need to address the future of AMD chemical research, MEND issued an open Request for Proposals, the terms of reference of which are summarized below:

- The state-of-the-art of chemical treatment of AMD, sludge densification, sludge stabilization and disposal are to be reviewed. The review is to include a summary of the chemistry of precipitation reactions, and physical and chemical properties of treatment sludges.
- A key part of the summary will be a description of the implications of long term treatment (i.e. lime consumption, sludge volumes, effect of local conditions on sludge).
- Capital and operating costs incurred at five AMD sites, including remote locations, are to be summarized. In addition, the implications (i.e. sludge storage and maintenance requirements) of operating such treatment systems for in excess of 100 years are to be assessed. The assessment is to address the requirement (if any) for sludge stabilization.
- Targeted research to fill technology gaps (if any) are to be identified.

The deliverables were to include:

1. A summary of the state-of-the-art, in manual format, of the chemical methods of treatment of acidic drainage. The manual was to include:
 - range of contaminant concentrations normally encountered in acidic drainages;
 - review of chemistry of reactions and properties of sludge;
 - design criteria and costs for widely used and best available treatment

- technology;
 - storage and disposal of treatment products; and
 - summary of known methods for stabilizing or "fixing" treatment products.
2. Recommendations for research and development work on chemical treatment and sludge stabilization and minimization.
 3. Presentation of a seminar on the chemical treatment of acidic drainage to the MEND Treatment Committee.

This study specifically addresses chemical treatment facilities. Other aspects of an overall chemical treatment system such as the water management system, sludge disposal area, infrastructure, pipelines and pumping stations are not included in this study. Costs associated with these items may be greater than those for the chemical treatment facility.

During the course of this study, treatment facilities were found to typically operate in full compliance with effluent targets. As such, secondary water treatment (e.g. CO₂ for adjustment of pH) used prior to discharge have not been reviewed within the context of this report.

1.2 INFORMATION SOURCES

Information on current treatment technology and sludge characteristics was gathered by reviewing recent technical literature and through discussions with specialists - some of whom authored the literature reviewed. The results of this review are detailed in Appendix A.

Information on industry practices was obtained from discussions with contacts at mining companies, industry associations, government ministries and agencies, and others. The list of industry contacts was designed to provide information on AMD treatment at:

- base metal, gold, uranium, and coal producers throughout Canada;
- both small mines (under 500 tpd ore production) and large mines;
- active and recently closed mines; and
- new mines either being developed or at the advanced feasibility stage.

Persons contacted were asked to comment on post closure AMD chemical treatment requirements (if any) and requirements for future research in the area of AMD chemical treatment.

Additional technical and cost information was obtained from suppliers and wastewater treatment specialty firms.

1.3 REPORT ORGANIZATION

This report is organized in a format designed to assist decision makers in evaluating latent post-closure chemical treatment strategies. The report is not intended to be a design manual. It may also be a valuable tool to those assessing AMD chemical treatment practices for proposed or active mines.

The report is organized into three main parts as follows:

- Part I reviews the theoretical basis of AMD generation and treatment; and summarizes AMD treatment practices used in Canada. Cost data are presented for selected AMD treatment systems. Chapter 5 provides a step-through guide to key issues for evaluating alternative AMD chemical treatment strategies.
- Part II addresses the treatment of AMD over an extended period of time following mine closure. Three types of lime based treatment systems (conventional, high density sludge, and enhanced high density sludge) are evaluated under various scenarios. Capital and treatment costs, and sludge production rates are estimated using computer modelled projections.

The long term post-closure treatment of AMD is evaluated using case studies of representative sites. Sludge disposal options are also evaluated.

Analyses are organized to serve as both a reference and guide to users involved in evaluating long term, post-closure, AMD chemical treatment strategies.

- Supplementary information is provided in Part III (appendices).

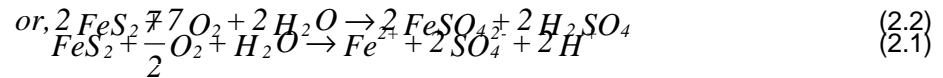
2.0 GENERATION AND CHEMICAL TREATMENT OF AMD

Acid mine drainage (AMD) is a general term used to describe water that has been contaminated by the by-products of reactions associated with the oxidation of sulphide minerals. AMD is typically acidic with elevated concentrations of suspended solids, heavy metals, and sulphate.

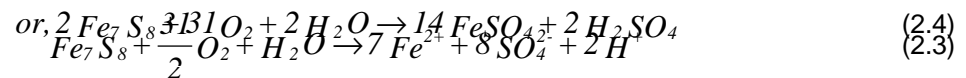
2.1 AMD GENERATION

The oxidation of the predominant sulphide minerals, pyrite and pyrrhotite, can be expressed by the following stoichiometric equations.

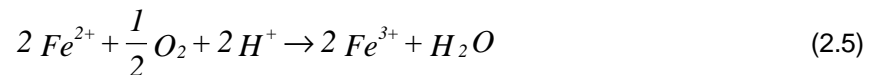
Pyrite Oxidation:



Pyrrhotite Oxidation:

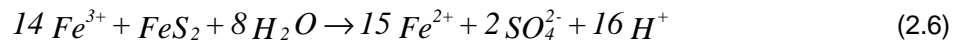


Ferrous iron (Fe^{2+}) is oxidized to its ferric state as follows.

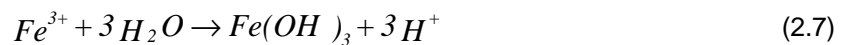


The reaction given by Equation 2.5 is dependent upon the pH of the solution and presence of catalysts. Under alkaline conditions, $\text{Fe}(\text{OH})_2$ is formed as indicated in Figure 2.1.

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



Ferric iron does not remain in solution much above pH 2 to 3 where it is hydrolyzed to $\text{Fe}(\text{OH})_3$ as shown by equation 2.7.



The sensitivity of ferric iron to variations in pH is shown in Figure 2.1.

Sulphide minerals, other than pyrite, have different reaction mechanisms, stoichiometries, and reaction rate limiting factors. A listing of common sulphide minerals and ionic oxidation products is provided in Table 2.1.

In some situations, the acidity of AMD is buffered by naturally available excess alkalinity. For instance, the pH of AMD generated from the oxidation of reactive sulphide minerals in a waste rock pile may be raised, even neutralized, by available alkaline materials that the AMD comes in contact with. Naturally buffered AMD may contain elevated metal and sulphate concentrations.

One of the major concerns with acid production is the release of heavy metals into solution. Heavy metals may be solubilized by the acidic dissolution of metal oxides or carbonates or by the oxidation of metal sulphides. These common metal sulphides are listed on Table 2.1. Because several of these metals have high solubilities at near neutral pH, hydrolysis to metal hydroxides may not occur until the pH is raised. With acid seepages especially where reducing conditions exist, water can contain thousands of mg/L reduced iron (Fe^{2+}) and many tens of mg/L of heavy metals such as nickel or zinc and still have a neutral pH.

2.2 CONVENTIONAL CHEMICAL TREATMENT OF AMD

The primary objective of the chemical treatment of AMD is to produce an effluent acceptable for discharge to the receiving environment.

Conventional AMD chemical treatment processes involve five key areas which are:

1. Neutralization of acidity.
2. Aeration.
3. Settling and disposal of sludge.
4. Polishing of effluent.
5. Chemical distribution and process control.

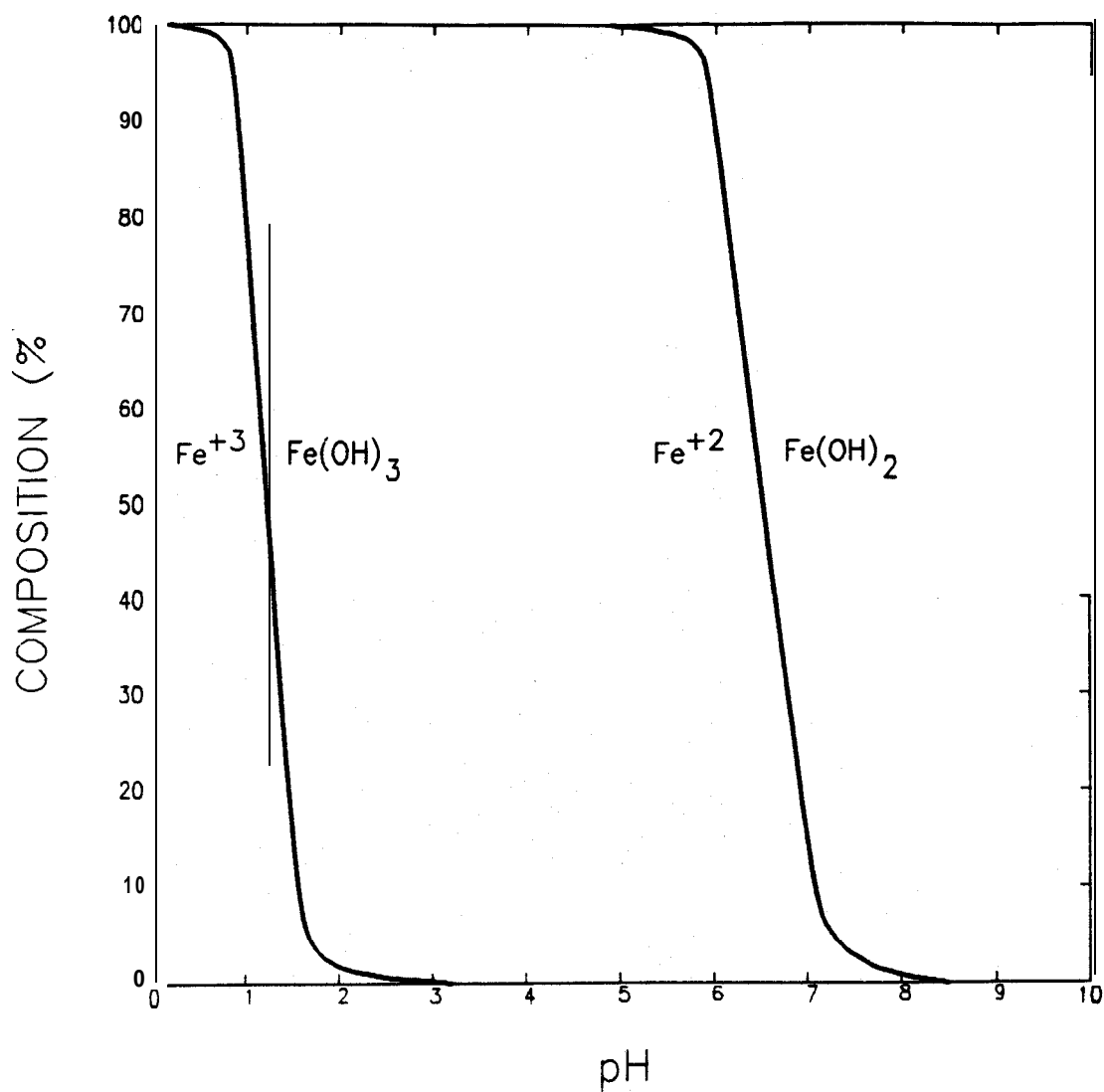
2.2.1 Neutralization of AMD

The acidity of AMD is neutralized by the addition of alkali material. Alkalis typically used in the treatment of AMD include:

- limestone (calcium carbonate)
- lime (calcium oxide)

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.)

Table 2.1

COMMON SULPHIDE MINERALS AND OXIDATION PRODUCTS

Element	Mineral		Ionic Oxidation Products ⁽¹⁾
Iron	Fe S ₂ Fe _{1-x} S	Pyrite/Marcasite Pyrrhotite	Fe ³⁺ , SO ₄ ²⁻ , H ⁺
Zinc	ZnS	Sphalerite	Zn ²⁺ , SO ₄ ²⁻ , H ⁺
Copper	CuFeS ₂ CuS Cu ₅ FeS ₄ Cu ₂ S	Chalcopyrite Covellite Bornite Chalcocite	Cu ²⁺ , Fe ³⁺ , SO ₄ ²⁻ , H ⁺ Cu ²⁺ , SO ₄ ²⁻ , H ⁺ Cu ²⁺ , Fe ³⁺ , SO ₄ ²⁻ , H ⁺ Cu ²⁺ , SO ₄ ²⁻ , H ⁺
Arsenic	FeAs S As S As ₂ S ₃	Arsenopyrite Realgar Orpiment	Fe ³⁺ , AsO ₄ ³⁻ , SO ₄ ²⁻ , H ⁺ AsO ₄ ³⁻ , SO ₄ ²⁻ , H ⁺ AsO ₄ ³⁻ , SO ₄ ²⁻ , H ⁺
Lead	PbS	Galena	Pb ²⁺ , SO ₄ ²⁻ , H ⁺
Nickel	NiAs (Fe, Ni) ₉ S ₈	Niccolite Pentlandite	Ni ²⁺ , AsO ₄ ³⁻ , H ⁺ Fe ³⁺ , Ni ²⁺ , SO ₄ ²⁻ , H ⁺
Mercury	HgS	Cinnabar	Hg ²⁺ , SO ₄ ²⁻ , H ⁺
Cobalt	CoAsS	Cobaltite	Co ²⁺ , AsO ₄ ³⁻ , SO ₄ ²⁻ , H ⁺

Note:

- (1) At the end of complete oxidation. Unstable ferrous iron (Fe²⁺) and S₂O₃²⁻ may be present.
This table modified from Table 2.2-1 (SRK 1989).

Table 2.2

COMMONLY USED ALKALIS⁽¹⁾

Agent	Chemical Formula	Equivalent Basicity Factor⁽²⁾	Rounded Cost of Basicity⁽³⁾
High calcium lime	CaO	1.00	1.0
High calcium hydrate	Ca(OH) ₂	1.33	1.6
Dolomitic lime	CaO·MgO	0.86	1.0
Dolomitic hydrate	Ca(OH) ₂ ·MgO	1.02	1.4
High calcium limestone	CaCO ₃	1.79	0.3
Dolomitic limestone	CaCO ₃ ·MgCO ₃	1.65	0.3
Sodium hydroxide (caustic soda)	NaOH	1.43	8.8
Soda ash (trona)	Na ₂ CO ₃	1.89	3.8
Magnesium oxide	MgO	0.72	3.4
Magnesium hydroxide	Mg(OH) ₂	1.04	4.9

Notes:

- (1) Adapted from (Stokowski, et al. 1992)
- (2) Relative weight of reagent required as compared with CaO.
- (3) Relative cost as compared with CaO (Transportation not included).

Table 2.3

AVERAGE CHEMICAL COMPOSITION OF LIMESTONE

Compound	Percentage (By Wt)
CaO	42.57
CO ₂	41.54
MgO	7.89
SiO ₂	5.19
Al ₂ O ₃	0.81
H ₂ O	0.77
Fe ₂ O ₃	0.54
K ₂ O	0.33
TiO ₂	0.06
Na ₂ O	0.05
SO ₃	0.05
Other	<u>0.16</u>
	100.00

Modified from Table 11.5, Hurlbut and Klein (1977).

- hydrated lime (calcium hydroxide)
- caustic soda (sodium hydroxide), and
- to a lesser extent, soda ash (sodium carbonate).

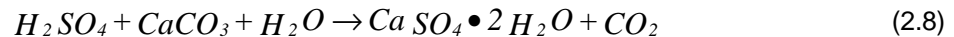
Equivalent alkalinities of each of these reagents are shown on Table 2.2. Some alternative chemicals are discussed in Section 2.4.1.

2.2.1.1 Limestone

Limestone for the most part consists of calcite (CaCO_3) along with naturally present impurities. The chemical composition of an average limestone is provided in Table 2.3. Reactivity is assessed based on available CaCO_3 or CaO . As such, limestones with high calcium limestone (CaCO_3) content provide more efficient neutralizing capability than dolomitic limestone ($\text{CaMg}(\text{CO}_3)_2$).

Limestone is the least cost alkali and may be used in its raw state either in crushed or lump form. Commercially available limestone typically has a CaCO_3 content in the range of 93% (Harrison 1969).

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



The reaction product gypsum ($\text{CaSO}_4 \bullet 2\text{H}_2\text{O}$) is present in soluble and/or precipitate form depending upon solution concentration. Supersaturation of gypsum can lead to scale formation.

The reaction between limestone and sulphuric acid (equation 2.8) occurs slowly due to:

- The 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.

Neutralization of AMD with limestone can be improved by using ground limestone and mechanical mixing. Carbon dioxide gas released during the limestone neutralization process can interfere with the settling of precipitates although this is normally not a serious issue.

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).

Limestone is often overlooked as a neutralization agent because of its poor reactivity at near neutral pH even though it can be highly cost effective. Where pH values must be raised to above 6.5, a second stage of alkaline addition is normally required (e.g. NaOH, Ca(OH)₂). For strong strength AMD solutions, limestone can meet typically 90 to 95% of the alkali demand at perhaps one third the cost of quicklime. Furthermore, sludges may be more granular and dense (Akman 1982).

The one problem with limestone treatment as a sole neutralization reagent is the lack of efficiency in the precipitation of several heavy metals, in particular, iron, nickel, zinc and cadmium. At pH levels below 6.0, these metals are not effectively precipitated.

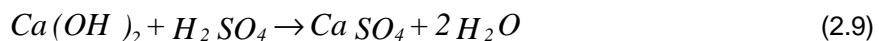
2.2.1.2 Lime

Lime is a term used to describe calcined forms of limestone.

Calcium carbonate (CaCO₃) is burned in a kiln at approximately 1000 °C to drive off carbon dioxide (CO₂) gas and produce the residual product CaO - known as quicklime or burned lime. Quicklime presents several operational concerns including the risk of chemical burns to personnel and the need for dry storage as CaO is hygroscopic.

Quicklime is more effective in treating acidity if it is slaked (reacted) with water to form hydrated lime - Ca(OH)₂. Quicklime is often slaked at an AMD treatment site using a ball mill, or a slaking system which may include slurry degritting equipment. This latter is normally not required for AMD treatment as the slaked slurry is used directly for pH adjustment.

The neutralization reaction between hydrated lime and the sulphuric acid present in AMD is as follows (Harrison 1969):



The chemical composition and neutralization effectiveness of quicklime is dependent upon the composition of the calcined limestone. For instance, high calcium quicklime (CaO) with a magnesium oxide content of less than five percent by weight is effective over a wide pH range. The retention time required to neutralize sulphuric acid using high calcium quicklime, or hydrated lime, is shown in Figure 2.2 (generalized reaction

rate curves). Figure 2.2 also shows the retention time for neutralization using a magnesium quicklime or hydrated lime containing in the order of five to thirty five percent MgO. Note that MgO and $\text{Mg}(\text{OH})_2$ are effective in neutralizing to a pH of about 10 and require a longer retention time compared to CaO or $\text{Ca}(\text{OH})_2$.

Figures 2.3 and 2.4 provide detailed hydrated lime consumption curves for commercial grade high calcium and dolomitic hydrate, respectively. The figures show that 12 g of $\text{Ca}(\text{OH})_2$ are required per 1,000 g of 1.5% of H_2SO_4 solution to raise the solution pH to just above 11; while 12 g of $\text{Ca}(\text{OH})_2 \cdot \text{MgO}$ would raise the pH of 1,000 g of 1.5% H_2SO_4 solution to just above 9.0. In more simple terms, 0.78 g of $\text{Ca}(\text{OH})_2$ is required per gram of acidity to raise the pH to 11, while 0.78 g of $\text{Ca}(\text{OH})_2 \cdot \text{MgO}$ per gram of acidity is required to raise the pH to 9.0.

Figures 2.5 and 2.6 provide detailed neutralization reaction time curves for the high calcium and dolomitic hydrate, respectively. Figure 2.5 shows that 12 g of $\text{Ca}(\text{OH})_2$ can raise the pH of a 1.5% H_2SO_4 solution to just above 11 in under three minutes. Figure 2.6 shows that 12 g of $\text{Ca}(\text{OH})_2 \cdot \text{MgO}$ will raise the pH of a 1.5% H_2SO_4 solution to just above 9.0 in five minutes.

Dolomitic hydrate is, therefore, a good alternative to high calcium hydrate in applications where maximum required pH is less than 9. It is also cheaper and produces less sludge (due to the solubility of MgSO_4). However, if magnesium removal is necessary, lime addition would be required creating greater sludge volumes.

2.2.1.3 Caustic Soda (Sodium Hydroxide)

Caustic soda (NaOH) is used to treat low volume and moderately acidic drainage. In such applications the higher cost of NaOH, as compared to lime, is outweighed by overall convenience. As with lime, proper handling procedures must be used with this chemical.

NaOH is available in bead or prill form. It can also be supplied in a 50% NaOH slurry which freezes at 12 °C as shown in Figure 2.7. The minimum freezing point (-20 °F) occurs at an 18% NaOH solution. The relatively high freezing point and costs associated with the transport of the water in the NaOH solution make NaOH solutions unsuitable in some situations. When used to neutralize AMD, caustic soda produces a high quality effluent. The formation of precipitates is limited due in part to the high solubility of sodium salts (Na_2SO_4).

Neutralization retention time is typically in the order of two minutes.

FIGURE 2.2

GENERALIZED REACTION RATES FOR CALCIUM AND MAGNESIUM HYDROXIDES AND FOR CORRESPONDING LIMESTONES

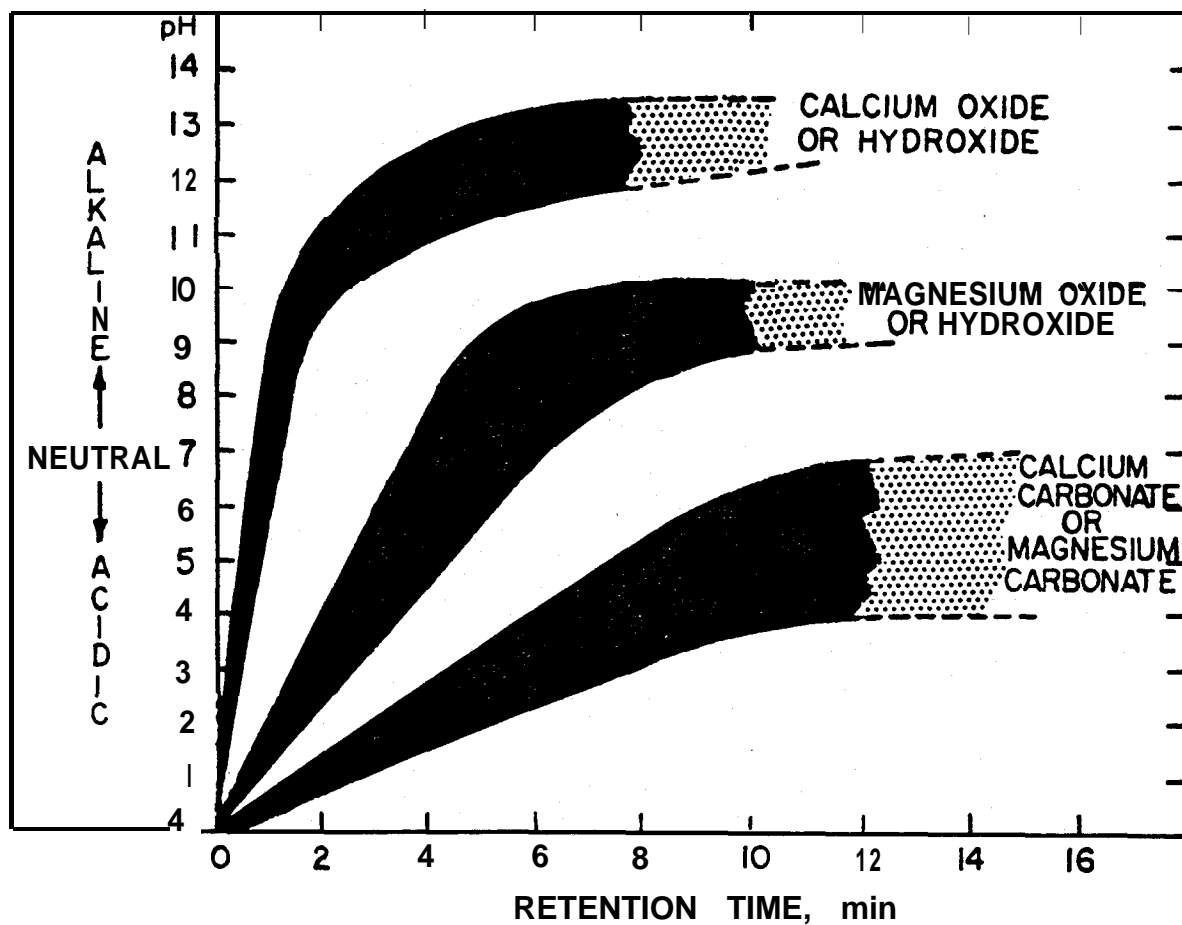


FIGURE 2.3

**HIGH CALCIUM HYDRATE REQUIREMENT CURVE
(GRAMS HYDRATE per 1000 GRAMS 1.5% H_2SO_4)**

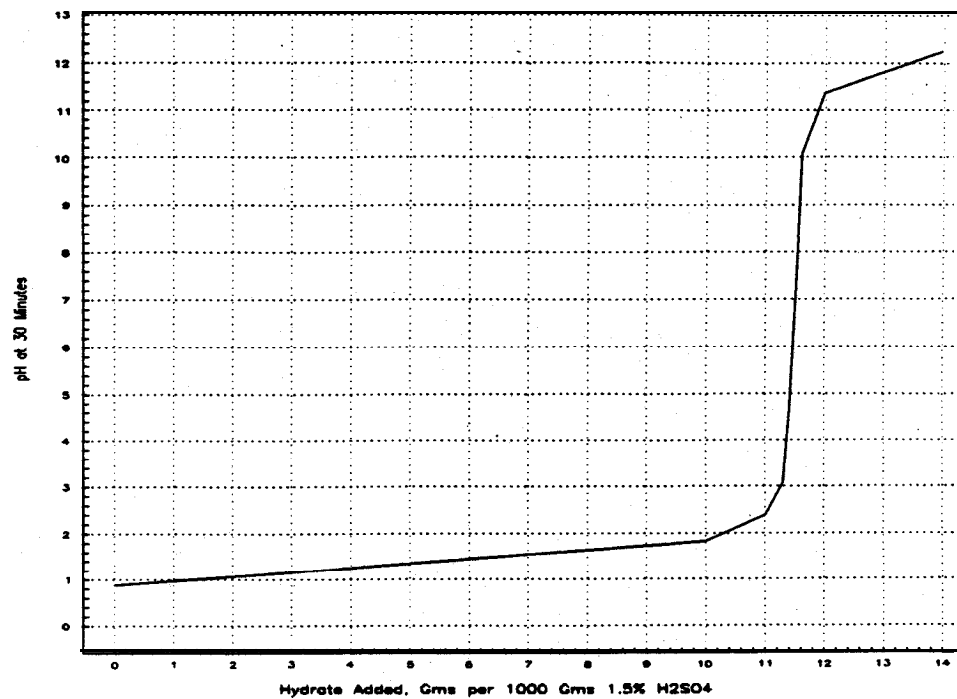


FIGURE 2.4

**DOLOMITIC HYDRATE REQUIREMENT CURVE
(GRAMS HYDRATE per 1000 GRAMS 1.5% H_2SO_4)**

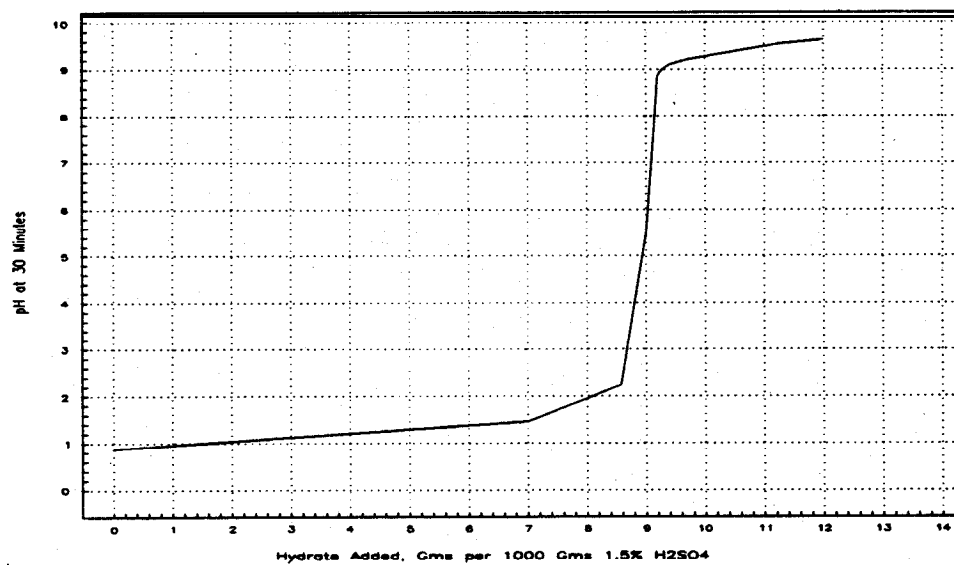


FIGURE 2.5

HIGH CALCIUM HYDRATE NEUTRALIZATION CURVE (GRAMS HYDRATE per 1000 GRAMS 1.5% H_2SO_4)

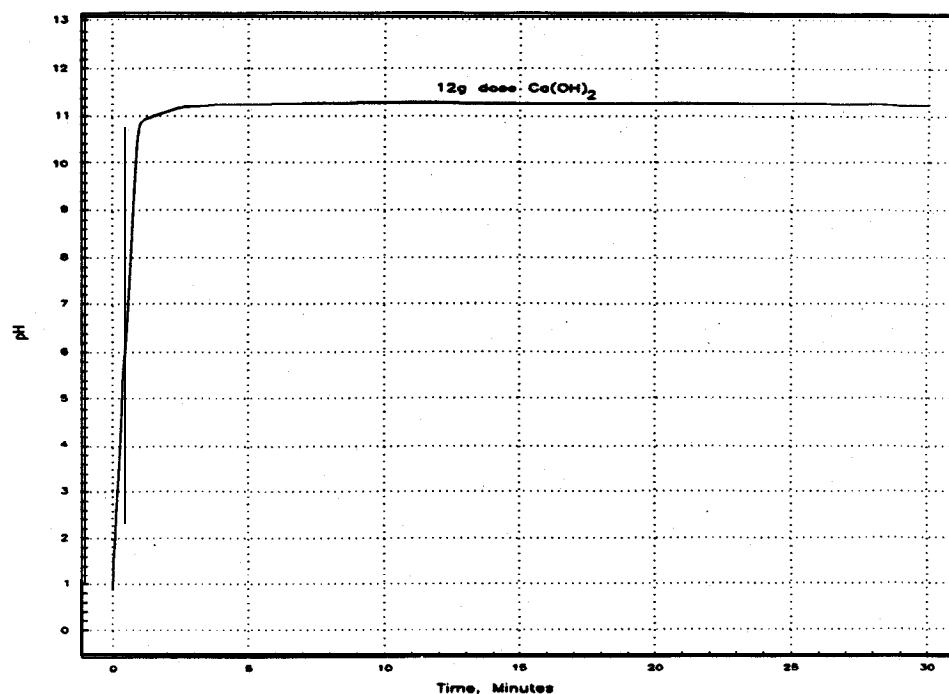
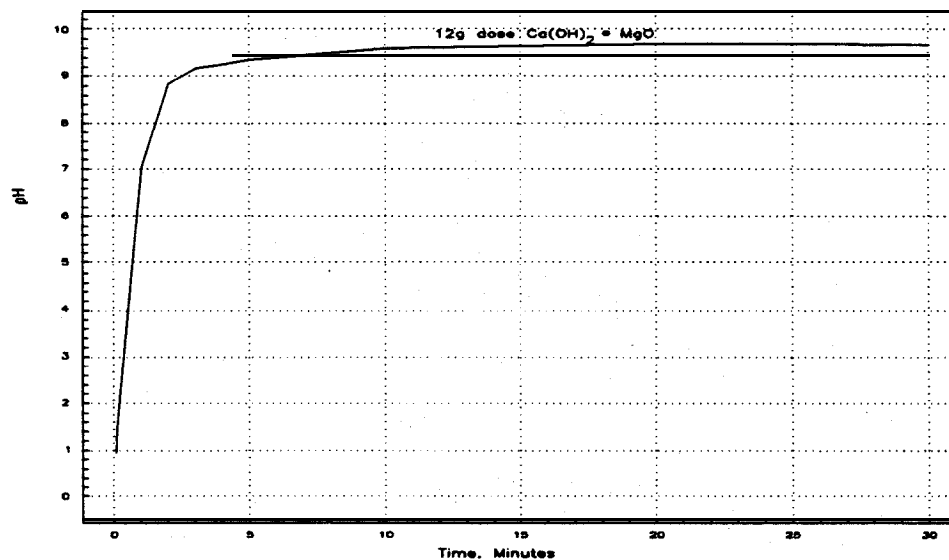


FIGURE 2.6

DOLOMITIC HYDRATE NEUTRALIZATION CURVE (GRAMS HYDRATE per 1000 GRAMS 1.5% H_2SO_4)



Caustic soda is useful in treating low volume, high sulphate drainage (in excess of 2,500 mg/L sulphate) as gypsum is not formed as a by-product.

2.2.1.4 Soda Ash

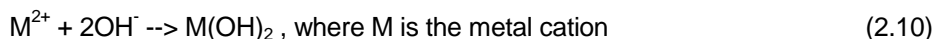
Soda ash does not appear to be used directly for AMD chemical treatment in Canada, although technical literature suggests it has been used to neutralize acidity at coal mines in the United States.

The use of soda ash (Na_2CO_3) is limited to the chemical treatment of low volume, acidic drainage with low ferrous iron concentrations.

Soda ash is purchased in prill or flake form. AMD may be treated by dissolving the prills in the drainage flow although control of reagent addition rates is very difficult.

2.2.2 Precipitation of Metals with Lime

The neutralization of acid mine drainage removes dissolved heavy metals by the formation of metal hydroxides which are sparsely soluble at neutral pH's. The reaction leading to precipitation of heavy metals can be expressed as follows:



Most of the metals are typically precipitated as hydrated metal complexes, $\text{M}(\text{OH})_2 \cdot n\text{H}_2\text{O}$, however, carbonate complexes may also control solubility:



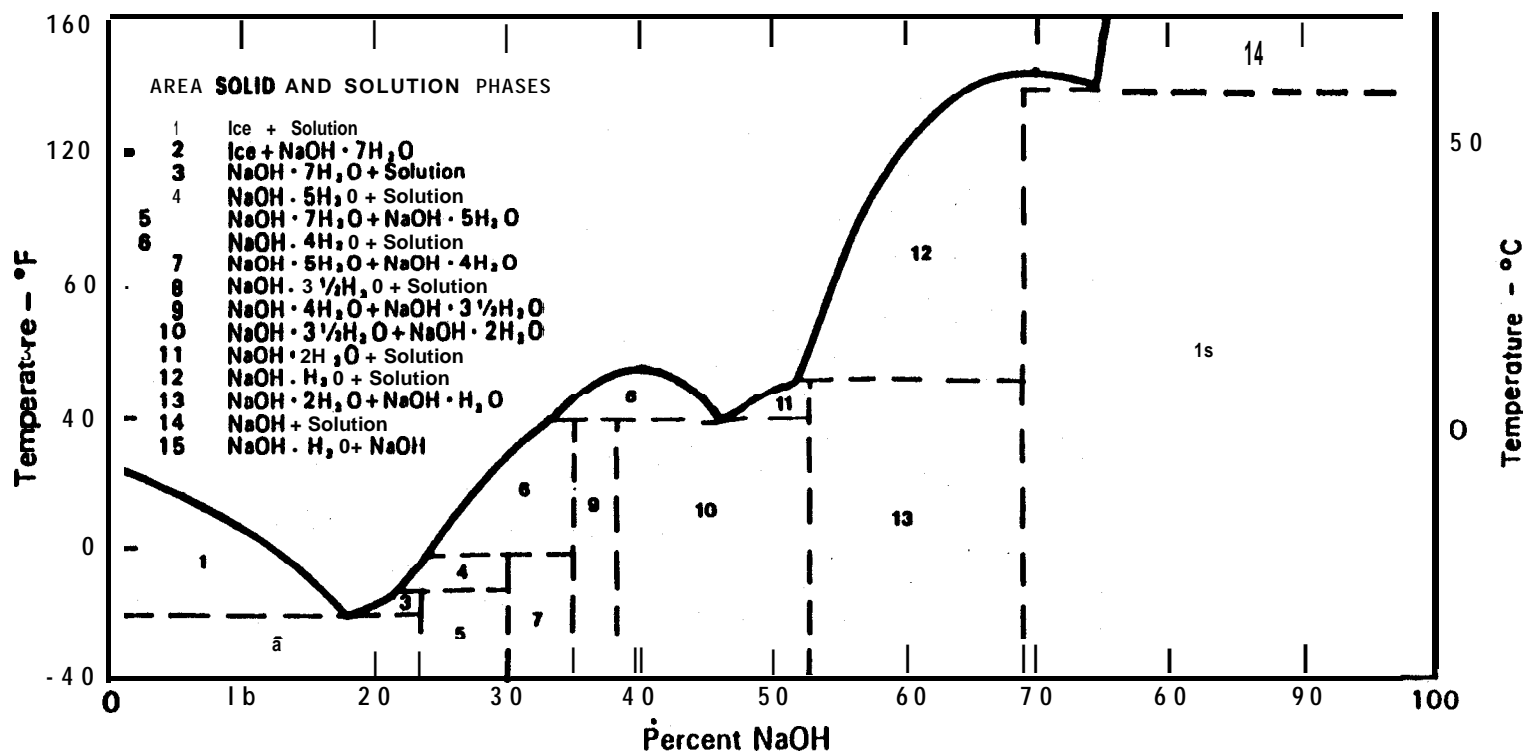
For the precipitation of heavy metals as hydroxides, the solubilities are controlled mass action as expressed by the solubility product, K_{sp} , defined as follows:

$$K_{\text{sp}} = [\text{M}^{2+}] [\text{OH}^-]^2 \quad (2.12)$$

The concentration of hydroxides ions $[\text{OH}^-]$ is a function of pH:

$$[\text{OH}^-] = 10^{(\text{pH}-14)} \quad (2.13)$$

FIGURE 2.7
FREEZING POINTS OF CAUSTIC SODA SOLUTIONS



The solubilities of metal hydroxides are, thus, directly related to the pH of the solution. This is illustrated by the theoretical solubility curves shown on Figure 2.8. As the pH of AMD is neutralized metal hydroxide precipitates are formed. The solubilities of the metal ions are a function of the solution pH as shown on Figure 2.8 but generally speaking, the minimum solubilities occur in the pH range of 7 to 9.

Hydroxide sludges produced by conventional lime treatment processes have very low solids contents. Sludges are discussed in greater detail in Section 3.0.

2.2.3 Precipitation with Other Reagents

Several acidic drainage streams in Canada contain metals which do not precipitate as metal hydroxides or carbonates. The most common include antimony, arsenic, molybdenum and radium-226.

i) Antimony

Antimony is present as a sulphide mineral in some mine tailings. Antimony precipitation experience is limited however antimony has been precipitated both as an iron co-precipitate and with lime. The chemistry of precipitation is similar to arsenic, however, removal efficiency is not as good.

ii) Arsenic

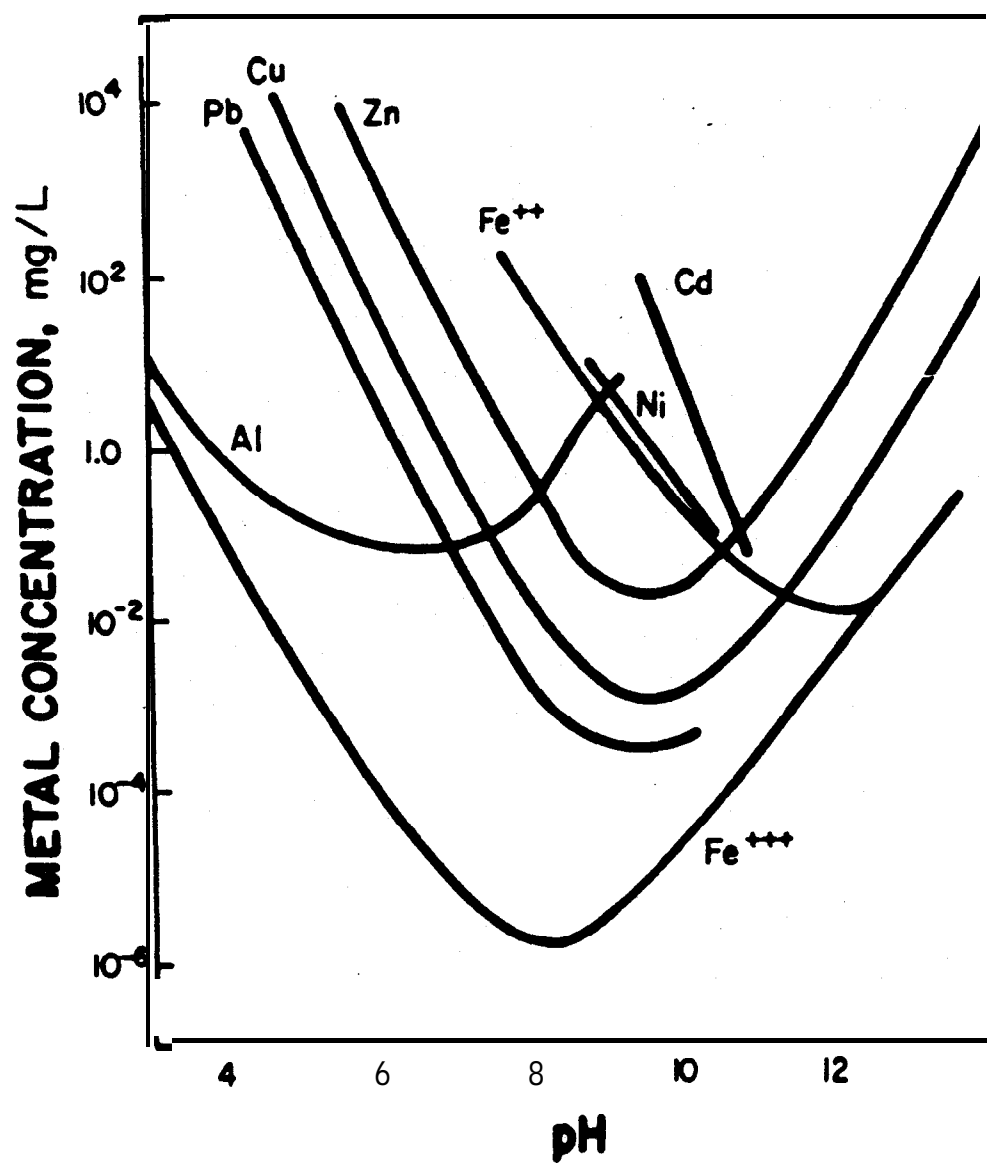
By far the most common contaminant is arsenic. Arsenic is generally mobilized from sulphide minerals such as arsenopyrite and gersdorffite.

Arsenic is normally present in as As(V) in mining effluents and is readily precipitated by many di or tri-valent cations as a co-precipitate. Often times in acid mine waters, specific chemical addition is not required as arsenic co-precipitates with dissolved iron, aluminum. etc... upon neutralization. Where iron addition is required the iron salts ($\text{Fe}_2(\text{SO}_4)_3$, and FeCl_3) are most commonly used. Effective treatment can be achieved at Fe:As ratios of 2:1 and greater, however, sludge stability improves with higher iron to arsenic ratios. Effluent levels of <0.5 mg/L are normally achievable.

iii) Molybdenum

Molybdenum is mobilized by the oxidation of MoS producing soluble molybdenum. There are only a few locations where molybdenum is an issue. In these instances molybdenum is co-precipitated with iron under marginally acidic conditions. The primary problem is that the resultant sludges are not stable under alkaline

FIGURE 2.8
METAL HYDROXIDE SOLUBILITIES



conditions. Iron co-precipitation can typically reduce levels to less than 1 to 2 mg/L.

iv) *Radium*

Radium is readily removed from solutions under either acidic, neutral or alkaline conditions by co-precipitation with barium sulphate. Typically barium chloride is added to mine waters at a rate of 10 to 100 mg/L depending on the radium concentration. The barium (radium) sulphate co-precipitate is quite stable since barium sulphate is only slightly soluble in water. However, the higher the barium to radium ratio is, the less mobile radium is in the sludge.

2.2.4 Sulphide Precipitation of Metals

Sulphide has not been commonly used for chemical treatment of metals in acidic mine waters. The basic mechanism involves the addition of a soluble metal sulphide to form an insoluble metal sulphide. Common sulphide reagents include sodium sulphide (Na_2S), sodium hydro sulphide (NaHS), iron sulphide (FeS) and calcium sulphide (CaS). The primary drawback to sulphide precipitation is the high cost. Palm (1988) provides the following summary of the advantages and disadvantages of sulphide precipitation.

Advantages	Disadvantages
The sulphide process has the ability to remove chromates and dichromates without preliminary reduction of the chromium to the trivalent state.	Sulphide reagent will produce hydrogen sulphide fumes when it comes in contact with acidic wastes. This can be prevented by maintaining the pH of the solution between 8 and 9.5 and may require ventilation of the treatment tanks.
The high reactivity of sulphides with heavy metal ions and the insolubility of metal sulphides over a broad pH range are attractive features compared with the hydroxide precipitation process.	As with hydroxide precipitation, excess sulphide ions must be present to drive the precipitation reaction to completion. Since the sulphide ion itself is toxic, sulphide addition must be carefully controlled to maximize heavy metals precipitation with a minimum of excess sulphide to avoid the necessity of post-treatment. Where excess sulphide is present, aeration of the effluent stream would be necessary to oxidize residual sulphide to the less harmful sulphate.

Sulphide precipitation, unlike hydroxide precipitation, is relatively insensitive to the presence of most chelating agents and eliminates the need to treat these wastes separately.	The cost of sulphide precipitants is high in comparison with hydroxide precipitants, and disposal of metallic sulphide sludges may pose problems.
--	---

2.3 LIME TREATMENT PROCESSES

2.3.1 Basic Technology

Figure 2.9 is a schematic diagram depicting a lime neutralization system typical of the basic technology in common use in the industry.

Acidic drainage is mixed with lime slurry in a neutralization tank. Single stage or two stage neutralization may be employed depending on the chemical nature of the drainage and the neutralization chemical(s) employed. Figure 2.9 depicts a two stage neutralization system.

Flocculant may be added to the settling pond influent to promote settling. Some of the overflow from the pond is used for reagent make-up; most is discharged to the environment.

This technology, which is widely practiced, generates low density sludge and requires large areas of land for settling/clarification ponds.

2.3.2 High Density Sludge Process

The high density sludge process (HDS) is a mechanical technique used to improve the physical properties of the sludge. The process can be adapted to conventional equipment.

A typical flowsheet for the HDS process is shown in Figure 2.10. After neutralization (3) (see Figure 2.10), flocculant is added to the treatment water which is pumped (5) to the HDS thickener. Some of the underflow sludge from the thickener (up to 50% of the influent flow) is recycled back (14) to the beginning of the treatment process. The recycle sludge is mixed with the lime slurry in a sludge/lime mix tank and the resulting solution (19) is mixed with acidic drainage in the chemical oxidation reactor (neutralization tank). A portion of the overflow from the HDS thickener is used for reagent make-up (9). The remainder is either discharged to the receiving environment or passed through a polishing pond (18) before final discharge.

The mixing of the sludge with the lime slurry alters the physical nature of the sludge particles. The result is that the particles, during the neutralization that follows, grow larger than those resulting from a low density

FIGURE 2.9

CASE 1: BASIC TECHNOLOGY

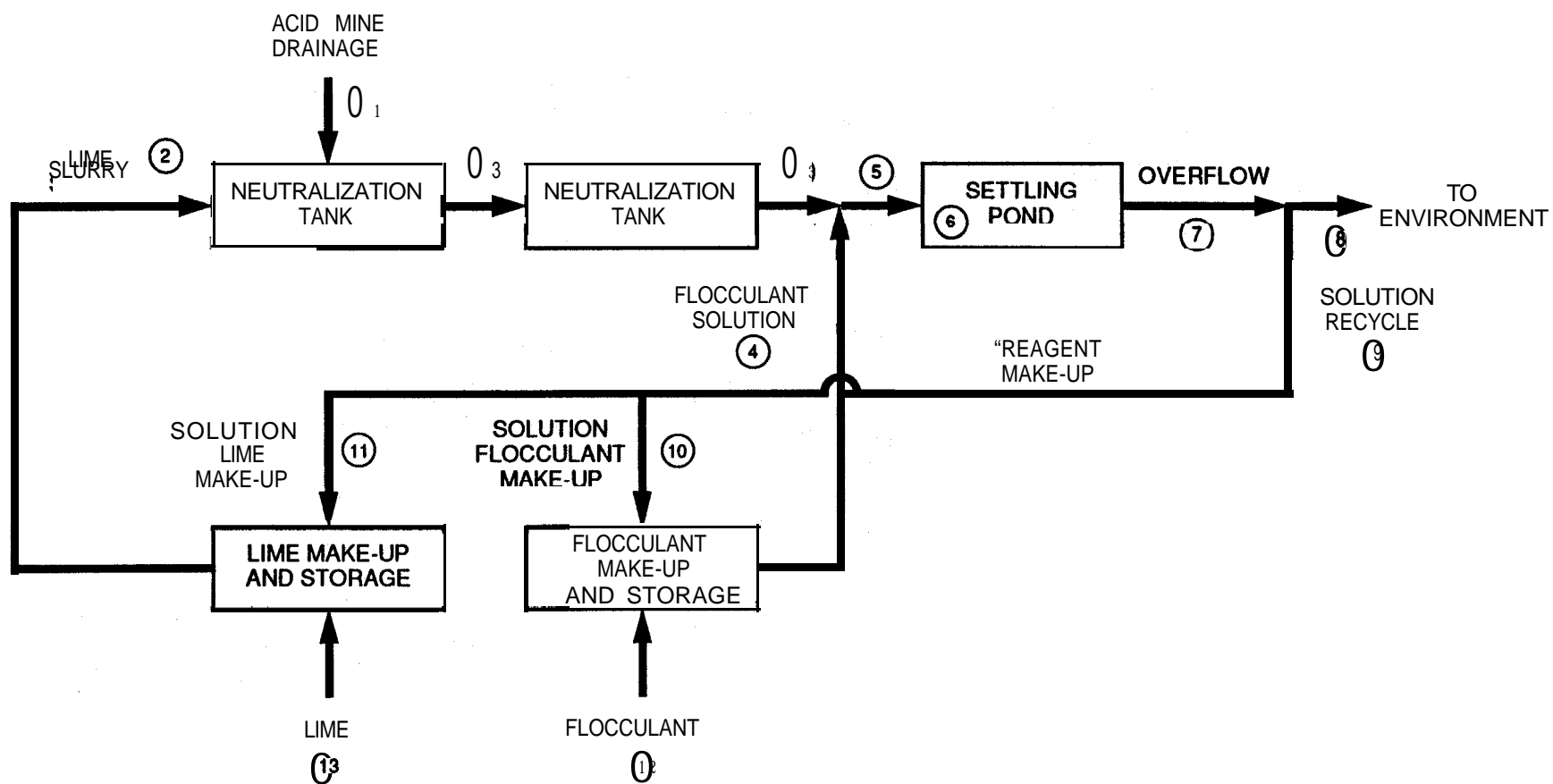
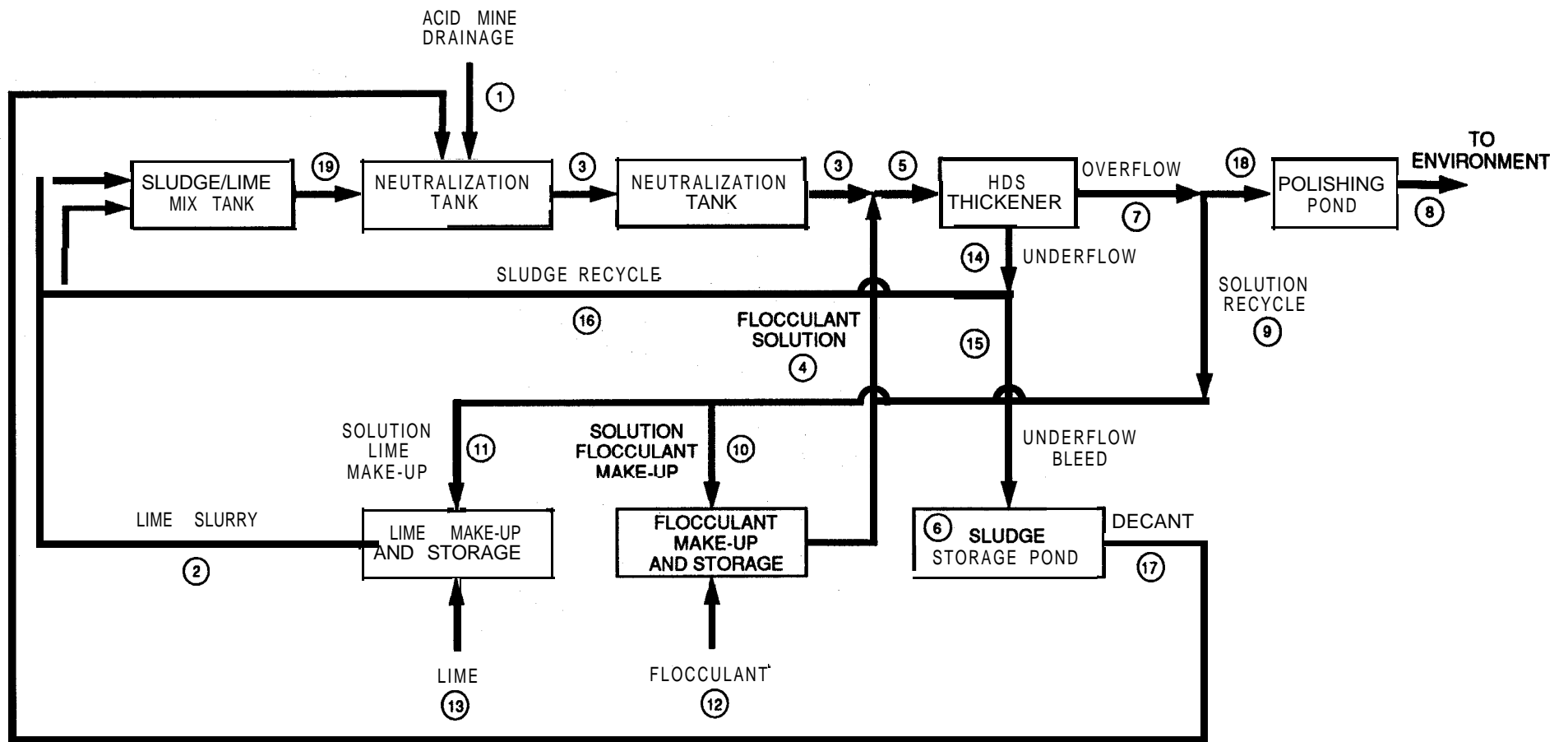


FIGURE 2.10
CASE 2: CURRENT ADVANCED TECHNOLOGY



sludge process. The new sludge particles are also more rounded and smooth. They are hydrophobic in nature, tending to attract heavy metals and repel water. As a result, the sludge is more dense and drains readily to achieve a high solids content.

A basic technology system (shown in Figure 2.9) can be converted to an HDS process (Figure 2.10) by the addition of an HDS thickener and a sludge/lime mix tank. Several variations on the basic technique are available (Cominco Engineering Services Ltd., Hudson Bay Mining and Smelting Co. Ltd., Tetra Technologies Inc.).

2.3.3 Further Refinements to Lime Treatment Processes

A modification of conventional treatment processes is illustrated in Figure 2.11. This process is the same as the high density sludge process shown on Figure 2.10 but has additional mechanical dewatering equipment. In this case, a pressure filter is depicted since the effectiveness of pressure filters is not as sensitive to sludge characteristics as some other devices. This type of system would be designed to provide a sludge with a high solids content and thus further reduce sludge volumes.

2.4 NON-CONVENTIONAL CHEMICAL TREATMENT PROCESSES

2.4.1 Alternative Chemicals

A variety of non-conventional materials and chemicals have been investigated for their potential use in treating acid drainages. Potential benefits of some of these may include one or more of cost savings, ease of handling, reduced sludge volumes, improved sludge stability or improved effluent quality. Most alternative chemicals also have certain trade-offs.

Many of these materials have been developed and used for industrial processes but may be applicable to some sites or conditions for AMD treatment.

Insoluble Starch Xanthate (ISX)

ISX is a cereal grain-based product developed by the U.S. Department of Agriculture for metals removal at low cost. It has been used primarily for treating waste water from electroplating processes. A number of case studies have been compiled (Wing 1983) but no applications to AMD are documented. The reagent adsorbs heavy metals by exchanging sodium and magnesium ions for heavy metal cations. The metals for which the process is most effective include Al, Zn, Cr, Cd, Hg, Ni, Cu, Sn, Au and Ag. Of these, it is known to

CASE 3: ENHANCED HIGH DENSITY SLUDGE TREATMENT



have been used for the removal of Ni, Cd, Cu, Cr and Hg (Hauck and Masoonian 1990).

The sludge settles rapidly and is easily dewatered, and can be removed by pressure filtration. Metals are effectively immobilized in the sludges. Metals can be recovered from ISX sludges by incinerating or treatment with nitric acid.

Sodium Borohydride

Sodium borohydride (NaBH_4) was developed primarily for removing mercury from discharges but can also be used for removing other heavy metals (Canadian Mining Journal 1980). It reduces metals to their elemental form. Metals precipitate without the generation of sludge and are recovered directly by rise of vacuum filtration. The reagent is expensive and its addition must be closely monitored in order to control the boron concentration in the effluent.

Zeolites

Zeolites are an industrial mineral product. They can selectively exchange pollutants such as sulphur dioxide, hydrogen sulphide, nitrogen oxides, iron and heavy metals for magnesium, sodium, calcium or other alkali earth metals. The drainage is not generally neutralized. Zeolites may be suitable for specialized applications such as the Britannia Mine in British Columbia where they were recently tested for copper removal from acid rock drainage (Vos 1992), since copper is the only contaminant of concern and buffering of acidity is not a problem.

These investigations into the use of zeolites involved laboratory testing of six zeolites. The one found most effective was Pine Valley phillipsite which is reported to be available at a cost of \$400 U.S./tonne plus shipping. The daily requirement is estimated to be 311 tonnes to treat a flow of $518 \text{ m}^3/\text{h}$ at 18 mg/L copper. Further investigations into the use of zeolites at this site are required.

Sulphide Precipitation (see also Section 2.2.4)

Excellent removal of metals can be obtained by sulphide precipitation, however, excess sulphide forms noxious hydrogen sulphide gas. A ferrous sulphide process has been developed (Permutit Co, Sulphex process) which overcomes this Problem.

Excess iron is precipitated in hydroxide form. The correct dosage of sulphide is critical to avoid some heavy

metals (mercury, tin, silver) from resolubilizing. Sulphide sludges may oxidize, forming sulphuric acid and causing heavy metals to leach.

Magnesium Compounds

Magnesium oxide (MgO) can be used to remove metals as hydroxides. Highly soluble Epson salts may be formed during neutralization. The sludge produced is reported to be 20 to 30% of the volume of sludge produced by lime neutralization. Because MgO is quite insoluble, a plug flow or parallel batch reactor system is required for continuous processing. The reaction requires 5 to 15 minutes.

Magnesium oxide is much more expensive than quick lime. The cost adjusted for basicity is more than three times as high (Stokowski et al. 1992).

Other compounds used occasionally for neutralizing acidity are magnesium hydroxide $[Mg(OH)_2]$ or magnesite $[Mg(CO_3)_2]$. Both of these are industrial minerals. Natural magnesite is also available.

Trapzene

Laboratory testwork using trapzene (calcium peroxide) produced a dense, low volume sludge of hydrous metal oxides. Good metal removals (including manganese) were achieved at a pH of 6.0 to 6.5.

Field trials were not able to overcome reagent mixing and sludge handling problems. Further research was abandoned because of the high cost of production for trapzene (Ziemkiewicz 1994).

Other Compounds and Products

A number of other products have been proposed as cost effective neutralizing agents. These include ammonia, potassium carbonate waste products such as basic slag, phosphate mining refuse, cement kiln dust, fly ash, carbide lime, spent bed lime and some mine tailings (Stokowski et al. 1992).

A two stage neutralization process employing hydrogen peroxide and anhydrous ammonia has been used where availability of power is a problem.

Ammonia is not often used because of the toxicity of un-ionized ammonia (NH_3) in effluent to aquatic life. If an excess of ammonia is used, it may hinder precipitation of some heavy metals.

Use of waste products may reduce reagent costs, however they may not achieve complete neutralization by themselves. There is also the possibility of introducing undesirable elements into the effluent or the sludge. Sludge volumes may increase significantly.

2.4.2 Alternative Processes

A number of techniques for extracting metals selectively from wastewater have been proposed or tested for use in treating AMD. The cost of metal recovery can, in some cases, be offset by the value of metals extracted if metal concentrations (such as copper) in the effluent are high. Removal of metals may also lead to the generation of less sludge in a form that will be less prone to leaching of residual metals.

Methods for removal and recovery of metals include biosorption, selective precipitation, electrowinning, ion exchange and solvent extraction. Further discussion on these methods can be found in reports authored by Dinardo, *et al* (1991a and 1991b).

2.4.2.1 Copper Cementation

The process of copper cementation on iron involves the electrochemical precipitation of copper from solution as follows:



A number of other reactions take place simultaneously, causing large amounts of iron to be consumed. The efficiency of the copper cementation process is dependant on a number of factors. Problems may include a high consumption of iron, slow reaction rate, poor efficiency of removal, poor quality of the cement and high water content.

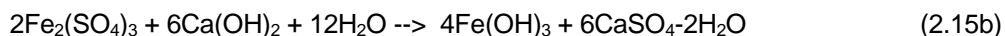
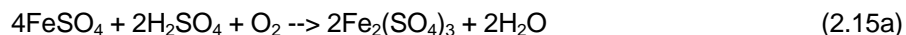
Recent efforts have been directed towards the development of reactors to efficiently treat dilute copper solutions such as AMD. CANMET has developed two such reactors; however, both still require further work including bench scale testing and economic evaluation.

Bench scale tests conducted at the Berkeley Pit in Butte, Montana, indicated that copper cementation could be accomplished with pieces of scrap iron (Huang and Liu 1993).

2.4.2.2 Selective Iron Removal

By removing iron (and most of the sulphate) selectively from the AMD, heavy metals are left in solution, facilitating later recovery. Ferric iron precipitates at much lower pH's (< pH 4.0) than ferrous iron (pH 9.5).

The ferrous iron is oxidized to the ferric form as follows:



The addition of lime precipitates ferric hydroxides and gypsum. This process is largely dependant on pH and temperature.

Although most of the other metals remain in solution, copper co-precipitates with the iron. If copper content is significant, the copper should be recovered prior to iron precipitation. The iron precipitate is suitable for disposal or a number of potential uses. Research into possible uses or means of disposal indicates potential for by-product uses as coagulants, mine backfill, or in production of concrete, bricks, pigments or magnetite.

Further research has been suggested regarding the potential uses of by-products and improving removal methods and rates.

2.4.2.3 Selective Precipitation of Other Metals

Selective precipitation of metals is dependant on their solubilities. These vary with pH, temperature and oxidation state. By controlling these factors and by the use of complexing agents, nickel and zinc may be removed selectively.

2.4.2.4 Ion Exchange

Ion exchange is a well established method of removing metal ions from contaminated water, producing potable water. Its application to AMD has been limited due to its cost and maintenance considerations. Recovery of copper, nickel, cobalt, arsenic, mercury and uranium is "technically and economically feasible" (Dinardo *et al* 1991a).

In ion exchange, ions are interchanged between an aqueous solution and a solid medium (ion exchange resin).

Anion and cation resin beads replace metal ions with H^+ , OH^- or other ions. "Loaded" resin beads are regenerated by acid washing or caustic. Metals may be recovered from the acid or caustic solution by

solvent extraction or electrowinning.

There are several processes for ion exchange including the Desal, modified Desal, Sul-biSul, Sirotherm and two resin processes (Dinardo et al. 1991, Ritcey 1989, U.S. EPA 1983). The original Desal process is more suited to alkaline waters with low iron concentrations than to treatment of AMD.

The modified Desal process may be the most promising ion exchange process for treatment of AMD (Dinardo et al. 1991). A weak-base anion resin exchanges sulphate and other anions for bicarbonate. The solution is then aerated, oxidizing the iron. Lime treatment then precipitates metallic hydroxides and the effluent is filtered after settling. The process produces potable water. It is limited to drainage with less than 2,200 mg/L sulphate. The presence of ferric iron may cause problems by ferric hydroxide precipitates in the anion bed.

A demonstration plant for AMD treatment by the Modified Desal Process was built in the early 1970's in Pennsylvania. Capital costs were \$2.3 million U.S. Operating costs in 1975 were \$0.14/m³ U.S. for 2,300 m³/d capacity.

The Sul-biSul process employs strong cation and anion exchange resins. Metal ions are exchanged for H⁺ ions in the cation exchanger. In the anion exchanger, sulphate ions are converted to bisulphate. The anion exchange resin is regenerated by a reversal of the process, using feed water to convert bisulphate back to sulphate ions. This inefficient method of regeneration is one of the limitations of this process. The use of this process for treatment of AMD is considered uneconomical (U.S. EPA 1983).

The Sirotherm process uses hot water rather than chemicals to regenerate resins. The resins contain both a weak acid and base in one bead.

The two resin process uses strong acid and weak base cation and anion exchangers, respectively. Capital and operating costs are significantly higher than those for the modified Desal process (U.S. EPA 1983).

According to Dinardo et al. (1991), the sale of metals recovered as a result of ion exchange should offset costs; however this is highly site-specific. One review of AMD treatment and metal recovery options at Britannia Mine (SRK and Gormely 1991) found ion exchange to be uneconomical.

Further research into the use of ion exchange for AMD treatment is required. Although preliminary work indicates that this process is economically feasible, the suitability of ion exchange as a long term (i.e. post closure) treatment option has not been demonstrated.

2.4.2.5 Solvent Extraction

Solvent extraction is highly developed for extraction of organics and for uranium recovery and is used in a number of industries including the petroleum industry. One of the main problems associated with this method is contamination of the effluent with the solvent.

The principle of solvent extraction is that a contaminant will be transferred from water to a solvent in which its solubility is higher than that in water. Solvents are chosen to extract contaminants selectively. The contaminants are removed from the solvent and the solvent is reused.

This technique may be used for recovering eluted metals from ion exchange resins. The use of solvent extraction in treating AMD has not been demonstrated.

2.4.2.6 Other Methods of Metal Recovery

Sludge volumes are reduced in Japan by recovering iron oxide in the form of ferrite and hematite (Yamabe 1990). The ferrite method of recovery employs pretreatment, bacterial oxidation, neutralization, ferrite production and magnetic separation. The result is a 20% reduction in sludge volume and a ferrite material that can be reused.

Hematite is produced by a process of arsenic removal at pH 4.3, co-precipitating the arsenic with iron followed by biological oxidation, neutralization and firing of the final product. The resultant hematite is a marketable grade of pigment. Sludge volumes are reduced by 46%.

3.0 LIME TREATMENT SLUDGE

3.1 SLUDGE CHARACTERISTICS

The characteristics of sludge produced by acid mine drainage (AMD) treatment processes vary depending on the properties of the drainage, the treatment process and the neutralizing agent.

Limestone (carbonate) neutralization produces a dense, granular sludge which settles rapidly and compacts well. The volume of the sludge is often less than that generated using other precipitation agents. As discussed previously, the usefulness of limestone is limited since it is only effective up to pH's of less than 7.

Lime (hydroxide) sludges tend to be gelatinous and voluminous. They settle slowly without flocculant addition. Sludge volume is greater than that for carbonate sludges. Hydroxide sludges produced by conventional treatment processes have very low solids contents. The low density is due to the fine amorphous nature of the precipitates and water which is chemically bonded to sludge particles and is thus resistant to dewatering and compaction.

Caustic soda (NaOH), which is infrequently used, produces sludges which settle slowly. Sludge volume is typically greater than lime sludges where gypsum is not formed. Caustic soda sludges are often described as being slimy. Sludges generated from treatment with soda ash are also more voluminous than lime sludges.

3.2 SLUDGE PRODUCTION

Sludge production from an AMD source can be massive. For example, consider a base metal tailings with 35% metal sulphide (assume FeS_2 is prime element). One cubic metre of tailings at 1.7 t/m^3 would contain about 0.6 t of pyrite. The oxidation and release of all reaction products could produce 2.3 t of sludge from 1.7 t of tailings. At 5% solids in the sludge, 1 cubic metre of tailings could produce AMD which when treated could produce about 46 m^3 of sludge. Even when dewatered to 40% solids assuming a density of approximately 0.67 dry t/m^3 , the sludge volume would be 3.4 times the original volume of the tailings.

The density of the sludge produced will depend upon a number of factors. Some of the key factors affecting the volume of sludges generated by conventional treatment processes are:

- i) the initial strength of the AMD solution;
- ii) the key metal elements;

iii) the reagent used for precipitation.

The discussions that follow deal with each of the above items.

i) *Solution Strengths*

High strength solutions by their very nature produce high solids contents. For example, a solution with 25,000 mg/L of acidity could contain 25,000 mg/L of sulphate and 7,500 mg/L of iron. The addition of 92% CaO would produce the following sludge per m³ of water treated (assuming 1.25 x stoichiometric demand).

5 kg unreacted lime/limestone	
40 kg of CaSO ₄ · 2H ₂ O	
14 kg of Fe(OH) ₃	_____
59 kg dry solids/m ³	

Assuming one third of the water is released after settling and treatment, this sludge would have a density of more than 8% solids. Ongoing settling and gravity concentration would increase sludge densities further.

In contrast, for a low strength solution, no gypsum is formed leaving iron, or other metals (e.g Ni, Zn) as the primary hydroxide precipitate. These solutions do not typically form dense sludges by conventional methods unless they are purposely dewatered (sludge drying beds, freeze thaw techniques, etc.).

ii) *Metal Elements*

Several metals are known to produce low density sludges. Perhaps the most common metal is zinc. When zinc is the prime precipitate, density may be less than one or two percent solids for a conventional treatment process.

iii) *Reagent*

Few data are available on the effects of neutralizing agents on characteristics of sludges produced. (Ackman 1982). Sludges generated from limestone neutralization tend to be denser than sludges generated by other neutralizing agents.

Sodium sludges (from caustic soda and soda ash) are more voluminous than lime sludges. In a study of sludges in Pennsylvania (Ackman 1982), one AMD treatment plant reported sludges with 2% solids from

treatment with sodium hydroxide and another reported 1% solids in sludges from sodium carbonate neutralization. The average sludge solids for the 24 plants reporting values (22 plants used lime treatment) was roughly 2.5%.

Magnesium oxide is reported to produce sludges that after standing occupy less than one third the volume of other sludges.

3.2.1 Sludge Volumes and Densities

Since most treatment plants keep few records on sludge production, little information is available. Volumes of sludge generated by conventional AMD treatment are typically in the range of 5 to 10% of the volume of the raw wastewater treated but may be up to a third of the daily flow. Actual volumes depend on the characteristics of the drainage and the method of neutralization. In selected cases where AMD strengths are very high, it is possible to produce almost 1 m³ of low density sludge per m³ of water treated.

In one study of Pennsylvania plants (all producing metal hydroxide sludge), an average of 1,050 m³/d of sludge was produced per plant or about 12% of the volume of raw wastewater (Ackman 1982). The largest volume observed in that study of sludge generated per volume of wastewater treated was 34% corresponding to the maximum reported raw water acidity and iron concentrations of 2,390 mg/L and 929 mg/L, respectively. The sludges had an average solids content of 1.7% by weight.

A survey of Canadian facilities (Gionet et al. 1987) indicated that the annual mass of sludge being produced by the 42 facilities surveyed (28 base metal, 8 precious metal and 6 uranium) was 140,000 dry tonnes. Most of this was from base metal mines (85%) and uranium mines (15%). Table 3.1 shows sludge solids percentages data from base metal mines obtained as part of the Gionet study.

La Mine Doyon was reported to produce 100,000 m³/a of sludge at 5 to 10% solids by weight. Equity Silver Mines treated 800,000 m³/a of acid mine drainage generating 80,000 m³/a (10% by volume) of sludge at 6 to 7 % solids by weight.

Reported solids contents of sludge vary greatly depending not only on the characteristics of the sludge itself but also on whether densities are reported before or after drying or other dewatering practices. Low density hydroxide sludges rarely achieve more than 2 to 3% solids (Environment Canada 1975). Other references indicate sludge densities in the order of 1 to 5% (Gionet et al. 1987) or 0.5 to 4.5% using settling ponds (U.S. EPA 1983). Clarifier underflows yield slightly higher densities in the order of 1 to 7% (U.S.EPA 1983).

Results of studies at a pilot plant operated at the Brunswick Mining and Smelting Company (Environment Canada 1975) demonstrated that high strength AMD can yield sludge with clarifier underflow solids contents as high as 40% without sludge recycle.

3.3 CHEMICAL COMPOSITION

The chemical compositions of sludges are highly variable and are greatly influenced by the chemical nature of the raw wastewater and the neutralization agents and operations employed. A limited amount of analytical testing has been conducted on sludge samples. Sludge from coal operations is described as being, "generally composed of hydrated ferrous or ferric oxides, gypsum (calcium sulphate), hydrated aluminum oxide, varying amounts of sulphates, calcium, carbonates, bicarbonates, and trace amounts of silica, phosphate, manganese, titanium, copper, and zinc." (U.S.EPA 1983 as cited from Lovell, H.L. 1973. *An Appraisal of Neutralization Process to Treat Coal Mine Drainage.*) Results of Lovell's chemical analysis of sludge samples generated from different drainages and treatment processes that display these characteristics are shown on Table 3.2.

Results of testing of individual sludge samples from selected Canadian facilities (Gionet et al. 1987) are shown on Tables 3.3 (a) and 3.3 (b). The results indicate that the main components of those sludges were calcium (11.4%), iron (6.5%) and zinc (6.1%) (Gionet et al. 1987). Metal analyses of eight sludge samples from the Noranda company (Vachon et al. 1987) indicated the main metallic components to be iron and zinc ranging from 5% to 32% and 2% to 17%, respectively.

3.4 SLUDGE STABILITY

3.4.1 Overview

Few data are available regarding the long term stability of AMD sludges. As a general comment, if sludges are maintained in a geochemical environment similar to that in which they were produced, few concerns should arise as the metals mobility is typically controlled by hydroxide/carbonate equilibrium.

Virtually all equilibrium reactions are reversible, therefore some level of metals mobility can be expected; however, as a general comment, metals mobility from sludges has not proven to be a major issue.

Table 3.1

SURVEY OF SLUDGE DATA - SOLIDS PERCENT

Plant	Percent Solids	Comment
BM-1	5%	No clarifier, disposal to tailings basin.
BM-1	1%	Settling ponds.
BM-1	1%	No clarifier, disposal to tailings basin.
BM-2	3%	Conventional clarifier, no sludge recycle.
BM-6	2%	Reactor clarifier, no sludge recycle.
PM-2	15-20%	Reactor clarifier, no sludge recycle.
BM-7	1%	Clarifier, no sludge recycle.
BM-5	2%	Reactor clarifier, sludge recycle.
BM-4	10-15%	Reactor clarifier, sludge recycle.
BM-3	7-10%	Sludge recycle operation.
BM-8	5%	No clarifier.
BM-9	20-30%	High density sludge operation.
PM-1	2-5%	Settling ponds.
PM-3	2-5%	Reactor clarifier, no sludge recycle.
BM-11	5-10%	Sludge lagoon.
BM-10	5-8%	Sludge pond.

BM - Base metal industry facility

PM - Precious metal industry facility

Source: Gionet et al. 1987.

Table 3.2

CHEMICAL ANALYSES OF SLUDGES

Weight, % (dry basis 105°C-24 hr)

Alkali Used	Hydrated Lime - Air Oxidation			Hydrated Lime Bio- oxidation	Hydrated Dolomite	Calcined Dolomite		
Mine Water	Bennett's	Proctor 1	Proctor 2	Proctor 2	Proctor 2	Tyler	Proctor 1	Proctor 2
COMPONENT								
Al	3.8	4.7	3.1	8.0	2.8	5.5	4.5	4.8
Fe	19.5	17.7	23.1	24.3	13.0	7.4	13.5	23.2
Ca	6.9	5.8	5.2	4.8	17.2	10.7	6.7	5.2
Mg	6.6	4.3	5.1	1.3	3.8	11.8	9.8	5.8
SO ₄	5.7	6.8	5.8	11.5	4.4	1.6	2.3	5.5
H ₂ O at 180°C	12.5	15.8	14.8	--	10.2	8.7	11.7	14.7
COMPOUND COMPOSITION								
Al (OH) ₃	11.1	13.7	8.9	23.1	8.2	16.0	13.2	13.9
Fe(OH) ₃	37.6	34.0	44.3	46.6	24.9	14.2	25.9	44.7
CaCO ₃	11.4	7.5	7.0	0.0	38.3	25.0	14.4	7.2
MgCO ₃	--	--	--	--	--	21.0	12.0	6.1
3MgCO ₃ ·Mg(OH) ₂ ·3H ₂ O	25.2	16.4	19.4	5.1	14.4	22.4	24.6	15.6
CaSO ₄ ·2H ₂ O	10.7	12.7	10.9	20.7	8.4	3.1	4.4	10.4
Total	96.0	84.3	90.5	95.5	94.2	101.7	94.5	97.9

Source: U.S. EPA 1983 based on Lovell 1973.

Table 3.3 (a)

SLUDGE PHYSICAL PROPERTIES ANALYSIS

	Total Solids %	Suspended Solids %	pH	Density g/mL	Sulphate wt%
BASE METAL SLUDGE					
BM-1	2.08	1.37	9.56	1.005	0.86
BM-2	3.63	3.22	10.30	1.010	0.05
BM-3	7.64	7.60	8.46	1.048	2.84
BM-4	20.55	-	9.38	1.135	0.45
BM-5	3.93	2.88	9.35	1.013	0.11
BM-6	1.87	1.22	8.22	1.003	0.43
BM-7	0.59	0.55	8.80	1.003	0.12
BM-8	0.35	0.16	9.84	1.000	0.12
BM-9 Fresh	20.60	-	9.43	1.132	1.87
BM-9 Aged	79.00	-	8.59	2.200	9.72
BM-10 Fresh	15.40	-	9.42	1.060	1.17
BM-10 Aged	25.90	-	9.16	1.170	2.83
BM-11	48.7	-	10.97	1.220	3.60
PRECIOUS METAL SLUDGE					
PM-1	2.81	2.23	10.68	1.008	1.00
PM-2	2.31	2.02	9.40	1.003	0.15
PM-3	2.01	0.76	7.47	1.004	0.15

Source:Gionet et al. 1987.

Table 3.3 (b)

SLUDGE METALS ANALYSES

	WEIGHT (%) (based on dry weight)													
	Al	As	B	Ca	Cd	Cu	Fe	Mg	Mn	Na	Ni	Pb	Sb	Zn
BASE METAL SLUDGE														
BM-1	1.9	-	6.5	1.8	-	-	3.7	2.5	2.1	-	-	-	-	6.3
BM-2	0.63	1.2	2.2	1.1	2.4	-	1.2	5.6	0.7	1.8	-	2.0	-	7.0
BM-3	-	-	1.1	0.8	-	-	-	-	-	-	-	-	-	27.4
BM-4	-	-	-	34.4	-	-	0.6	1.2	-	-	-	-	-	5.2
BM-5	-	-	0.63	16.0	-	-	0.7	3.1	-	3.3	-	-	-	1.4
BM-6	-	-	-	8.2	-	-	29.4	2.1	-	-	-	-	-	2.6
BM-7	-	-	6.6	16.5	-	-	10.1	4.5	0.5	-	6.3	-	-	-
BM-8	-	-	-	14.7	-	-	6.6	4.4	-	-	-	-	-	1.6
BM-9 Fresh	1.0	-	-	2.5	-	-	25.3	7.3	1.5	-	-	-	-	2.4
BM-9 Aged	1.9	-	-	8.1	-	2.5	25.0	3.1	1.8	-	-	0.66	-	2.5
BM-10 Fresh	3.0	-	-	3.9	-	-	19.3	5.1	0.5	-	-	-	-	1.4
BM-10 Aged	2.0	-	-	5.8	-	-	20.5	4.2	-	-	-	-	-	0.9
BM-11	1.2	-	-	8.2	-	-	2.0	1.0	-	-	-	-	-	14.3
PRECIOUS METAL SLUDGE														
PM-1	2.4	-	2.1	20.8	-	-	2.7	1.6	-	-	-	-	-	-
PM-2	7.3	-	-	26.5	-	6.5	38.4	1.2	-	-	1.7	-	5.4	-
PM-3	-	1.5	-	13.6	-	-	16.9	-	-	6.5	-	-	-	-

Source: Gionet et al. 1987.

Table 3.4

SLUDGE LEACHATE ANALYSIS*

	Leaching** Procedure	Initial pH	Final pH	As (mg/L)	Cd (mg/L)	Cr (mg/L)	Cu (mg/L)	Fe (mg/L)	Ni (mg/L)	Pb (mg/L)	Sb (mg/L)	Zn (mg/L)
BASE METAL SLUDGE												
BM-1	L1	4.00	8.96	-	0	-	0	0	0	0	-	0
	L2	2.50	6.70	-	0.1	-	0	0.3	0	0	-	16.0
	L3	4.00	4.00	-	0.1	-	0.3	0.5	0.2	0	-	95.0
	L4	2.30	2.30	-	0.1	-	0.4	45.0	0.3	0	-	120.0
	L5		4.66	-	0.1	-	0.3	2.0	0	0	-	90.0
	L6		9.83	-	0	-	0	0	0	0	-	0
BM-2	L1	4.00	9.86	0.006	0	-	0.3	0	0	0	-	0
	L2	2.50	8.90	-	0.2	-	0.3	0	0	0	-	0
	L3	3.90	3.90	-	63.0	-	0.3	1.0	0.5	6.7	-	220.0
	L4	2.67	2.67	2.7	63.0	-	0.4	4.1	0.6	4.2	-	225.0
	L5		5.47	0.57	59.0	-	0.2	0.3	0.5	12.0	-	208.0
	L6		10.39	-	0.1	-	0	0	0	0	-	0
BM-3	L1	4.00	8.30	-	0.1	-	0	0		0	-	1.3
	L2	2.50	6.96	-	0.7	-	0	0	0	0	-	7.5
	L3	4.05	4.05	-	3.2	-	21.0	1.0	0.3	1.5	-	1900.0
	L4	2.56	2.56	-	3.2	-	21.0	6.4	0.3	2.0	-	1900.0
	L5		5.52	-	2.7	-	18.0	0.3	0.4	2.0	-	1900.0
	L6		8.77	-	<0.1	-	0	0	0.2	0	-	2.7
BM-4	L1	4.00	9.39	-	0	0	0	0	0	0	-	0
	L2	2.50	8.72	-	0	0	0.1	0	0	0	-	0
	L3	4.10	4.10	-	2.1	0	12.0	3.5	0.8	0	-	970.0
	L4	2.59	2.59	-	2.2	0	13.0	22.0	1.0	0.5	-	970.0
	L5	4.50	6.25	-	0.4	0	2.0	0	0.7	0	-	680.0
	L6		9.85	-	0	-	0	0	0	0	-	1.5
BM-5	L1	4.00	9.32	-	0	-	0	0	0	0	-	0
	L2	2.50	8.87	-	0	-	0	0	0	0	-	0
	L3	4.00	4.21	-	0.4	-	2.0	3.0	0.8	0	-	310.0
	L4	2.50	2.58	-	0.4	-	3.0	25.0	0.9	0.5	-	375.0
	L5	4.50	5.30	-	0.4	-	1.0	1.0	0.7	0	-	400.0
	L6		8.47	-	0	-	0	0	0	0	-	0.8
BM-6	L1	4.00	8.20	-	0	-	0	0	0	0	-	0
	L2	2.50	5.62	-	0.1	-	0.7	2.0	0	0	-	13.0
	L3	4.00	4.13	-	0.1	-	0.3	2.5	0	0	-	34.0
	L4	2.50	2.40	-	0.1	-	0.3	87.0	0.3	0	-	30.0
	L5	4.50	4.60	-	0.1	-	0.3	1.0	0.2	0	-	21.0
	L6		7.88	-	0	-	0	0	0	0	-	0

Table 3.4 Cont'd

BASE METAL SLUDGE LEACHATES, CONT'D												
BM-7	L1	4.00	8.66	-	0	-	0	0.5	1.2	0	-	0
	L2	2.50	6.78	-	0	-	0	0.5	9.5	0	-	0
	L3	4.00	4.24	-	0	-	0.8	0.3	28.3	0	-	0.6
	L4	2.50	2.40	-	0	-	1.1	42.0	33.0	0	-	0.6
	L5	4.50	4.64	-	0	-	1.0	1.0	27.5	0	-	1.1
	L6		8.91	-	0	-	0	0.5	1.0	0	-	0
BM-8	L1	4.00	8.98	-	0	-	0.3	0	0	0	-	0.9
	L2	2.50	3.16	-	0	-	0.7	6.1	0	0	-	5.9
	L3	4.00	4.03	-	0	-	0.3	3.1	0	0	-	5.7
	L4	2.50	2.67	-	0	-	0.5	22.0	0.3	0.1	-	6.1
	L5	4.50	4.61	-	0	-	0.5	2.0	0.2	0.2	-	6.5
	L6		9.05	-	0	-	0	0	0	0	-	0.1
BM-9	L1	4.00	9.10	-	-	0	0	0	0	0	-	0.1
	L2	2.50	8.87	-	-	0	0	0	0	0	-	0.1
	L3	4.00	4.34	-	1.5	-	11.0	0	2.3	1.0	-	365.0
	L4	2.50	2.72	-	1.8	-	66.0	125.0	2.5	5.0	-	420.0
	L5	4.50	7.87	-	0	-	0	0	0	1.0	-	0.1
	L6		9.23	-	0	-	0	0	0	0	-	0.1
BM-9-0	L1	4.00	8.27	-	0	-	0	0	0	0	-	0.1
	L2	2.50	8.17	-	0	-	0	0	0	0.3	-	0.1
	L3	4.00	4.27	-	1.2	-	0.8	0.5	4.5	1.0	-	850.0
	L4	2.50	3.29	-	2.3	-	7.5	6.0	5.5	4.0	-	1265.0
	L5	4.50	7.40	-	0	-	9	0	9	0.7	-	0.2
	L6		9.17	-	0	-	0	0	0	0	-	0.1
BM-10	L1	4.00	9.28	-	0	-	0	0.5	0	0	-	0
	L2	2.50	9.10	-	0	-	0	0.5	0	0	-	0.1
	L3	4.00	4.10	-	0.4	-	18.6	1.0	1.0	0.3	-	232.0
	L4	2.50	2.54	-	0.5	-	49.0	770.0	1.3	0.8	-	266.0
	L5	4.50	7.17	-	0	-	0	0.5	0.2	0.4	-	1.4
	L6		9.17	-	0	-	0	0	0	0	-	0
BM-10-0	L1	4.00	9.14	-	0	-	0	0.5	0	0	-	0
	L2	2.50	8.88	-	0	-	0	0.5	0	0	-	0.1
	L3	4.00	4.22	-	0.3	-	6.6	2.0	0.7	0	-	170.0
	L4	2.50	2.73	-	0.8	-	58.0	220.0	0.8	0.4	-	330.0
	L5	4.50	7.90	-	0	-	0	0	0.2	0.4	-	0.1
	L6		9.03	-	0	-	0	0	0	0	-	0

Table 3.4 Cont'd

BM-11	L1	4.00	11.07	-	0	-	0	0	0	0	-	0.3
	L2	2.50	11.07	-	0	-	0	0	0	0	-	0.2
	L3	4.00	4.15	-	18.0	-	55.0	1.0	1.3	0	-	5120.0
	L4	2.50	2.56	-	21.0	-	93.0	690.0	1.5	1.9	-	5380.0
	L5	4.50	10.49	-	0	-	0	0.5	0.3	0.4	-	0.1
	L6		11.16	-	0	-	0	0	0	0	-	0
PRECIOUS METAL SLUDGE LEACHATE												
PM-1	L1	4.00	10.67	-	0	-	0.2	1.5	0	0	-	0.1
	L2	2.50	10.06	-	Tr	-	0.2	0.5	0	0	-	0
	L3	4.00	4.21	-	0.1	-	11.0	0	1.3	0	-	7.6
	L4	2.50	2.62	-	0.1	-	13.0	67.0	1.5	0	-	8.1
	L5	4.50	4.72	-	0.1	-	11.0	14.0	1.0	0	-	7.5
	L6		9.30	-	0	-	0	0	0	0	-	0
PM-2	L1	4.00	9.40	-		-	1.7	8.6	0.5	0	1.1	0.1
	L2	2.50	7.98	-	0	0	0.4	1.5	0.5	0	-	0
	L3	4.00	4.13	-	0	-	40.0	0.3	18.3	0	-	2.0
	L4	2.50	2.56	-	-	-	55.0	94.0	21.1	0	0.014	2.4
	L5	4.50	7.32	-	0	0	39.0	0.5	13.6	0	0.11	2.3
	L6			-	0	0	0.2	1.0	0	0	-	0
PM-3	L1	4.00	7.30	0.012	0	-	0	0	0	0	-	0
	L2	2.50	3.40	-	0	-	4.4	1.0	0	0	-	1.6
	L3	4.0	4.02	-	0	-	3.4	0	0	0	-	1.5
	L4	2.50	2.57	0.118	0	-	4.7	55.0	0	0	-	1.6
	L5	4.50	4.57	0.014	0	-	3.2	0	0.2	0.3	-	1.4
	L6		7.50	-	0		0	0	0	0	-	0

Note:

*
 (-) not determined
 (o) below detection limit

** Leaching Procedure

L1 - 1/10 dilution of sludge in H₂SO₄ solution at initial pH 4
 L2 - 1/10 dilution of sludge in H₂SO₄ solution at initial pH 2.5
 L3 - 1/10 dilution of sludge in H₂SO₄ solution maintained at pH 4
 L4 - 1/10 dilution of sludge in H₂SO₄ solution maintained at pH 2.5
 L5 - 1/10 dilution of sludge in acetic acid and sodium acetate solution at initial pH 4.5
 L6 - 1/10 dilution of sludge in distilled water

Source: Gionet et al. 1987.

Table 3.5

DISSOLUTION OF Cu-Pb-Zn SLUDGE

pH of Leach Solution	4.0	5.0	7.0
Cu (mg/L)	1,520	47	0.3
Zn (mg/L)	2,330	570	5.3
Fe (mg/L)	4.7	0.2	0.5
Wt. Loss (%)	4.0	1.6	1.2

Reference: Environment Canada 1975 based on 1973 Chemical Buyers Guide.

Table 3.6

**FRACTION OF IRON SOLUBILIZED AT pH 3 FROM
SLUDGE TREATED WITH THE LISTED CHEMICAL**

Iron Level	Na₂CO₃	NaOH	Ca(OH)₂
Low	0.58	0.12	0.11
Medium	0.69	0.09	0.16
High	0.13	0.04	0.04

Whether or not similar benefits occur with other heavy metals such as zinc is not known.

Source: Watzlaf and Casson, 1990.

Table 3.7

CANADIAN SLUDGE DISPOSAL PRACTICES

Method of Disposal	No. Reported	% of Total
Tailings Ponds	14	35%
Settling (Sludge) Ponds	17	43%
Recycled to Smelter	4	10%
Landfill	2	5%
Lake	2	5%
Open Pit Mine	1	2%

Source: Gionet 1987.

Table 3.8

PRELIMINARY EVALUATION OF SLUDGE TREATMENT COSTS

Principal Revenue and Costs		\$Cost or Revenue Per Wet ton of Sludge
REVENUE:	Revenue from copper recovery 166 lbs. Cu at \$Cdn. 1.15 =	190.00
COST:	Transportation allowance Smelter treatment allowance Moisture Penalty (60%)	(40.00) (100.00) <u>(70.00)</u>
Subtotal (Loss)		(20.00)*

*

Does not include additional costs that would be incurred for: sampling and assaying; contaminant penalties; special handling or the costs incurred at the AMD treatment facility to dry the sludge to 60% moisture prior to shipment.

The concern over metals leaching from AMD sludges arises from the fact that the composition of sludges include a variety of metal oxides and metals in other forms which can mobilize under certain conditions. For example, if sludges are exposed to low pH water, metals will be dissolved. As well, if adequate buffering is not available, some dissolution of precipitated metal can occur if exposed to near neutral water. The level of mobility is a strong function of metals present and the physico-chemical properties of the sludge.

3.4.2 Factors Affecting Stability

The following is a review of some of the key factors which can affect sludge stability.

i) Excess Buffering Capacity

Sludges which have excess lime (generally as $\text{Ca}(\text{OH})_2/\text{CaCO}_3$) are less likely to be leachable. Under alkaline conditions most metals are virtually insoluble. Even nickel and zinc are only sparingly soluble when pH levels are maintained above 8.5. For disposal of sludges in a landfill with percolation of rainfall, concern arises as to whether the metals will be mobilized by marginally acidic rain. If the landfill permitted 0.25 m of rain to enter the sludge and react, the rain water would be neutralized and some alkali/metals dissolution would occur. Typical alkali demand to raise pH of rain water to greater than 8.5 would be perhaps 20 mg/L of CaCO_3 . This would consume about 5 g $\text{CaCO}_3/(\text{m}^2 \text{ a})$. For a 3 metre deep deposit of sludge at 40% solids and 10% free CaCO_3 there would be 0.2 t CaCO_3/m^2 of landfill which could consume acidity from about 40,000 years of incident rainfall. Although some modest pH depression could occur, no major metals mobility is expected. Testwork completed by Gionet et al. (1987) confirmed that leaching with distilled water had minimal effects on metals mobility. Of 16 sludges leached with distilled water at a solids:liquid ratio of 1:10, 10 showed no metals mobilized. Of the remaining, zinc was mobilized at levels ranging from 0.1 to 2.7 mg/L in 6 leachates while nickel was mobilized at 0.2 mg/L in one leachate.

In summary, metals mobility should be a minor concern when sludges contain some level of excess lime. This presents a potential concern when caustic or soda ash are employed as these reagents are highly pure and fully react leaving no excess alkalinity to buffer potential pH depression from rain water.

ii) Iron Content and State

Iron hydroxides as amorphous solids can assist in controlling mobility of many metals. Iron serves as a co-precipitate for several metals (e.g. arsenic, manganese, molybdenum) and also provides adsorption sites for removal of many metals (arsenic, nickel, etc.). The relative iron content can be important with sludge stability improving with increasing iron:metals ratios (Watzlaf and Casson 1990).

The oxidation state can also impact on sludge stability. If sludges contain ferrous hydroxide ($\text{Fe}(\text{OH})_2$), this precipitate can mobilize at pH levels of <8.5 to 9. This contributes iron to solution and may well release metals which are contained as adsorbed species. Conversely, if precipitated in the ferric form as ferric hydroxide ($\text{Fe}(\text{OH})_3$), iron is mobilized at pH levels of <2 to 3, above which the iron hydroxides assist in controlling metal mobility.

iii) Gypsum

Gypsum precipitates are soluble. As a general rule, gypsum content is very high for many sludges and dissolution maintains saturation. This does not appear to have any great effect on metals mobility except perhaps radium-226. Radium-226 mobility is generally controlled by metal sulphates. Radium can be released by gypsum dissolution if radium is co-precipitated with gypsum. Furthermore, if gypsum becomes depleted, sulphate levels decline making other radium containing co-precipitates more soluble (e.g. BaSO_4).

iv) Crystallinity/Sludge Age

The type of sludge formed (amorphous vs. crystalline) may have an impact on metals mobility. Certain crystalline minerals are less mobile than their amorphous precipitates (e.g iron). Few data are available to confirm whether mobility is decreased by changing the physical nature of the precipitate. Gionet et al. (1987) report no change in sludge solubility between old and fresh sludges. Watzlaf et al. 1990 indicate aging reduces the mobility of iron and manganese and further indicates aging in air rather than under water was more effective.

v) Acidification

Virtually all sludges become unstable when acidified. Results of various leaching tests on sludges using five acid solutions and distilled water are reported in Table 3.4 (from Gionet et al. 1987). These are based on batch testing in which samples were agitated for a 24-hour period. As expected, metal solubilities are a direct function of the leaching pH.

Similar results are reported by Environment Canada (1975) as shown in Table 3.5. These results are for column tests in which a sludge formed from lime neutralization was leached for several days with solutions at the indicated pH's.

vi) *Chemical Precipitant*

The effectiveness of various alkalis on sludge stability is not well known. Watzlaf and Casson (1990) concluded that lime and caustic produced sludges that had better chemical stability to acid leachate than did sodium carbonate produced sludges. Selected results are summarized in Table 3.6.

3.4.3 High Density Sludge

The High Density Sludge (HDS) process creates a denser sludge through mechanical means. Conventional equipment can be adapted to produce these high density sludges. In this process, sludge is returned from the final clarifier. The return sludge is blended with lime then reprocessed with raw wastewater in the chemical oxidation reactor. The rate of sludge return is adjusted to achieve maximum density. Testing of sludge recirculation volumes of up to 50% indicated that the highest sludge densities are obtained with a 50% recycle rate (Yamabe 1990).

The sludge recycle process promotes growth of larger sludge particles than conventional methods. The particles tend to attract heavy metals and repel water. Particles are changed from appearing ragged and porous to being rounder and of higher density, making filtration easier and reducing moisture content in the final sludge.

With gravity settling, a solids content of 25% may be typical. Dewatering can further reduce the water content to 40% (Tetra Technologies n.d.). In actual applications, reported sludge solids contents have varied from 20 to 25% at Brunswick Mining, over 20% at Les Mines Gallen, and between 25 to 30% at La Mine Doyon. The 20+% solids sludge from the Sullivan mine near Kimberley, B.C. is reported to drain freely and rapidly achieve 40 to 50% solids. A pilot plant at Brunswick Mining demonstrated an increase in solids from 2% to 15% as a result of sludge recycle.

It should be noted that high densities are not generally achieved immediately following start-up. At Kimberley and Matabi, sludge was shipped from another treatment plant in order to get the process started. At Brunswick Mining, the process was started at reduced flows in order to build up sludge densities. Full production commenced when sludge densities reached 12%. They continued rising, reaching 18% after one week and 20+% in the second week.

The stability of the sludge from the HDS process at the Sullivan mine is attributed to the high iron to metals ratio. The iron apparently co-precipitates with calcium onto the recycled sludge particles. The addition of iron to AMD is suggested by Murdock et al. (1994) in cases of low iron concentrations as a means of improving sludge stability. Also of importance to the sludge stability is the complete oxidation of ferrous iron during

treatment.

3.4.4 Other Concerns

In addition to the concerns regarding sludge volumes, concerns have been raised about the toxicity and long term stability of sludges. In the United States, the Federal Solid Waste Act sets out specific requirements for the disposal of hazardous materials in a section of the Act referred to as Subtitle C. AMD chemical treatment sludges are, in many cases, considered to be equivalent to tailings solids. Questions are, however, being posed as to whether or not sludges in the United States should be disposed of in accordance with Subtitle C.

Concerns that some AMD treatment sludges could be considered to be hazardous waste have also been raised in Canada. One study carried out by Gionet et al. (1987) compared sludge leach test results to limits included in Quebec's Hazardous Waste Regulations. Results indicated that zinc, nickel, cadmium, and copper concentrations in leachate exceeded the regulatory requirements in up to 50% of the samples tested. The report stated that:

The Quebec Hazardous Waste Regulations require solid wastes classified as hazardous to be disposed to an approved site. The situation is similar in the other provinces. The results of this study suggest that effluent treatment sludges produced by the Canadian Mineral Industry effluent treatment facilities are hazardous in many cases, and that the current disposal methods are inadequate from the regulatory point of view. As indicated, in many cases these sludges are currently disposed with mine tailings.

3.5 DEWATERING OF SLUDGES

The extent to which a sludge can be dewatered depends on its chemical properties and its physical properties such as initial solids content, age, temperature, viscosity and compressibility. A number of processes are available for dewatering sludges; these are described in the following sections.

3.5.1 Natural Dewatering

Lagoons or settling ponds, singly or in series or parallel are commonly used to consolidate and thicken sludge to a more easily handled form.

Drying of sludge on a porous bed may yield up to 20% solids but is only suitable for low rates of sludge production. The approximate drying area that might be required for a 4000 m³/d plant would be 7000 m². Types of filter media that have been used include sand, crushed limestone, gravel and coal. Removing the final dried sludge from the bed can present a problem. The effects of regional weather patterns on this method must be considered.

Noranda's Waite Amulet plant used a sand bed underdrainage system. A sludge with an initial solids content of 6 to 8% was dried to about 17% solids. Freezing further dewatered the sludge to about 20%. The freezing of sludge frees water molecules which then drain freely from sludge after thawing. The more coarse, granular sludge particles settle to about 30% solids (Environment Canada 1975).

3.5.2 Mechanical Dewatering

3.5.2.1 Vacuum Filtration

The most common type of vacuum filter is the revolving drum. The filter media (cloth) can be made from a number of different materials including polyethylene. The drum rotates slowly (less than one revolution per minute) with approximately 25% of its surface area submerged. The vacuum cells that run along the length of the drum draw a cake to the filter media. As the drum continues to rotate, drying occurs and the cake is removed by air blasting or scrapers.

Vacuum filtration may achieve 24 to 35% solids and may be more economical for sludge with an initial solids content of 5% or more than for sludges with low (<2%) solids contents since filtration rates for these are low. Tests conducted by Lovell (as cited by U.S.EPA 1983) yielded filtration rates of 74 to 150 kg/(m² d) for sludges with less than 2% solids and 610 to 1600 kg/(m² d) for sludges with 5% or higher solids contents.

3.5.2.2 Pressure Filtration

Pressure filtration uses a similar principle to vacuum filtration. Sludge is fed into filtration chambers under pressure. The solids are held within the chambers while liquid is forced through the filter medium. Once the chambers are full or a desired maximum pressure is obtained, the chambers are opened and the filter cake removed.

Pressure filters have been effectively used in dewatering AMD sludge in a pilot plant, achieving 38 to 45% solids (Environment Canada 1975). The EPA Design Manual (U.S.EPA 1983) indicates much lower actual solids contents of 9 to 26% from pressure filtration.

Operating costs tend to be high and operation is not continuous making it inappropriate for dewatering of large quantities of sludge.

3.5.2.3 Centrifugation

Centrifuges consist of revolving solid bowls into which the sludge is fed. The dewatered sludge is removed by either a screw conveyor or a blade scraper. Centrifugation may be effective for some sludges and unsuitable for others depending on the initial sludge characteristics.

3.5.2.4 Other Methods

Testing has been conducted on the feasibility of applying an electrical current as a method for increasing sludge densities. In a full scale test conducted in Washington, a current was applied between buried and floating electrodes in a sludge pond. The results were solids contents of 26 to 30% by weight. Most of the sludge became very firm except for the upper 10 to 15% and outlying areas which were softer but cohesive. Detailed design methods for this system are available (Sprute et al. 1988).

3.6 SLUDGE DISPOSAL

Table 3.7 provides a breakdown of sludge disposal practices at Canadian operations surveyed during an earlier study (Gionet et al. 1987). Current sludge disposal practices used in Canada include:

1. permanent deposition in settling basins, tailings basins, open pits or quarries, or special cells;
2. haulage off-site to another facility for permanent storage;
3. recycling to metallurgical process/smelter.

The disposal of sludge that will be produced following mine closure has yet to be resolved at several operations. Current practices are discussed in greater detail in Section 4.0.

Sludge disposal practices addressed in technical literature indicate that:

- Disposal in abandoned deep mines is a common practice in the United States, subject to guidelines that the sludge pH be at least 7.0 and that all iron be in the ferric form. The Surface Mining Control and Reclamation Act (1977) in the United States requires that all acid forming mine waste be covered with material that can achieve an ecologically stable level of use.
- Pilot work has been done by Equity Silver Mines Ltd. on placing sludge within acid rock dumps. This proved to be unsuccessful as much of the sludge redissolved. (SENES 1987).
- At the Sullivan mine near Kimberley, B.C., an excess of lime is added to the dewatered sludge from the HDS process before discharge to the impoundment area. As shrinkage and cracking occur, atmospheric carbon dioxide reacts with the added lime to form calcium carbonate and improves the stability of the sludge. According to Murdock et al. (1994), based on monitoring of wells surrounding the sludge impoundment area, "to date, re-release of the metals to the environment is not occurring, and therefore the sludge is stable."
- Methods of converting sludge to stable forms by chemical fixation with proprietary chemicals and/or encapsulation have been proposed but the feasibility of the processes have not been demonstrated. These methods generally involve the addition of stabilizing chemicals and/or cement to harden the material or encapsulation in polyurethane, polyethylene, asphalt or concrete.

3.6.1 Smelting of Sludges

In concept, revenue from recycled metals could be used to offset, at least in part, the cost of AMD treatment and provide a permanent sludge disposal solution. The recovery of metal from sludges was discussed with contacts at smelters.

It was found that:

- Sludge is being recycled to smelters when the sludge is acceptable both physically and chemically for processing; however, this practice is not wide spread.
- The selective recovery of metals from sludges at AMD chemical treatment plants has been considered on several occasions both in Canada and the United States. Evaluations carried out to date indicate that when elevated metal concentrations are present in sludge, the

revenue from metal recovery can only offset about 40 percent of the sludge treatment/metal recovery cost.

Smelters have considered receiving and custom treating AMD chemical treatment sludges. Smelters are permitted as metallurgical facilities, as opposed to waste disposal facilities, and their operations are governed by conditions established by both the companies and regulatory agencies. As such, sludges must meet certain basic criteria:

- metal concentrations are to be sufficient to permit economical removal;
- the sludge cannot contain free standing water; and
- the concentration of contaminants must not exceed specified limits.

From an operating view point, the smelting of sludges present problems due to:

- their physical form which dictates special handling including thawing during cold weather months;
- obtaining a representative smelter assay sample; and
- potentially elevated concentrations of undesirable contaminants such as arsenic, cadmium, and bismuth. The collection and disposal of such contaminants presents additional costs and liabilities to smelter operators.
- potential effect on metallurgical operations and product quality.

As part of this study, the cost to treat a sludge containing 60% moisture and a 5% Cu content (on a wet basis equivalent to 12.5% on a dry basis) was evaluated on a preliminary basis. It was found that smelter schedule charges (treatment costs) are high when compared to the sludge value. It was suggested that revenue from recovered metal would be insignificant when compared to total smelter treatment costs. The preliminary cost analysis is provided in Table 3.8.

The potential exists, however, to upgrade sludges to make them suitable as smelter feed. The key requirements for a sludge suitable as smelter feed are envisaged to be:

1. A minimum metal value of approximately \$100 per wet ton of sludge;
2. A relatively dry sludge - a moisture content of 25% would be more than acceptable; and
3. Relatively clean sludge with no or low concentrations of specific contaminants such as arsenic, antimony, bismuth, cadmium, and selenium.

At present, sludge from one AMD chemical treatment facility is dried and rail hauled over considerable distance to a smelter. The sludge metal content ranges from 7 to 10% Cu (on a dry basis) and moisture content is approximately 60% by weight.

3.6.2 Reprocessing of Sludges

Recovery of metals from hydroxide sludges from the metal finishing and electrochemical machining industries has been proposed as an alternative to disposal as hazardous waste (Twidwell et al. 1990). The methods tested on these types of sludges may be applicable to AMD chemical treatment sludges.

Because of high costs and small-scale generators, a central treatment facility is proposed as the only realistic means of implementing such treatment. Each metal is removed selectively by individual processes. The process tested by Twidwell et al. (1990) involves the dissolution of metals by leaching with sulphuric acid. Once redissolved, the solution undergoes the following processes:

- copper removal by solvent extraction;
- oxidation and removal of ferric iron;
- chromium removal by phosphate precipitation;
- removal of cadmium by cementation on zinc and filtration; and
- sulphide precipitation of nickel.

These procedures follow the same general methods as those described in Section 2.4.2 for selective metal removal from AMD. A high degree of metals removal and a high degree of purity can be achieved by these methods. The procedure is still experimental and is not known to have been tested on AMD sludges. No information is available on the potential cost, the value of recovered precious metals, disposal of by-products such as residual sludge left after leaching or residual leachate solution, or the potential for use (or disposal) of recovered metals.

Procedures employed would vary depending on the properties of individual sludges. This would further

complicate implementation of sludge reprocessing.

3.6.3 Sludge Fixation and Encapsulation

Techniques for chemical fixation and encapsulation have developed for stabilizing wastes such as AMD sludges prior to disposal. Fixation generally involves the additions of proprietary chemicals to sludges. The mixture hardens shortly after placement in an appropriate disposal site. Encapsulation is used to prevent contact with water and thus limit leaching of toxic chemicals.

The Sealosafe process developed in Great Britain has been used to treat wastes such as metal finishing wastes and mine tailings. The waste is transported to a disposal site as a slurry after addition of reagents. It hardens to an inert form within a few days.

The Soliric process, developed by a Belgian firm (Cemstobel SA), employs a reagent and cement to stabilize and solidify waste material (Canadian Mining Journal 1980). The Chemfix process uses silicates and setting agents for fixation (Canadian Mining Journal 1980). The ARCHON process (ITEX Environmental Services Inc.) uses cement and lime, increasing waste volumes 5 to 25% (Toor n.d.). Cementitious materials are also produced by the PoZ-O-Tec process, IU Conversion Systems, (Canadian Mining Journal 1980). PoZ-O-Cap, marketed as a dust control agent, is a similar lime based cementitious material, designed to react in place to form a solid surface layer (Curtis n.d.). Many other proprietary systems are available.

Materials sometimes used for encapsulation include polyurethane, asphalt, concrete or polyethylene. In a method developed in the U.S., wastes are fixated with polybutadiene and encapsulated in polyethylene (Canadian Mining Journal 1980).

All of these processes have the disadvantage of increasing total disposal volumes required. In general, the increase in volume is equal to the volume of the additives or encapsulation materials. Because of physical characteristics, disposal may be even more difficult for the treated material than for the original sludge.

4.0 AMD CHEMICAL TREATMENT PRACTICES

4.1 GENERAL

Information regarding AMD chemical treatment practices was obtained through a review of current and relevant technical literature (summarized in Appendix A) and discussions with contacts at:

- mining companies;
- industry associations;
- research organizations, consultants, suppliers,
- water treatment specialty firms, and
- government ministries and agencies.

A listing of companies and organizations contacted is provided in Appendix B. The listing was designed to provide information on AMD treatment at:

- base metal, gold, uranium, and coal producers throughout Canada;
- both small mines (under 500 tpd ore production) and large mines;
- active and recently closed mines; and
- new mines either being developed or at the advanced feasibility stage.

4.2 OVERVIEW

Considerable experience has been attained in the design, operation, and maintenance of AMD chemical treatment facilities.

It was found that, with few exceptions, AMD is chemically treated using lime - usually sourced as quicklime or hydrated lime. Other alkalis used are limestone and sodium hydroxide.

Chemical treatment facilities in use at both active and recently closed mines include:

1. batch treatment;
2. continuous treatment with a low density sludge by-product; and
3. continuous treatment with a high density sludge by-product.

A wide range of physical components and sludge disposal methods are used as indicated in Table 4.1.

Efforts continue to be made at active mines to, whenever practical, prevent or inhibit the generation of acid. Some active sites, however, forecast extended post-closure AMD treatment. At some recently closed (or otherwise inactive) sites where AMD is a concern, treatment is forecast to be required for varying amounts of time ranging from a few years to hundreds of years.

At new mines, not yet in production, plans are to prevent AMD whenever possible. Chemical treatment systems, if required, will likely use proven lime neutralization technology.

4.3 INFORMATION BASE

The following key information was summarized for 14 sites:

- The characteristics of the inflow to the treatment facility in terms of flowrate, pH, and principal contaminant concentrations.
- The consumption of alkali used to neutralize acidity/precipitate metals.
- Whether or not mechanical aeration is used (if required) to oxidize ferrous iron.
- The consumption of flocculant (if used).
- Sludge characteristics and method of sludge disposal.
- The capital or estimated replacement cost of the chemical treatment facility (excluding the associated water management and sludge disposal systems).
- The direct cost of AMD chemical treatment.

The information is summarized in Table 4.2.

AMD at the 14 sites included in Table 4.2 is treated using either conventional or high density sludge type processes. At the 10 sites where conventional treatment is used there are wide ranges in physical layout, point of alkali addition, etc. as shown below.

TREATMENT FACILITIES

Table 4.1

PHYSICAL VARIATIONS IN AMD CHEMICAL TREATMENT SYSTEMS

Process Component	Physical Variations
NEUTRALIZATION WITH LIME	<ul style="list-style-type: none"> in AMD streamflow in basins in reactor(s) in reactor/clarifier(s) aeration not always used
PRECIPITATION	<ul style="list-style-type: none"> in reactor/clarifier(s) in thickeners in settling basins in tailings management areas flocculants not always used high density sludges are produced at some sites
SLUDGE DISPOSAL	<ul style="list-style-type: none"> in tailings management areas in settling basins in special cells or drying beds recycled to metallurgical process in at least two cases, sludge is transported to another site for disposal
POLISHED EFFLUENT	<ul style="list-style-type: none"> released to the receiving environment may be recycled to metallurgical process

INCLUDED IN INFORMATION BASE

Quantity	Site Number (as per Table 4.2)	Description
1	#1	- AMD is batch treated in a basin as required.
2	#2 to #3	- AMD stream flows are continuously treated as they flow to a settling basin.
7	#4 to #10	- AMD is continuously treated in reactors and a low density sludge is produced.
4	#11 to #14	- AMD is continuously treated using a high density sludge process.

A general discussion of the information is provided below.

General Characteristics of AMD:

The pH and concentrations of iron, zinc, copper, and lead contained in the inflow to the 14 treatment facilities is listed in Table 4.3. These are compared to typical assays of acidic waters as identified by Environment Canada (1975). The table indicates that there are wide variations in contaminant concentrations from site to site. This is to be expected given that chemical treatment inflow characteristics are largely dependent on site-specific factors such as:

- the nature of both reactive and acid buffering materials;
- the state of complex sulphide oxidation reactions;
- the stage of the acid generation/release process at the site;
- the pre-treatment mixing of diverse flows including AMD, tailings area decant and seepage, mine and mill water, and run-off;
- the inhibition of further AMD generation at some sites; and
- seasonal variations.

Table 4.2a

SUMMARY OF SELECTED SITE INFORMATION

Site No.	General Characteristics of AMD				Neutralization		
	Average Flowrate of Water Treated Daily	pH	Primary Contaminants		Alkali Purchased As	Alkali Consumption Per m ³ of Influent	Mixing Location
			Element	Concentration			
1	6,000 m ³ /day (avg.)	3	Fe, Zn, Cu	Not available	Ca(OH) ₂	1.0 kg/m ³	Batch addition to acid collection pond
2	47,000 m ³ /day (avg.)	3-7	Fe Zn Cu	<1-25 mg/L 1-100 mg/L <0.1-5 mg/L	CaO	0.38 kg/m ³	AMD stream flow to settling basin
3	42,000 m ³ /day (avg.)	3-3.5	Fe Zn Ni	4 mg/L <0.2 mg/L 1.5 - 2 mg/L	CaO	0.09 kg/m ³	AMD stream flow to natural basin
4	2,200 m ³ /day	2.4	Fe Zn Cu	800 mg/L 80 mg/L 120 mg/L	CaO	1.84 kg/m ³	Reactor
5	2,800 m ³ /day (avg.)	2-2.5	Zn	700 mg/L	Ca(OH) ₂	2.7 kg/m ³	Reactor
6	7,000 m ³ /day (avg.)	3.6	Fe Cu Zn SO ₄	474.7 mg/L 1.5 mg/L 43.49 mg/L 2902 mg/L	CaO	0.85 kg/m ³	Reactor
7	8,600 m ³ /day (avg.)	7.5	Fe Zn Cd	2 mg/L 5.5 mg/L <1 mg/L	CaO	0.06 kg/m ³	Two reactor tanks in series
8	10,400 m ³ /day (typical) (operated 7 to 8 months per year)	6.85-7.40	Fe Cu, Ni, Pb, Zn Mg	0.33 mg/L 0.10 mg/L (sum) 1.80 mg/L	Ca(OH) ₂	0.05 kg/m ³	Two treatment ponds

Table 4.2b

SUMMARY OF SELECTED SITE INFORMATION

Site No.	Mechanical Aeration		Precipitation			Sludge Characteristics and Disposal	Capital and Operating Cost	
	Is Mechanical Aeration Used?	Location	Flocculant Used	Flocculant Consumption	Point of Addition		Capital Cost *	Estimated Direct Operating Cost of AMD Treatment
1	No	--	None	--	--	Stored in collection treatment basin.	Not available	\$0.13/m ³
2	No	--	None	--	--	Sludge settles in a large basin. Sludge is dredged and placed in a special disposal cell. Sludge volume is reduced significantly through natural freeze/thaw process.	\$5,000,000 (est.)	\$1.05/m ³ (includes lime, labour, sludge disposal and maintenance costs)
3	No	--	None	--	--	Low density sludge settle in an extensive natural basin.	Not available	\$0.03/m ³
4	No	--	None	--	--	Treated AMD flows to a sludge pond where sludge is allowed to settle. Settled sludge is disposed in an open pit.	\$2,000,000 (est.)	\$1.14/m ³
5	Yes	Tanks	None	--	--	Low density sludge is pumped from a settling pond to a tailings management area.	\$250,000 (est.)	Labour \$0.05 Lime 0.30 Power <u>0.25</u> \$0.55/m ³
6	Yes	Tank	E-10	0.007 kg/m ³ 16,600 kg/yr	Thickener	Low density sludge is pumped to tailings management area.	\$5,000,000 (est.)	Approximately \$0.75/m ³
7	No	--	None	--	--	Sludge settles and remains in the two settling ponds.	\$700,000	\$0.01/m ³ (lime and electrical power)
8	Yes	Treatment Ponds	E-10	110 kg/yr	Stream flow to precipitation pond	Once each year sludge is pumped from the settling pond to the tailings management area.	Not available	Not available

*Where capital cost is unknown, an estimate of replacement cost may be provided.

Table 4.2b (Cont'd)

SUMMARY OF SELECTED SITE INFORMATION

9	No	--	None	--	--	Sludge settles in a settling pond. It is then pumped to the tailings management area.	not available	Not available
10	Yes	Tank	Polyelectrolyte	0.1-0.2 mg/L	Prior to Clarifier	Low density sludge is pumped to the tailings management area.	\$12,000,000 (est.)	Not available
11			E-10	20 kg/yr		Sludge produced by this high density sludge treatment facility is hauled off-site for permanent disposal.	\$1,500,000	Not available
12	Yes	Tanks	E-10	7 L/min	Unused Thickener	It is planned to increase sludge density to 25% solids. Sludge is permanently disposed of in cells.	\$5,000,000 (est.)	Not available
13	Yes	Lime Reactor Tank		1.86 mg/m ³	Clarifier	High density sludge is produced at a rate of 0.72 kg/m ³ . Sludge is disposed of at a monitored sludge impoundment site.	\$6,000,000 (est.)	
14	Yes	Lime Reactor Tank	721	10 L/min 3.2 mg/L	Flocculator	High density sludge produced at 20 to 25% solids is recycled to the lime/sludge mix tank or co-deposited with tailings.	\$10,400,000	Objective <\$0.75/m ³

* Where capital cost is unknown, an estimate of replacement cost may be provided.

Table 4.2a (Cont'd)

SUMMARY OF SELECTED SITE INFORMATION

			Mn	0.04 mg/L			
--	--	--	----	-----------	--	--	--

Table 4.2b (Cont'd)

SUMMARY OF SELECTED SITE INFORMATION

9	No	--	None	--	--	Sludge settles in a settling pond. It is then pumped to the tailings management area.	not available	Not available
10	Yes	Tank	Polyelectrolyte	0.1-0.2 mg/L	Prior to Clarifier	Low density sludge is pumped to the tailings management area.	\$12,000,000 (est.)	Not available
11			E-10	20 kg/yr		Sludge produced by this high density sludge treatment facility is hauled off-site for permanent disposal.	\$1,500,000	Not available
12	Yes	Tanks	E-10	7 L/min	Unused Thickener	It is planned to increase sludge density to 25% solids. Sludge is permanently disposed of in cells.	\$5,000,000 (est.)	Not available
13	Yes	Lime Reactor Tank		1.86 mg/m ³	Clarifier	High density sludge is produced at a rate of 0.72 kg/m ³ . Sludge is disposed of at a monitored sludge impoundment site.	\$6,000,000 (est.)	
14	Yes	Lime Reactor Tank	721	10 L/min 3.2 mg/L	Flocculator	High density sludge produced at 20 to 25% solids is recycled to the lime/sludge mix tank or co-deposited with tailings.	\$10,400,000	Objective <\$0.75/m ³

* Where capital cost is unknown, an estimate of replacement cost may be provided.

Table 4.2a (Cont'd)

SUMMARY OF SELECTED SITE INFORMATION

Site No.	Average Flowrate of Water Treatment Daily	pH	Primary Contaminants		Neutralization		
			Element	Concentration	Alkali Purchased As	Alkali Consumption Per m ³ of Influent	Mixing Location
9	40,000 m ³ /day (avg.) 150,000 m ³ /day (max)	2.5-7	Fe Zn Cu Cd	1 mg/L 5-50 mg/L 2-10 mg/L <1 mg/L	CaO	Not available	Reactor
10	100,000 m ³ /day (avg.)	4.2-7.7	Fe Ni Cu	10-27 mg/L 4-19 mg/L 0.5-2 mg/L	CaO	0.2 kg/m ³	Reactor
11	650 m ³ /day (avg.) 2,300 m ³ /day (max)	6.7-7.7	Fe Zn Cu Pb Ni	0.48 mg/L 0.73 mg/L 0.03 mg/L 0.03 mg/L 0.01 mg/L	CaO	0.02 kg/m ³	HDS reactor
12	14,400 m ³ /day (avg.)	3.5-5.5	Fe Zn	50 mg/L 200 mg/L	CaO	0.6 to 1.4 kg/m ³	HDS reactor
13	18,800 m ³ /day (avg.) 27,000 m ³ /day (peak)	3-5.3	Fe Zn Pb Cu	144 mg/L 28 mg/L 4.9 mg/L 0.15 mg/L	CaO	0.42 kg/m ³	HDS reactor
14	25,200 m ³ /day (avg.) 86,400 m ³ /day (max)	2.5-5.5	Fe Zn	150 mg/L 100 mg/L	CaO	0.49 kg/m ³	HDS reactor

Table 4.3

COMPARISON OF SELECTED HEAVY METAL CONTAMINANTS IN AMD
(Concentrations are in mg/L, Except for pH)

Selected Parameter	Environment Canada Data *				Selected Sites													
	Cu-Pb-Zn		Cu-Zn Operation Mine Water	Base Metal (Abandoned)														
	Mine and Surface Drainage	Mine Water			Site #1	Site #2	Site #3	Site #4	Site #5	Site #6	Site #7	Site #8	Site #9	Site #10	Site #11	Site #12	Site #13	Site #14
pH	4.0	2.0	3.0	2.6	3	3-7	3-3.5	2.4	2-2.5	3.6	7.5	6.8-7.4	2.5-7	4.2-7.7	6.6-8.2	3.5-5.5	3-5.3	2.5-5.5
Fe	79	1,830	11.7	1,300	?	4-25	4	800	--	474	2	0.33	1	10-27	0.48	50	144	150
Zn	118	1,090	0.4	3.4	?	1-100	<0.2	80	700	43	5.5	<0.1	5-50	--	0.73	200	28	100
Cu	17	11	0.0	2.5	?	<0.1-5	--	120	--	1.5	--	<0.1	2-10	0.5-2	0.03	0.15	--	--
Pb	0.4	58	0.11	0.5	?	--	--	--	--	--	--	<0.1	--	--	0.03	--	4.9	--
Average Flowrate of Water Treated (m ³ /day)					6,000	47,000	42,000	2,200	2,800	7,000	8,600	10,400	40,000	100,000	1,700	14,400	18,800	25,200

* Adapted from Table 2 (Environment Canada, 1975).

Table 4.3 also presents the average flowrate of water treated at the 14 sites. The average flowrates range from 2,200 to 100,000 m³/day. Peak flowrates are considerably higher in cases where limited storm water surge storage capacity is available.

Neutralization and Precipitation

As shown in Table 4.2, lime is used for neutralization/precipitation at the 14 selected sites.

At site number 1, AMD is batch treated in a basin using calcium hydrate. Precipitates settle in the basin without benefit of flocculant addition. The settled sludge remains *in-situ*.

At sites 2 and 3, acidic stream flows are continuously treated with slaked lime as they flow to sludge settling basins. The depth of settled sludge is monitored at both sites. At site 2, excess sludge is dredged and redeposited in the tailings management area. The dredging of sludge is not expected to be required at site 3.

At sites 4 to 10, acidic inflow is treated at conventional lime plants. The inflow is mixed with lime in reactors, some of which are mechanically aerated (to oxidize ferrous iron) and/or mechanically agitated (to mix the solution). The reactor overflow is then directed to a clarifier, or basin, for solid: liquid separation. Precipitates are settled to form low density sludge, and disposed of in several manners as indicated in Table 4.4.

4.4 DEWATERING AND HIGH DENSITY SLUDGE

The extent to which a sludge can be dewatered is affected by physical properties such as the sludge's initial solids content, age, temperature, viscosity and compressibility and by the sludges chemical properties. The effectiveness of the high density sludge process or any dewatering process is dependant on these parameters.

At sites 11 to 14, high density sludge type treatment plants are used to treat acidic inflows, with some proprietary modifications, as follows.

Acidic inflow is combined with a lime slurry in a rapid mix tank which overflows to a reactor/clarifier. The rate of lime slurry addition to the rapid mix tank is controlled to maintain the pH set point of the reactor/clarifier. Flocculant is added to promote sludge formation.

The reactor/clarifier underflow sludge is recycled to the rapid mix tank. The rate of sludge recycle is controlled to maintain sludge density. Excess sludge is removed for permanent disposal.

Table 4.5

DISPOSAL OF HIGH DENSITY SLUDGE

Site Number	Average Water Inflow Rate to Treatment Plant	Sludge Production		Permanent Sludge Disposal
		Percent Solids	Sludge Production	
11	2,300 m ³ /day	20%		Excess sludge is pumped to a temporary holding tank and later trucked to a tailings management area.
12	14,400 m ³ /day	25% planned		
13	18,800 m ³ /day		0.72 kg/m ³	
14	25,200 m ³ /day	20-25%		

5.0 KEY POST CLOSURE TREATMENT ISSUES

The following key issues need to be taken into consideration when evaluating options for the long term, post mine closure, chemical treatment of acid mine drainage (AMD).

i) Inhibition of AMD

Whenever reasonable, action should be taken to prevent or inhibit the further generation of acid drainage. This should apply to every stage of mine development, waste generation and waste disposal.

ii) Post Mine Closure Scenario

At active mine sites, the stream flow or ponded water that is chemically treated often consists of a mixture of AMD and diverse flows such as mine water, process water, tailings area decant, seepage, and run-off. The cessation of mining or metallurgical processing activities may, therefore, reduce the volume of water to be treated and alter contaminant concentrations.

The recycling of treated water to the process during the active mine life would be discontinued once the mine is closed.

iii) Long Term Maintenance

Services previously indirectly provided by an active mining operation may have to be provided by a stand alone treatment facility.

Access to remote sites would have to be maintained as required.

Permanent treatment plant staff or frequent regular plant maintenance would be required. This may dictate the need for a permanent camp under some circumstances.

iv) Compatibility of the Overall Treatment System

This manual focusses on aspects related to the chemistry of AMD treatment. It should be kept in mind, however, that chemical treatment systems consist of four principal components as indicated below:

Principal Component	Purpose
---------------------	---------

Collection	- Collect AMD and other flows and divert to a treatment pond/plant
Treatment	- Chemical treatment
Treated Water Release/Recycle	- Polishing of treated water (if required) and release/recycle
Sludge Disposal	- Permanent sludge disposal

To be effective, an AMD treatment system has to be compatible with site-specific criteria and conditions such as:

- the AMD collection and storm water (Regional storm or other design storm) management system; and
- limits on the timing of discharge and treated water quality.

v) Prediction of AMD Generation

A scientific prediction of AMD generation including AMD volumes, acidity, and contaminant concentrations is required to ensure that an appropriately sized treatment facility is provided.

The flushing of contaminants from active waste rock over time is schematically shown in Figure 5.1. Line "a" represents contaminant loadings due to the leaching and flushing of readily soluble reaction products. Line "b" represents the time delayed release of AMD, while line "c" represents the combined contaminant loading.

Such predictions are critical for informed long term planning. For instance, if a mine closes shortly after the flushing of acid begins (point A on Figure 5.1), post-closure chemical treatment demands would be expected to increase.

vi) Capital Cost

Additional funding may be required to expand or replace chemical treatment facilities. Some treatment plant operators have suggested that significant cost allowances be included for the commissioning of new or upgraded treatment facilities.

vii) Capital Cost Allowances

The 1994 Canadian Federal Budget proposed changes in the taxation of payments to mine reclamation funds (Wipprecht, 1994).

Some reclamation activities can be performed while the mine is in operation, while others must wait until the mine ceases production. Post-closure reclamation activity generally runs about one to four years although in some cases, it is much more difficult and will continue longer.

Under current income tax rules, mine reclamation expenses are deductible in computing a taxpayer's income only in the year they are incurred. Contributions by a taxpayer to a trust fund set up to finance future reclamation work would not qualify for a deduction in computing income for tax purposes because the contribution would only be used in the future to satisfy the taxpayer's obligations. Mandatory contributions, in combination with the current income tax rules, can lead to two problems for mining companies:

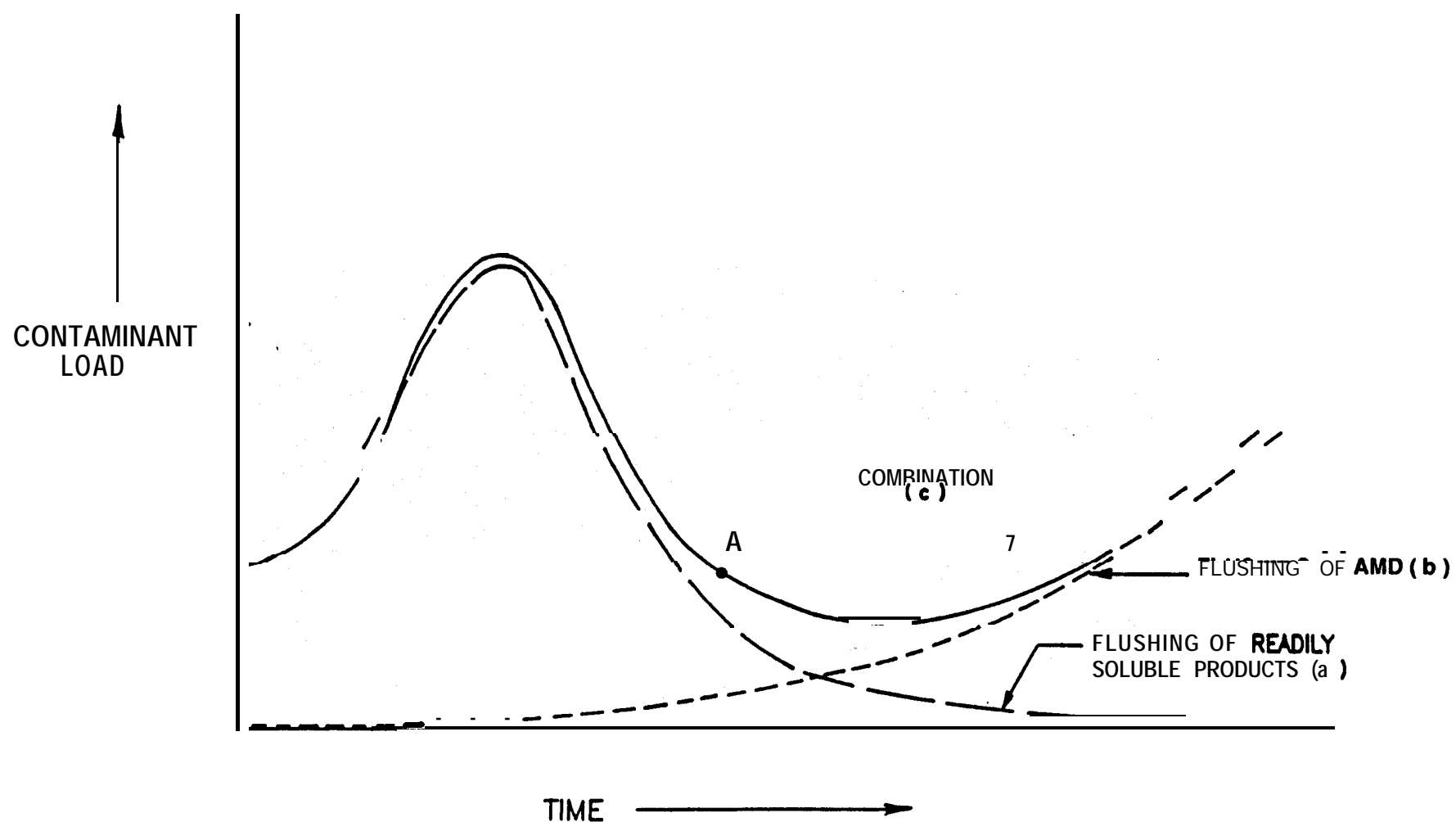
- first, they can give rise to cash-flow problems for mining companies, especially if the reclamation cost requirements substantially increase due to unforeseen environmental obligations; and
- second, some companies, particularly single-mine companies, may be unable to fully utilize the deduction for actual reclamation expenses, since the majority of these expenses occur at the end of the life of the mine, when it no longer produces income.

The budget proposes to change the income tax treatment of contributions made to prescribed mine reclamation trusts. The income tax rules relating to mine reclamation are proposed to be amended as follows:

- a deduction will be permitted for contributions to qualifying mine reclamation trust funds made after 22 February 1994 pursuant to a statutory obligation to make such contributions;
- income earned in such trusts will be subject to tax each year;
- all withdrawals from the trust will be included in computing the income for tax purposes of the recipient;

FIGURE 5.1

FLUSHING OF CONTAMINANTS FROM WASTE ROCK OVER TIME



- reclamation costs will continue to be fully deductible at the time incurred; and
- contributions, trust earnings and withdrawals will not be taken into account for the purposes of determining a taxpayer's resource allowance.

Income tax treatment of mine reclamation funds:

<u>Summary of changes</u>	<u>Current</u>	<u>After budget⁽¹⁾</u>
Contributions	Not deductible	Deductible
Income of the fund	Taxable	Taxable
Withdrawals	Not taxable	Taxable
Mine reclamation	Deductible	Deductible

(1) Fund contributions, earnings and withdrawals do not affect the resource allowance calculations.

The trustee of a qualifying trust can include a government or a third-party trustee. The federal government will continue discussions with officials from the provincial and territorial governments to establish the minimum standards acceptable for such trusts. Qualifying trusts will include only those trusts to which contributions are first made after 22 February 1994.

viii) Operating Cost

Funding needs to be put in place to cover long term, chemical treatment operating and maintenance costs. Principal direct cost components are; direct labour, reagents, and electrical power. Changes in sludge disposal practices could increase the direct cost.

ix) Sludge Disposal

Sludge production from an AMD source can be massive. In extreme situations, the cumulative volume of sludge produced over the long term can exceed the volume of stored tailings. Therefore, the volume of sludge to be produced should be estimated, and plans made for its proper disposal.

Methods of increasing solids contents can have very significant impacts. For instance, increasing sludge solids from 1% to 10% produces approximately 1/10 the total sludge volume. Even an increase in solids from 15% to 30% reduces sludge volumes by roughly half.

Concerns have been raised about the long term chemical stability of some sludges, and about the associated potential liability. Consideration of sludge stability is prudent when evaluating AMD treatment alternatives and sludge management issues. Further technical research is required in this area.

x) Continued Environmental Protection

The chemical treatment system will be expected to continue to operate in compliance over the long term. A chemical treatment facility should, therefore, be designed to operate reliably over the long term.

As AMD chemical treatment requirements are site-specific additional key issues may need to be addressed.

PART II

LONG TERM POST-CLOSURE TREATMENT OF AMD AND RELATED COSTS

6.0 MODELLED AMD TREATMENT COSTS

Preliminary capital and operating costs for three types of lime-based acid mine drainage (AMD) treatment facilities are presented in this section.

6.1 BASIS OF COST ESTIMATES

6.1.1 Treatment Facility - Capital and Operating Costs

Six cost estimating models were developed: three for capital costs and three for operating (treatment) costs. The models dealt specifically with lime-based AMD treatment facilities (i.e. treatment ponds or plants) where AMD is neutralized and precipitates are settled.

The models were based on:

1. conventional lime treatment facilities producing low density sludges;
2. high density sludge treatment facilities; and
3. enhanced high density sludge treatment facilities.

Descriptions and flowcharts of these types of treatment facilities (Figures 2.9 to 2.11 inclusive) are provided in Section 2.3.

Capital and operating costs were modelled for each of the above three types of treatment facilities under various scenarios based on:

- three different acidic water inflow rates of 55, 190 and 820 m³/hr, and
- three different inflow acidity concentrations (taking into account metal concentrations) of 50, 500, and 5,000 mg/L.

The volume of sludge produced in each scenario was also estimated.

The capital cost estimate for a new treatment facility with all new equipment includes:

- building and foundation costs;
- the AMD neutralization circuit equipment costs;
- the solid/liquid separation circuit equipment costs;
- treatment facility services costs;
- polishing pond costs;
- instrumentation and electrical components costs;
- construction costs including overheads at 13% and engineering, procurement, and project management at 15%;
- miscellaneous spare parts at 2%; and
- a contingency of 25%.

The three capital cost estimating models exclude costs for:

- a site water (storm) management system;
- site infrastructure including access, electrical power distribution to the treatment facility, and support facilities/services;
- an AMD collection system;
- tertiary water treatment, if required, (e.g. CO₂ injection to adjust pH) prior to release;
- associated investigative and permitting costs; and
- sludge disposal.

Users of the manual are reminded that the cumulative cost of such additional items can exceed the capital cost of a treatment facility alone.

The three operating cost estimating models include costs for:

- reagents;
- flocculant;
- operating labour;
- maintenance labour and consumables;
- electrical power consumed;
- indirect support costs at 10%; and
- a contingency of 10%.

Details regarding the basis for capital and operating cost estimates are provided in Appendix C.1.

Actual capital and treatment costs are highly dependant upon site-specific conditions. As such, the estimated costs are considered to be preliminary and order of magnitude, however, useful for discussion purposes. The estimated costs should not be used for budgetary purposes as site-specific conditions may add considerably to costs.

6.2 TREATMENT FACILITY - CAPITAL AND OPERATING COSTS

The following subsections summarize estimated costs. Additional detailed cost information is included in Appendix C.2

6.2.1 Conventional Treatment Facility

Table 6.1 summarizes the capital and annual operating cost of a conventional treatment facility for various inflow rate and acidity scenarios. Table 6.2 summarizes the sludge volume and tonnage produced annually for each scenario. Sludge disposal costs are not included in Table 6.1.

6.2.2 High Density Sludge Treatment Facility

Table 6.3 summarizes the capital and annual operating cost of a high density sludge type treatment facility for various inflow rate and acidity scenarios. Table 6.4 summarizes the sludge volume and tonnage produced annually for each scenario.

6.2.3 Enhanced High Density Sludge Treatment Facility

In this application, the sludge produced by a high density sludge treatment system is further dewatered using filters.

Table 6.5 summarizes the capital and annual operating cost of such a system for different acidic water inflow rates and acidity concentrations. Sludge production for the different scenarios is summarized in Table 6.6.

6.3 CAPITAL COST CURVES

Figures 6.1, 6.2 and 6.3 are graphical presentations of the modelled treatment facility capital costs versus the acidic water inflow rates for conventional, high density sludge and enhanced high density sludge treatment facilities, respectively.

Table 6.1

**CONVENTIONAL TREATMENT FACILITY
CAPITAL AND TREATMENT COSTS
(TREATMENT FACILITY ONLY)**

Flowrate of Influent to be Treated	Parameter	Influent Acidity (mg/L)		
		50	500	5,000
55 m ³ /hr (900 L/min)	capital cost	\$850,000	\$1,100,000	\$1,300,000
	operating cost	\$160,000/a	\$220,000/a	\$500,000/a
190 m ³ /hr (3,200 L/min)	capital cost	\$1,000,000	\$1,200,000	\$1,600,000
	operating cost	\$220,000/a	\$390,000/a	\$1,100,000/a
820 m ³ /hr (13,600 L/min)	capital cost	\$2,100,000	\$2,400,000	\$3,300,000
	operating cost	\$530,000/a	\$910,000/a	\$4,200,000/a

Table 6.2

**CONVENTIONAL TREATMENT FACILITY
SLUDGE PRODUCTION**

Flowrate of Influent to be Treated	Sludge Production	Influent Acidity (mg/L)		
		50 ⁽¹⁾	500 ⁽¹⁾	5,000 ⁽²⁾
55 m ³ /hr (900 L/min)	sludge m ³ /a ⁽³⁾	480	4,800	72,000
	sludge t/a (dry)	24	240	3,600
190 m ³ /hr (3,200 L/min)	sludge m ³ /a ⁽³⁾	1,660	16,600	249,000
	sludge t/a (dry)	83	830	12,500
820 m ³ /hr (13,600 L/min)	sludge m ³ /a ⁽³⁾	7,200	720,000	1,080,000
	sludge t/a (dry)	360	3,600	54,000

Notes:

- 1) assumes 1 t of metal hydroxide sludge produced/t of acidity treated.
- 2) assumes 1.5 t of metal hydroxide plus gypsum/t acidity treated.
- 3) assumes 5% solids for all sludges.

Table 6.3

**HIGH DENSITY SLUDGE TREATMENT FACILITY
CAPITAL AND TREATMENT COSTS
(TREATMENT FACILITY ONLY)**

Flowrate of Influent to be Treated	Parameter	Influent Acidity (mg/L)		
		50	500	5,000
55 m ³ /hr	capital cost	\$1,300,000	\$1,500,000	\$1,800,000
	operating cost	\$190,000/a	\$250,000/a	\$530,000/a
190 m ³ /hr	capital cost	\$1,800,000	\$2,000,000	\$2,400,000
	operating cost	\$270,000/a	\$450,000/a	\$1,200,000/a
820 m ³ /hr	capital cost	\$3,900,000	\$4,200,000	\$5,100,000
	operating cost	\$640,000/a	\$1,000,000/a	\$4,300,000/a

Table 6.4

**HIGH DENSITY SLUDGE TREATMENT FACILITY
SLUDGE PRODUCTION**

Flowrate of Influent to be Treated	Sludge Production	Influent Acidity (mg/L)		
		50 ⁽¹⁾	500 ⁽¹⁾	5,000 ⁽²⁾
55 m ³ /hr (900 L/min)	sludge m ³ /a ⁽³⁾	81	810	12,200
	sludge t/a (dry)	24	240	3,600
190 m ³ /hr (3,200 L/min)	sludge m ³ /a ⁽³⁾	280	2,800	42,200
	sludge t/a (dry)	83	830	12,500
820 m ³ /hr (13,600 L/min)	sludge m ³ /a ⁽³⁾	1,200	12,200	183,000
	sludge t/a (dry)	360	3,600	54,000

Notes:

- ¹⁾ assume 1 t of metal precipitates/t acidity treated.
- ²⁾ assume 1.5 t of metal precipitates plus gypsum/t of acidity treated.
- ³⁾ assumes 25% solids and density of 1.18 t/m³ (total weight).

Table 6.5

**ENHANCED HIGH DENSITY SLUDGE TREATMENT FACILITY
CAPITAL AND TREATMENT COSTS
(TREATMENT FACILITY ONLY)**

Flowrate of Influent to be Treated	Parameter	Influent Acidity (mg/L)		
		50	500	5,000
55 m ³ /hr	capital cost	\$1,400,000	\$1,900,000	\$2,500,000
	operating cost	\$270,000/a	\$340,000/a	\$760,000/a
190 m ³ /hr	capital cost	\$2,100,000	\$2,600,000	\$4,300,000
	operating cost	\$400,000/a	\$590,000/a	\$1,600,000/a
820 m ³ /hr	capital cost	\$4,400,000	\$5,000,000	\$12,000,000
	operating cost	\$780,000/a	\$1,300,000/a	\$5,200,000/a

Table 6.6

**ENHANCED HIGH DENSITY SLUDGE TREATMENT FACILITY
SLUDGE PRODUCTION**

Flowrate of Influent to be Treated	Sludge Production	Influent Acidity (mg/L)		
		50 ⁽¹⁾	500 ⁽¹⁾	5,000 ⁽²⁾
55 m ³ /hr (900 L/min)	sludge m ³ /a ⁽³⁾	46	460	6,900
	sludge t/a (dry)	24	240	3,600
190 m ³ /hr (3,200 L/min)	sludge m ³ /a ⁽³⁾	160	1,600	24,000
	sludge t/a (dry)	83	830	12,500
820 m ³ /hr (13,600 L/min)	sludge m ³ /a ⁽³⁾	690	6,900	104,000
	sludge t/a (dry)	360	3,600	54,000

Notes:

- 1) assumes 1 t of metal precipitate/t acidity treated.
- 2) assumes 1.5 t of metal precipitate plus gypsum/t acidity treated.
- 3) assume 40% solids - density of 1.3 t/m³ (total weight).

FIGURE 6.1

FLOW RATE vs. CAPITAL COST
FOR CONVENTIONAL TREATMENT

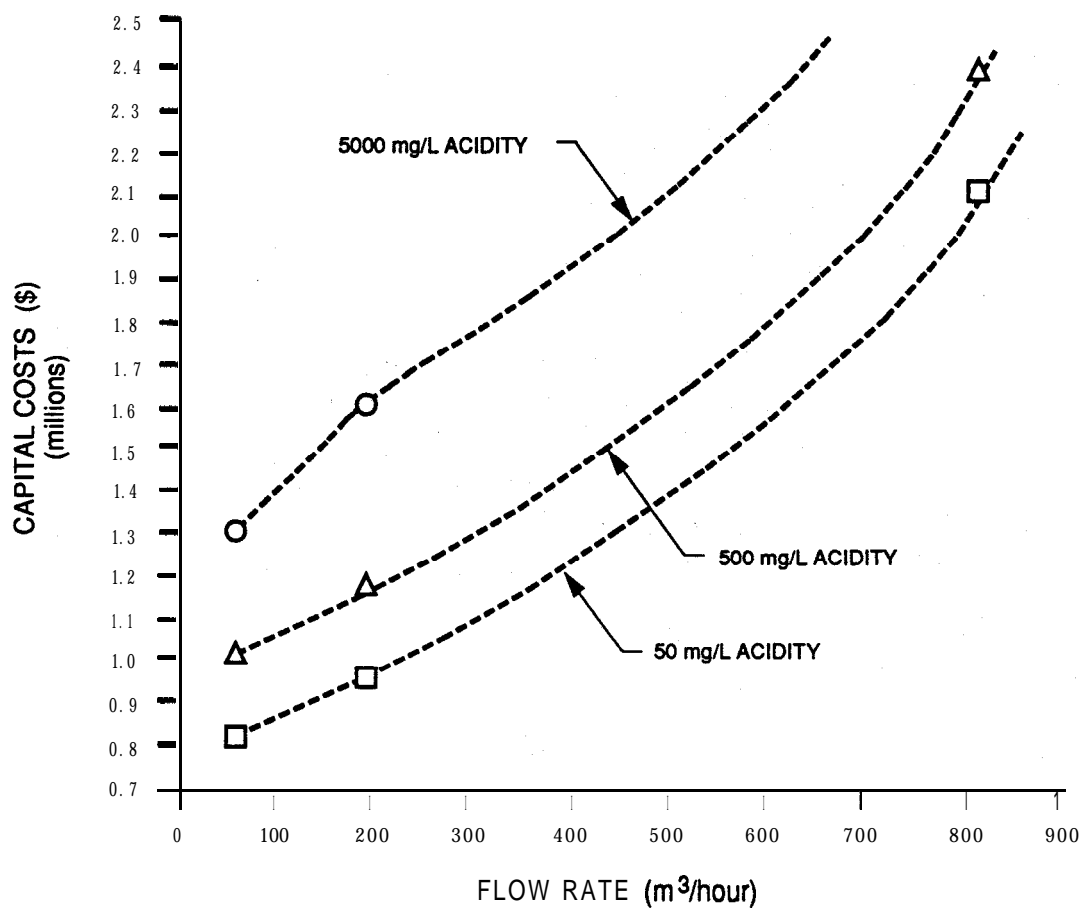


FIGURE 6.2

FLOW RATE vs. CAPITAL COST FOR HDS TREATMENT

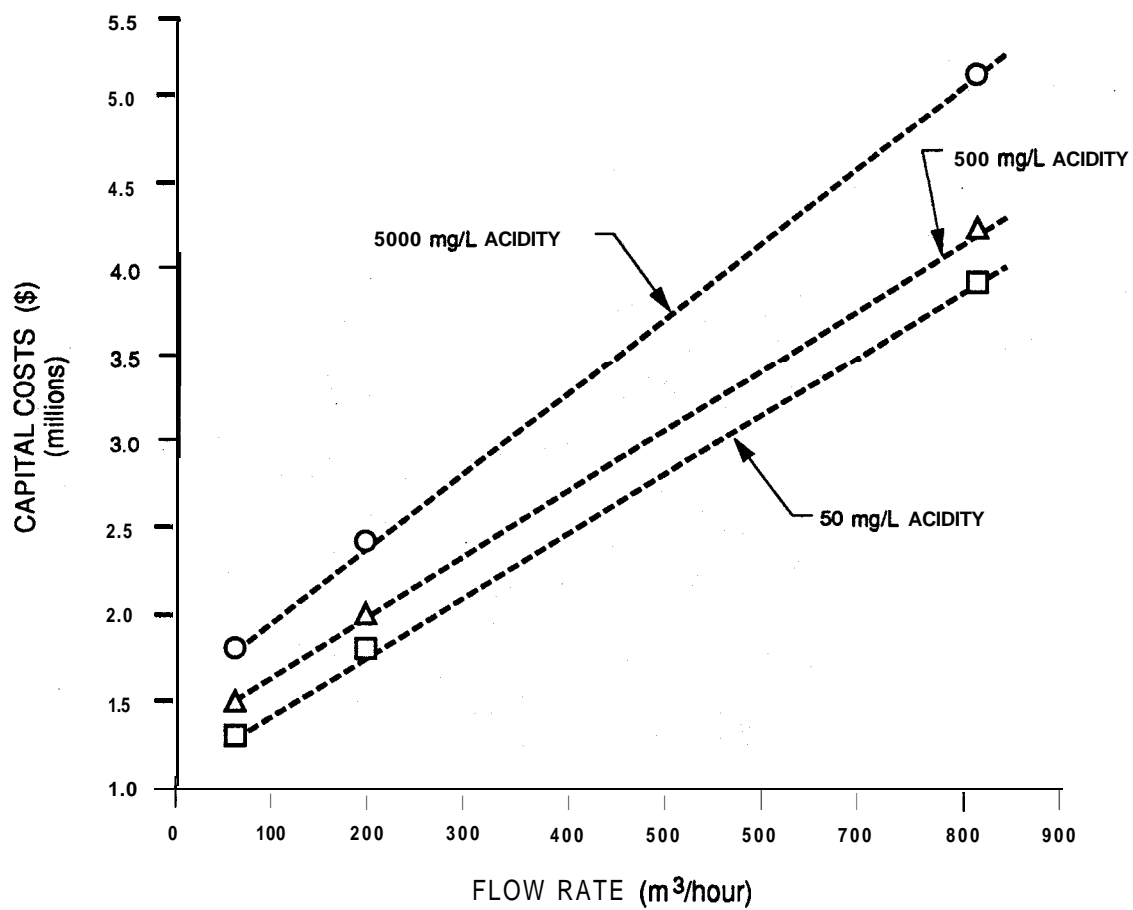
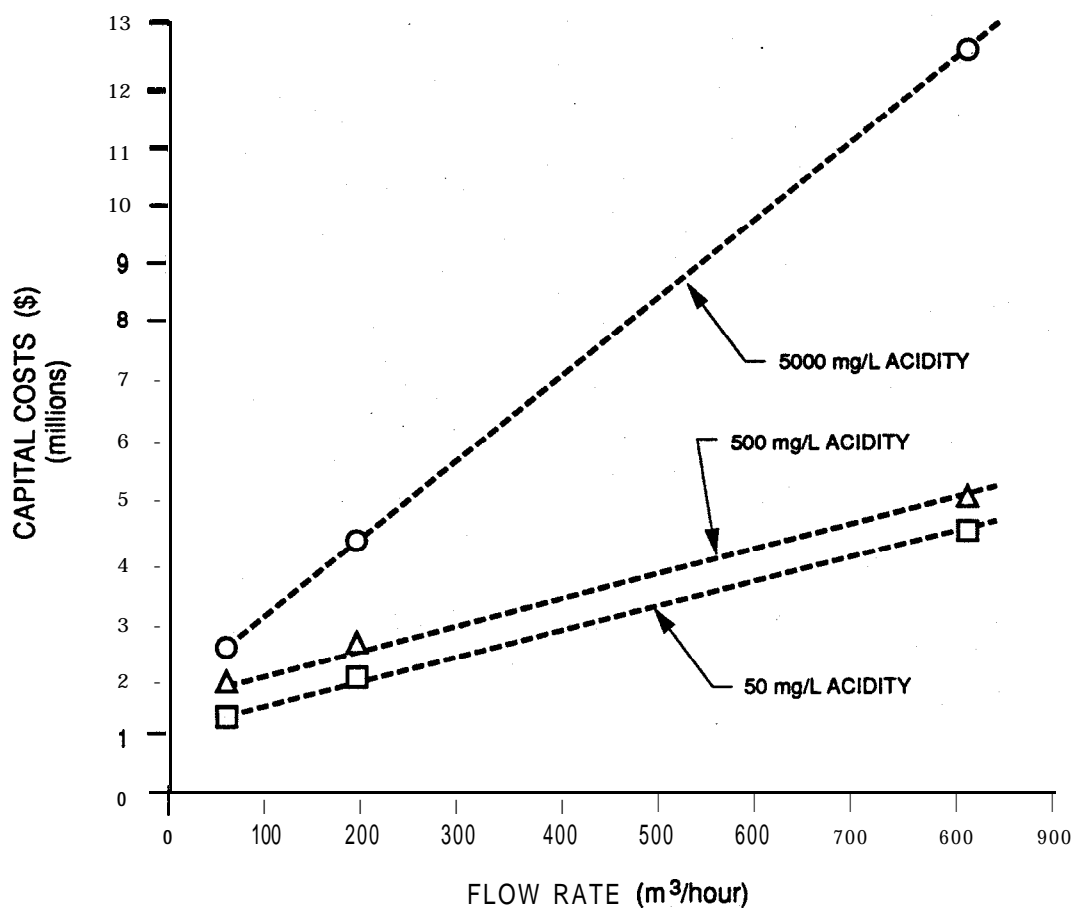


FIGURE 6.3

FLOW RATE vs. CAPITAL COST FOR ENHANCED HD TREATMENT



7.0 CASE STUDIES

This section presents four case studies which evaluate on a preliminary basis, the cost of post-closure AMD treatment.

In each case study, capital costs, annual operating costs, and annual sludge disposal costs are estimated for three types of chemical treatment facilities.

Each case study is based on assumed post-closure AMD treatment requirements at a site where AMD is currently treated. The case studies have been selected to present a wide range of treatment scenarios as outlined below.

Case Study Number	Scenario
1	A closed, remote site where simple batch lime treatment is used.
2	A closed, remote site where AMD is continuously treated using a conventional lime treatment plant.
3	An active site where an HDS type facility could continue to be used to treat AMD once the mine is closed.
4	An active site where a state-of-the-art HDS type facility could continue to treat acidic inflow after the mine is closed.

A common simplistic approach is used in each case study as outlined below.

Objective:

The objective of each case study is to evaluate post-closure AMD treatment and related sludge disposal costs.

Approach:

1. The capital cost of treatment facilities are estimated using the modelled costs (preliminary estimates) presented earlier in Section 6.0. Capital costs are estimated for conventional, HDS type, and enhanced HDS type treatment facilities.

2. The annual operating costs for the different treatment facilities are also estimated using the modelled cost data.
3. The quantities of sludge produced annually at each treatment facility are then estimated along with sludge disposal costs.
4. The net present value of a treatment facility capital cost, 100 years of annual treatment costs, and 100 years of annual sludge disposal costs is then calculated for each type of treatment facility.
5. Findings are reviewed and discussed.

The preliminary cost estimates are based on the key assumptions that:

1. AMD treatment will be required for 100 years (essentially perpetual);
2. the inflow rates and net acidities used are average, long-term values; and
3. annual operating and sludge disposal costs remain constant over time.

7.1 CASE STUDY NO. 1

7.1.1 General Description

This case study is based on a scenario where the mine has been closed for over ten years and the surface plant, including the power line, have been torn down. AMD, however, continues to be generated from diverse sources. The mine is in a remote location and road access has been maintained.

The batch treatment facility currently in use treats about 2,200,000 m³ of acidic water (typical pH 3) annually.

7.1.2 Chemical Treatment Process

AMD is batch treated as shown in the process flowsheet (Figure 7.1).

The treatment system operates as follows:

- Inflows including run-off and AMD from diverse sources are collected in a large natural basin.
- The pond acidity is monitored on a bi-weekly basis and neutralized as-required. Neutralization is achieved by adding sufficient hydrated lime (via a simple jet slurry system).
- Treated water is seasonally discharged to a wetland.
- The precipitates settle in the AMD collection/treatment pond.

The batch treatment system operates efficiently with minimal care and maintenance.

The AMD collection/treatment pond has ample capacity to store storm water. At present, sludge remains *in-situ* in the pond. In the future, excess sludge may have to be dredged from the pond.

Actual capital costs were in the order of \$50,000 for a diesel pump, jet slurry mixer, and discharge piping.

7.1.3 Post-Closure Treatment Cost

The following discussion is based on the assumption that an average of 6,000 m³ of acidic water (net acidity of 2,000 mg/L) will be treated daily over the next century.

Estimated treatment facility capital costs and annual treatment costs for the currently used batch treatment facility, and three types of continuous AMD treatment facilities are shown in Table 7.1.1. Cost estimating calculations are provided in Appendix D.1.

Table 7.1.1 indicates that the net present value of capital and treatment costs for the batch treatment system is the lowest at \$13,550,000.

The volume of sludge produced for each type of treatment facility was then estimated. As shown in Table 7.1.2 the volume of sludge produced over 100 years from the batch treatment system would be 8.76×10^6 m³. A HDS treatment facility would in comparison produce 1.4×10^6 m³.

Table 7.1.2 also presents the net present value for sludge disposal costs incurred over 100 years. The batch treatment system has the largest sludge disposal cost at \$11,070,000 and is based on the assumption that sludge will be dredged from the pond and redeposited in an engineered impoundment area.

Table 7.1.1

CASE STUDY 1
LONG TERM TREATMENT OPTIONS
(250 m³/hr @ 2,000 mg net acidity/L)

Item	Simple Batch Treatment	Conventional Treatment	HDS Type Treatment	Enhanced HDS Type Treatment
Capital Cost of Treatment Facility (A)	Not Applicable ⁽⁵⁾	\$1,500,000	\$2,300,000	\$3,200,000
Annual Treatment Cost	\$429,000 ⁽⁴⁾	\$770,000	\$830,000	\$940,000
CPVF ⁽¹⁾	31.60	31.60	31.60	31.60
Present Value Treatment Costs (B)	\$13,550,000	\$24,330,000	26,230,000	29,700,000
Net Present Value (A + B) ⁽²⁾	\$13,550,000	\$25,830,000	28,530,000	32,900,000
Relative Cost Comparison ⁽³⁾	1.00	1.91	2.11	2.43

Notes:

- (1) Cumulative present value factor (CPVF) calculated as follows:

$$CPVF = \frac{(1+i)^n - 1}{i(1+i)^n}$$

i = interest rate

n = number of years

discount factor of 3% over 100 years was used in the calculation.

- (2) Present day cost before sludge disposal costs.
(3) Subtotal divided by \$13,550,000.
(4) Based on an approximated \$0.195/m³ (\$0.13/m³ direct cost + 50% for indirects) of water treated (2,200,000 m³/yr).
(5) The total costs to install the batch treatment process in the tailings polishing pond was about \$50,000.

Table 7.1.2

CASE STUDY 1
LONG TERM SLUDGE PRODUCTION AND DISPOSAL COSTS

Item	Simple Batch Treatment	Conventional Treatment	HDS Type Treatment	Enhanced HDS Type Treatment
% Solids	5	5	25	40
t/yr ⁽¹⁾	4,380	4,380	4,380	4,380
Sludge Volume m ³ /yr	87,600	87,600	14,800	8,423
Total Sludge 100 yrs m ³	8.7 x 10 ⁶	8.7 x 10 ⁶	1.4 x 10 ⁶	0.8 x 10 ⁶
Disposal Cost \$/m ³ ⁽²⁾	\$350,400/yr	\$350,400/yr	\$59,200/yr	\$33,700/yr
NPV	\$11,070,000	\$11,070,000	\$1,870,000	\$1,060,000

Notes:

- (1) Assume 1 t sludge/t acidity treated.
(2) Typical impoundment and disposal cost for sophisticated engineered storage area.

Table 7.1.3

CASE STUDY 1
TOTAL TREATMENT AND DISPOSAL COST

Item	Simple Batch Treatment	Conventional Treatment	HDS Type Treatment	Enhanced HDS Type Treatment
Capital Cost of Treatment Facility	--	\$1,500,000	\$2,300,000	\$3,200,000
Net Present Value of Treatment Costs ⁽¹⁾	\$13,550,000	\$24,330,000	\$26,230,000	\$29,700,000
Net Present Value of Sludge Disposal Costs ⁽¹⁾	<u>\$11,070,000</u>	<u>\$11,070,000</u>	<u>\$1,870,000</u>	<u>\$1,060,000</u>
Total Net Present Value	\$24,620,000	\$36,900,000	\$30,400,000	\$33,960,000

Note:

⁽¹⁾ Based on 100 years of equal annual costs and a 3% discount factor.

Table 7.2.1

CASE STUDY 2
LONG TERM TREATMENT OPTIONS
(92 m³/hr @ 5,000 mg net acidity/L)

Item	Conventional Treatment	HDS Type Process	Enhanced HDS Type Process
Capital Cost of Treatment Facility (A)	\$1,400,000	\$1,900,000	\$2,800,000
Annual Treatment Cost	\$690,000	\$780,000	\$1,020,000
CPVF ⁽¹⁾	31.60	31.60	31.60
Present Value Treatment Costs(B)	\$21,800,000	\$24,650,000	\$32,230,000
Net Present Value (A + B) ⁽²⁾	\$23,200,000	\$26,550,000	\$35,030,000
Relative Cost Comparison	1.00	1.14	1.51

Notes:

- (1) Cumulative present value factor (CPVF) calculated as follows:

$$CPVF = \frac{(1+i)^n - 1}{i(1+i)^n}$$

i = interest rate

n = number of years

discount factor of 3% over 100 years was used in the calculation.

- (2) Present day cost before sludge disposal costs.
(3) Subtotal divided by \$23,200,000.

Table 7.2.2

CASE STUDY 2
SLUDGE PRODUCTION AND DISPOSAL

Item	Conventional Treatment	HDS Type Process	Enhanced HDS Type Process
% Solids	5	25	40
Annual Production t/yr ⁽¹⁾	6,050	6,050	6,050
Sludge Volume m ³ /yr	120,000	20,500	11,600
Volume/100 yrs m ³	12 x 10 ⁶	2.1 x 10 ⁶	1.2 x 10 ⁶
Disposal Cost Pit ⁽²⁾	\$120,000/yr	\$20,500/yr	\$11,600/yr
Disposal Cost Basin ⁽³⁾	\$480,000/yr	\$82,000/yr	\$46,400/yr
NPV Pit Disposal	\$3,790,000	\$648,000	\$367,000
NPV Engineered Basin Disposal	\$15,170,000	\$2,590,000	\$1,470,000

Notes:

- (1) Assumes 1.5 t metal precipitates and gypsum/t of acidity treated.
(2) Assumes cost for pit disposal is \$1/m³ to manage the system.
(3) Assumes cost for conventional disposal in an engineered basin is \$4/m³.

Table 7.2.3

CASE STUDY 2
TOTAL TREATMENT AND DISPOSAL COST

Item	Conventional Treatment	HDS Type Process	Enhanced HDS Type Process
Capital Cost of Treatment Facility (A)	\$1,400,000	\$1,900,000	\$2,800,000
Net Present Value of Treatment Costs (B) ⁽¹⁾	\$21,800,000	\$24,650,000	\$32,230,000
Net Present Value of Pit Disposal (C) ⁽¹⁾	\$3,790,000	\$648,000	\$367,000
Net Present Value of Sludge Disposal in Engineered Impoundment (D) ⁽¹⁾	\$15,170,000	\$2,590,000	\$1,470,000
Total NPV Pit Disposal (A + B + C)	\$26,990,000	\$27,198,000	\$35,397,000
Total NPV Impoundment Disposal (A + B + D)	\$38,370,000	\$29,140,000	\$36,500,000

Note:

⁽¹⁾ Based on 100 years of equal annual costs and a 3% discount factor.

Table 7.3.1

CASE STUDY 3
LONG TERM TREATMENT OPTIONS
 (780 m³/hr @ 1,000 mg net acidity/L)

Item	Conventional Treatment	HDS Type Process	Enhanced HDS Type Process
Capital Cost of Treatment Facility (A)	\$2,500,000	\$4,400,000	\$7,000,000
Annual Treatment Cost	\$1,230,000	\$1,330,000	\$1,700,000
CPVF ⁽¹⁾	31.60	31.60	31.60
Present Value Treatment Costs (B)	\$38,868,000	42,028,000	53,720,000
Net Present Value (A + B)	\$41,368,000	46,428,000	60,720,000
Relative Cost Comparison ⁽³⁾	0.89	1.00	1.31

Notes:

- (1) Cumulative present value factor (CPVF) calculated as follows:

$$CPVF = \frac{(1+i)^n - 1}{i(1+i)^n}$$

i = interest rate

n = number of years

discount factor of 3% over 100 years was used in the calculation.

- (2) Present day cost before sludge disposal costs.
 (3) Subtotal divided by \$46,428,000.

Table 7.3.2

CASE STUDY 3
SLUDGE PRODUCTION

Item	Conventional Treatment	HDS Type Process	Enhanced HDS Type Process
% Solids	5	25	40
Sludge Production t/yr ⁽¹⁾	2,730	2,730	2,730
Sludge Volume m ³ /yr	54,700	9,254	5,250
100 yr Production m ³	5.5 x 10 ⁶	0.93 x 10 ⁶	0.5 x 10 ⁶
Sludge Disposal Cost ⁽²⁾	\$218,800/yr	\$37,000/yr	\$21,000/yr
NPV Sludge Production	\$6,910,000	\$1,170,000	\$660,000

Notes:

- (1) Based upon monitoring data (production ≈ 0.4 kg/m³).
 (2) Assumes \$4/m³ for engineered storage reservoir.

Table 7.3.3

CASE STUDY 3

TOTAL TREATMENT AND DISPOSAL COST

Item	Conventional Treatment	HDS Type Process	Enhanced HDS Type Process
Capital Cost of Treatment Facility	\$2,500,000	\$4,400,000	\$7,000,000
NPV Treatment Costs ⁽¹⁾	\$38,868,000	\$42,028,000	\$53,720,000
NPV Sludge Disposal Costs ⁽¹⁾	\$6,910,000	\$1,170,000	\$660,000
Total Net Present Value	\$48,278,000	\$47,598,000	\$61,380,000

Note:

(1) Based on 100 years of equal annual costs and a 3% discount factor.

Table 7.4.1

CASE STUDY 4
LONG TERM TREATMENT OPTIONS
 (1,050 m³/hr @ 2,000 mg net acidity/L)

Item	Conventional Treatment	HDS Type Process	Enhanced HDS Type Process
Capital Cost of Treatment Facility (A)	\$3,800,000	\$6,000,000	\$15,000,000
Annual Treatment Cost	\$2,500,000	\$2,630,000	3,600,000
CPVF ⁽¹⁾	31.60	31.60	31.60
Present Value Treatment Costs (B)	\$79,000,000	83,100,000	113,760,000
Net Present Value (A + B)	\$82,800,000	89,100,000	128,760,000
Relative Cost Comparison ⁽³⁾	0.93	1.00	1.44

Notes:

- (1) Cumulative present value factor (CPVF) calculated as follows:

$$CPVF = \frac{(1+i)^n - 1}{i(1+i)^n}$$

i = interest rate

n = number of years

discount factor of 3% over 100 years was used in the calculation.

- (2) Present day cost before sludge disposal costs.
 (3) Subtotal divided by \$89,100,000.

Table 7.4.2

CASE STUDY 4
SLUDGE PRODUCTION AND DISPOSAL COSTS

Item	Conventional Treatment	HDS Type Process	Enhanced HDS Type Process
Sludge Density	5	25	40
Sludge Production t/yr	18,400	18,400	18,400
Sludge Volume m ³ /yr	368,000	62,400	35,400
Volume 100 yrs. m ³	36.8 x 10 ⁶	6.24 x 10 ⁶	3.5 x 10 ⁶
Disposal Cost ⁽¹⁾	\$1,470,000/yr	\$250,000/yr	\$142,000/yr
NPV Disposal Cost	\$46,500,000	\$7,900,000	\$4,470,000

Note:

- (1) Assumes sludges disposed at \$4/m³ in an engineered impoundment area.

Table 7.4.3

CASE STUDY 4
TOTAL TREATMENT AND DISPOSAL COST

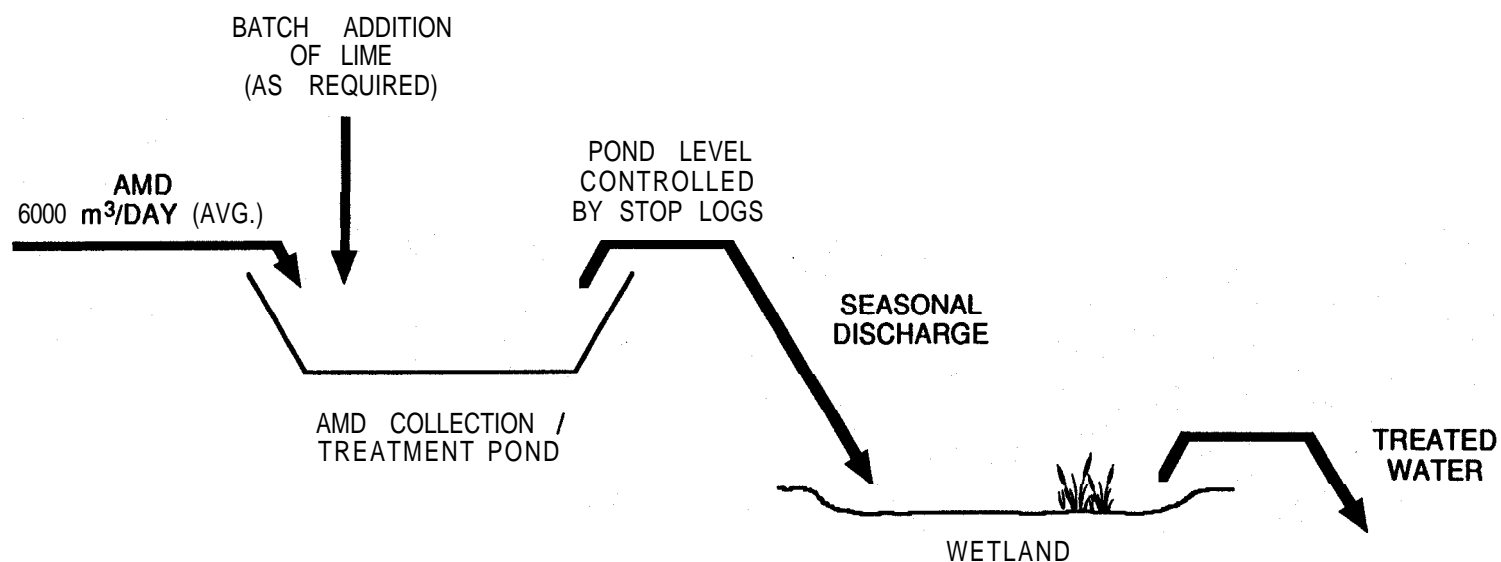
Item	Conventional Treatment	HDS Type Process	Enhanced HDS Type Process
Capital Cost of Treatment Facility	\$3,800,000	\$6,000,000	\$15,000,000
NPV Treatment Costs ⁽¹⁾	\$79,000,000	\$83,100,000	\$113,760,000
NPV Sludge Disposal Costs ⁽¹⁾	\$46,500,000	\$7,900,000	\$4,470,000
Total Net Present Value	\$129,300,000	\$97,000,000	\$133,230,000

Note:

(1) Based on 100 years of equal annual costs and a 3% discount factor.

FIGURE 7.1

PROCESS FLOWSHEET FOR CASE STUDY No. 1
BATCH TREATMENT PROCESS OF AMD



Total AMD treatment and sludge disposal costs are presented in Table 7.1.3. The currently used batch treatment system offers the lowest net present value at \$24,620,000.

The second lowest net present value is offered by the HDS type treatment facility. Its net present value of \$30,400,000, however, excludes the costs of an electrical power line and substations, and other supporting infrastructure required for a continuous treatment operation.

7.1.4 Discussion

The cost comparison provided in Table 7.1.3 indicates that the batch treatment system offers the lowest present day cost.

Batch treatment is possible at this closed site due to the considerable storage volume available in the AMD collection/treatment pond. Advantages offered by batch treatment systems include:

- the treatment system is effective and is the simplest to operate.
- long term care and maintenance requirements are minimized.
- the treatment facility does not need to be staffed on a continuous basis. It may be possible to schedule monitoring/treatment activities so that they are done on a bi-weekly or less frequent basis. Treatment may not be required during periods of low flow (i.e. cold weather months).
- as AMD treatment is not carried out on a continuous basis, requirements for on-site support infrastructure are minimal.
- electrical power requirements are minimal and could be met using a small generator set or other diesel powered equipment. A power line and substation(s) are not required.
- upfront capital costs are minimized.

Lime can be added to the acidic pond using either of two principal systems. In the first system, hydrated lime (trucked in or made up on-site) is discharged into the acidic pond using a pneumatic unloading truck and a jet slurry mixer. In the second system, lime slurry (or possibly hydrated lime) is added to the intake of a diesel powered pump (or dry lime is added to the intake of a wet well) and mixed with acidic water as it is

recirculated to the acidic pond.

A disadvantage to the batch treatment of AMD is the cumulative collection of sludge in the treatment pond. Excess sludge may need to be dredged from the pond and disposed elsewhere.

Batch treatment could also be applied to acidic water contained in an open pit.

If batch treatment was used at a location where the inflow volume was low, consideration could be given to the use of caustic soda instead of lime. The relatively high freezing point of caustic soda solutions may, however, present operating problems during cold weather.

7.2 CASE STUDY NO. 2

7.2.1 General Description

This case study is based on a scenario where the mine has closed but where AMD continues to be treated using a conventional treatment facility.

As part of the mine closure planning process, extensive state-of-the-art technical investigations and analyses were completed to address key AMD related issues such as:

- The prediction, through modelling of AMD characteristics and flows from various sources over time;
- Water management taking into account hydrology, hydrogeology, water quality, effects (if any) on the receiving environment, the needs of stakeholders, etc.;
- The identification of remedial works that could significantly reduce future AMD generation;
- Long term AMD treatment and sludge disposal requirements; and
- Associated capital and long term treatment costs.

Following the development and approval of the closure strategy remedial works were carried out to, where practical, inhibit or significantly reduce future acid generation.

At present, AMD originates from various sources including:

- mine site runoff;
- tailings dam seepage;
- reactive waste rock piles; and
- exposed, reactive mineralized zones.

A conventional treatment plant used to treat AMD when the mine was in production has been kept in service to treat the combined acidic inflow. It is estimated that the replacement value of the treatment plant is about \$1,500,000.

7.2.2 Chemical Treatment Process

The flowsheet for the currently used conventional treatment process is shown in Figure 7.2.

Inflows including AMD and run-off are collected in a water storage pond.

Acidic water from the storage pond is pumped to a lime reactor tank where it is mixed with a lime slurry. Overflow from the lime reactor is directed to a sludge settling pond. Treated water is released from the large sludge settling pond on a seasonal basis. Excess sludge is pumped from the settling pond to an open pit.

The conventional facility treats an average of 2,200 m³/day of acidic water (pH 2.4).

7.2.3 Post-Closure Treatment Cost

The costs of post-closure AMD treatment were estimated on a preliminary basis for three types of lime based continuous treatment facilities (conventional, HDS type, and enhanced HDS type treatment facilities).

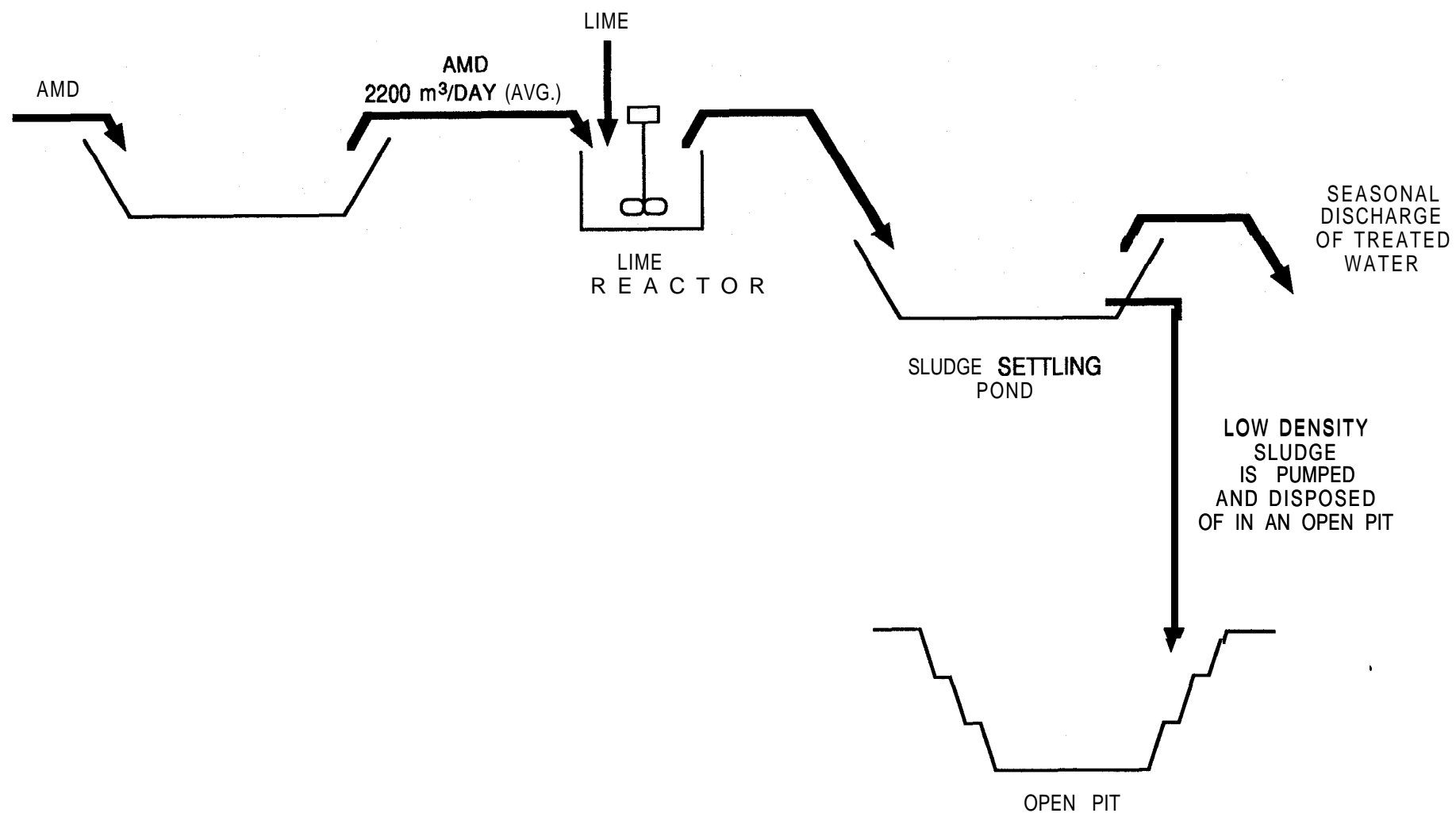
It was assumed that an average of 2,200 m³ of acidic water (net acidity of 5,000 mg/L including allowance for metal concentrations) will be treated daily over the next 100 years.

The estimated capital and annual treatment costs for the three treatment facilities are shown in Table 7.2.1. Cost estimating calculations are provided in Appendix D.2.

Table 7.2.1 indicates that a minimum net present value of \$23,200,000 (capital and treatment costs) is

FIGURE 7.2

PROCESS FLOWSHEET FOR CASE STUDY No. 2
CONVENTIONAL CONTINUOUS TREATMENT OF AMD



obtained using a conventional treatment facility.

Table 7.2.2 summarizes the volume of sludge that would be produced over 100 years of continuous treatment. The currently used conventional treatment system is estimated to produce in the order of $12 \times 10^6 \text{ m}^3$ of sludge over a century. By comparison, a HDS type facility would produce approximately $2 \times 10^6 \text{ m}^3$.

If it is assumed that the unit cost to dispose of sludge in the open pit is $\$1/\text{m}^3$, the cost (NPV) of pit disposal is $\$3,790,000$ for a conventional facility; $\$648,000$ for a HDS type facility; and $\$367,000$ for an enhanced HDS type facility.

If sludge is disposed of in an engineered impoundment at a unit cost of $\$4/\text{m}^3$, sludge disposal costs net present value (NPV) would be: $\$15,170,000$ for a conventional facility; $\$2,590,000$ for a HDS type facility; and $\$1,470,000$ for an enhanced HDS type facility.

The NPV of capital, and 100 years of treatment and disposal costs for the three types of treatment facilities are summarized in Table 7.2.3. The cost comparison indicates that the net present value for conventional and HDS type treatment facilities are similar in the range of $\$27,000,000$. An enhanced HDS type facility has a NPV in the range of $\$35,000,000$.

If the open pit were unavailable and sludge had to be deposited in an engineered impoundment area, an HDS type facility would be more attractive. As indicated in Table 7.2.3, the NPV in such a scenario would be: $\$38,370,000$ for a conventional facility; $\$29,140,000$ for a HDS type facility; and $\$36,500,000$ for an enhanced HDS type facility.

7.2.4 Discussion

The preliminary costing model used in the evaluation estimated the capital cost of the present conventional treatment plant to be $\$1,400,000$ which compares favourably to its estimated replacement cost.

The estimated treatment cost of $\$690,000/\text{yr}$ or $\$0.86/\text{m}^3$ of water treatment is lower than the reported all encompassing treatment cost of $\$1.14/\text{m}^3$ of water treated. The variance is likely due to site-specific requirements such as higher than estimated indirect support costs.

The modelled cost data indicates that, in this case, the continued use of the conventional treatment facility with pit disposal of sludge is economically warranted.

The use of open pits or quarries for sludge disposal can, therefore, be beneficial. In this case study the total cost (NPV) would increase greatly if the open pit were not available.

The currently used conventional treatment system offers several advantages including:

- continued use of an existing treatment facility;
- use of an open pit for sludge disposal; and
- although daily inspection is required, care and maintenance demands are modest.
- if in the unlikely event that untreated water is released to the settling pond (see Figure 7.2), the pond could be batch treated.

A key component of this treatment system is the availability of a suitable open pit with ample sludge storage capacity.

The use of conventional treatment/pit sludge disposal is applicable to many sites but likely more effective at sites having good road access and electrical power.

7.3 CASE STUDY NO. 3

7.3.1 General Description

In this case study a high density sludge treatment plant that has operated for over a decade could continue to be used following mine closure. The plant is currently used to treat a combination of flows including mine water, tailings area decant, seepage, and run-off.

The treatment facility was designed to operate with an average inflow of 16,500 m³/day (11,500 L/min); maximum normal inflow of 26,000 m³/day (18,000 L/min); and a peak capacity inflow of 39,000 m³/day (27,000 L/min). In 1993, the treatment plant operated 331 days, treating approximately 6,200,000 m³ of water-which equates to an average inflow of 18,700 m³/day (13,000 L/min).

Key contaminant concentrations of treatment plant influent and effluent observed shortly after the start-up of the plant are presented below. For comparison purposes recent data is also provided for a twelve month period ending May 1993.

INFLUENT AND EFFLUENT CHARACTERISTICS

Parameter	Performance Achieved Shortly After Start-up		Performance Achieved Over 12 Months Ending May 1993	
	Influent	Effluent	Influent	Effluent
pH	4.5	9.5	4.2	9.3
Fe	250 mg/L	<1.0 mg/L	144 mg/L	0.02 mg/L
Zn	22 mg/L	<0.2 mg/L	28 mg/L	0.1 mg/L
Pb	5 mg/L	<0.1 mg/L	4.9 mg/L	0.02 mg/L
Suspended Solids	75 mg/L	<15 mg/L	73 mg/L	10 mg/L

The cost to construct the treatment plant about 15 years ago was in the order of \$4,000,000. The capital costs of supporting infrastructure such as electrical power supply to the plant, and construction of a sludge disposal facility were additional.

7.3.2 Chemical Treatment Process

The process flowsheet for the AMD treatment plant is shown in Figure 7.3.

The inflow consisting of mine and mill waters is pumped to a rapid mix tank. An in-line surge tank is installed ahead of the rapid mix tank.

In the rapid mix tank, the inflow is combined with a lime slurry/recycled sludge mix. The pH of the rapid mix tank is used to control the rate of lime slurry addition in the lime slurry/recycled sludge mix tank. Overflow from the rapid mix tank drains to the lime reactor. The reactor is agitated and aerated.

Overflow from the lime reactor drains to a flocculator. Flocculant is added to the stream flow at several points as it enters the flocculator.

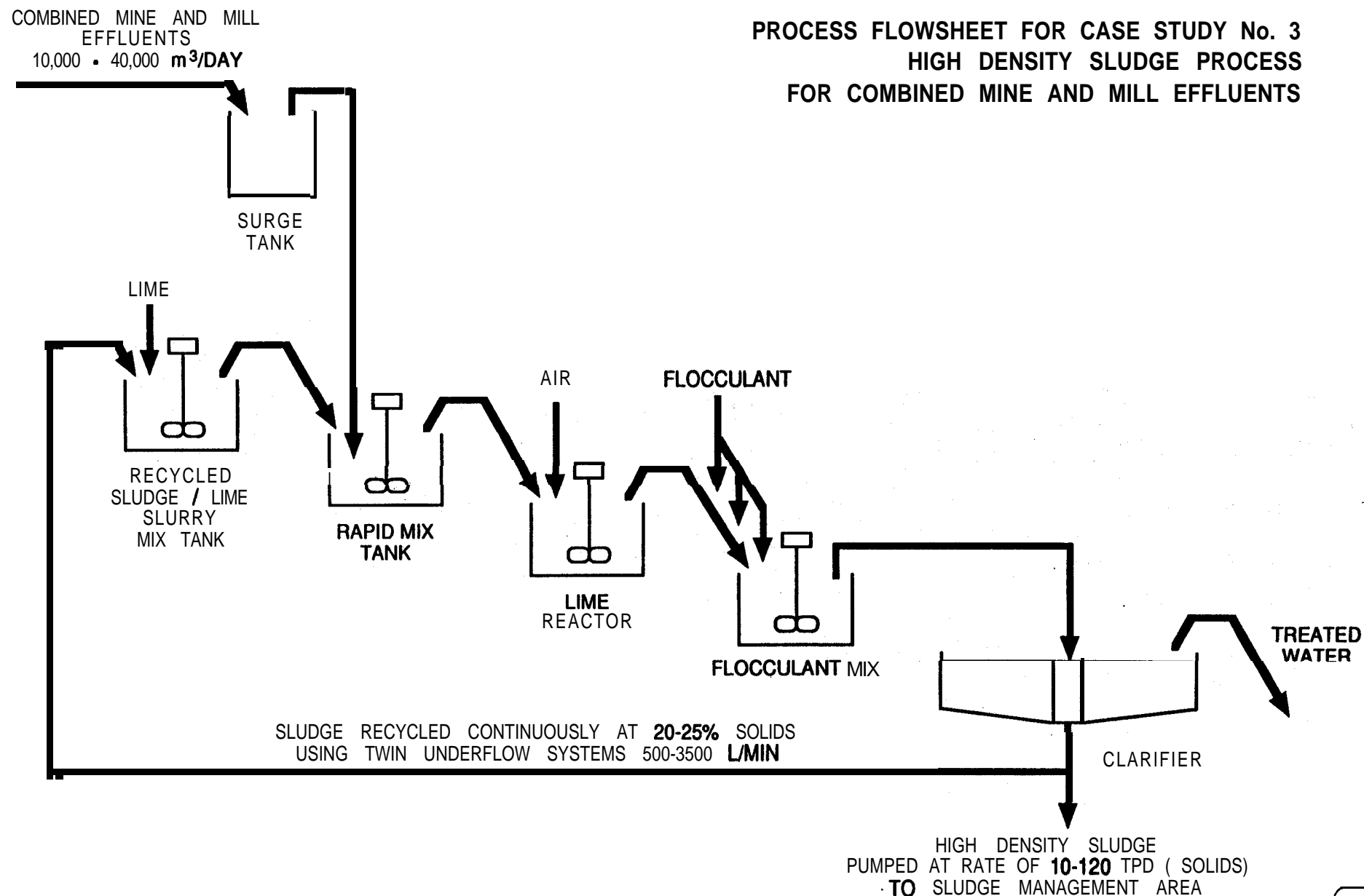
Settled sludge from the thickener underflow is continuously recycled back to the recycled sludge/lime slurry mix tank. The sludge is moved using twin pumping systems.

Overflow from the clarifier is directed to a polishing pond prior to being released.

7.3.3 Post-Closure Treatment Cost

FIGURE 7.3

PROCESS FLOWSHEET FOR CASE STUDY No. 3
HIGH DENSITY SLUDGE PROCESS
FOR COMBINED MINE AND MILL EFFLUENTS



SOURCE: ADAPTED FROM KUIT, 1980

Post-closure treatment costs were estimated for three types of lime based treatment processes as was done in the other case studies using the previously developed costing data.

It was assumed that an average of 18,700 m³/day of inflow having a net acidity of 1,000 mg/L will be treated on a continuous basis over the next 100 years.

The NPV of the three treatment facilities taking into consideration both capital cost and 100 years of treatment costs are summarized in Table 7.3.1. The estimated NPV for the currently used HDS facility is \$46,428,000; versus \$41,368,000 for a conventional treatment facility, and \$60,720,000 for an enhanced HDS type facility. Cost estimating calculations are provided in Appendix D.3.

The volume of sludge produced over 100 years of treatment plant operation is estimated to be 5.5 x 10⁶ m³ for a conventional facility, 0.93 x 10⁶ m³ for a HDS facility, and 0.5 x 10⁶ m³ for an enhanced HDS type facility. The NPV of sludge disposal costs are respectively, \$6,910,000, \$1,170,000, and \$660,000 (Table 7.3.2).

Table 7.3.3 summarizes the NPV of capital, treatment and disposal costs which are: \$48,278,000 for a conventional facility, \$47,598,000 for a HDS type facility, and \$61,380,000 for an enhanced HDS type facility.

7.3.4 Discussion

The estimated capital cost of the HDS type treatment facility is dependant upon the inflow rate and acidity selected. The capital cost for the HDS facility is estimated below for various flowrates.

Acidic Water Inflow Rate (at 1,000 mg/L Acidity)	Estimated Capital Cost of HDS Facility⁽¹⁾
780 m ³ /hr (assumed long term, post-closure average)	\$4,400,000
1,080 m ³ /hr (equivalent to maximum normal inflow of 26,000 m ³ /day used during actual design)	\$5,500,000
1,625 m ³ /hr (equivalent to peak capacity of 39,000 m ³ /day used during actual design)	\$7,000,000

⁽¹⁾ Approximated from Figure 6.8.

The HDS facility is understood to have been constructed for about \$4,000,000 nearly 15 years ago. The present value of the plant, using 3% compound interest, is in the range of \$6,200,000. The variance between the estimated and reported capital costs may, in part, be due to site-specific requirements such as designed over capacity to handle peak-flow conditions.

The preliminary cost comparison indicates that the HDS treatment facility and a conventional treatment facility have similar NPV's - the HDS facility having the lowest NPV. The HDS facility is estimated to produce approximately $4.5 \times 10^6 \text{ m}^3$ less sludge volume than a conventional facility over 100 years of operation.

7.4 CASE STUDY NO. 4

7.4.1 General Description

In this case study, a high density sludge treatment plant is used to treat a combined inflow consisting of AMD, tailings decant and seepage, mine water, and run-off. The plant could continue to be operated following mine closure.

The treatment plant was designed to operate under the flow conditions indicated below.

PARAMETERS USED IN DESIGN

Parameter	Influent		Effluent
	Average Expected Values	Normal Maximum Expected Values	Typical Values
Inflow	32,000 m ³ /day (22,000 L/min)	58,000 m ³ /day (40,000 L/min)	-- --
pH	3.5	2.0	9.5
Fe ²⁺	150 mg/L	230 mg/L	--
Zn	100 mg/L	200 mg/L	0.5 mg/L
Cu	--	3 mg/L	0.3 mg/L

Pb	--	2.5 mg/L	0.2 mg/L
----	----	----------	----------

Treatment system components were selected to provide a peak capacity of 86,000 m³/day (160,000 L/min) at which point metal loadings were expected to be near average expected values.

The plant has been used successfully over a wide range of flows which, to date, have typically ranged from 22,000 to 28,000 m³/day (15,000 to 20,000 L/min). The pH of the inflow has seasonal variations from 2.5 in summer to near 5.5 in winter.

The treatment plant was recently constructed at a cost of \$10,400,000.

7.4.2 Chemical Treatment Process

The process flowsheet for the AMD treatment plant is shown in Figure 7.4.

Inflows from various sources are collected in a buffer pond which provides both water storage and surge capacity.

Water from the buffer pond is pumped to a rapid mix tank where it is combined with a lime slurry/recycled sludge mix. The pH in the rapid mix tank is used to control the lime addition rate in the lime slurry/recycled sludge mix tank. Overflow from the rapid mix tank drains to the lime reactor. The mixture consisting of AMD, lime slurry, and recycled sludge is agitated and aerated in the lime reactor.

Overflow from the lime reactor drains to a flocculator. Flocculant (Allied Colloids 721) is added to the streamflow as it enters the flocculator. Mixed overflow is drained to the clarifier. Overflow from the clarifier is directed to a polishing pond prior to being released.

Underflow sludge is recycled to the lime slurry/recycled sludge mix tank. Excess sludge is pumped to the mill tailings box where it is combined with mill tailings.

7.4.3 Post-Closure Treatment Cost

For demonstration purposes the acidity used to calculate treatment and sludge disposal costs have been increased from about 800 to 1,000 mg/L to 2,000 mg/L to highlight the impact of sludge production on long term treatment costs.

The NPV of capital, and 100 years of treatment costs are presented for three types of treatment systems in Table 7.4.1. The currently used HDS treatment system is estimated, in this scenario, to have a NPV of \$89,100,000. A conventional facility is estimated to have a NPV of \$82,800,000 while that for an enhanced HDS is \$128,760,000.

In this scenario, the sludge volumes produced over a century of post-closure AMD treatment are considerable. The sludge volumes are: $36.8 \times 10^6 \text{ m}^3$ for a conventional facility; $6.24 \times 10^6 \text{ m}^3$ for a HDS type facility; and $3.5 \times 10^6 \text{ m}^3$ for an enhanced HDS type facility. The NPV's of sludge disposal costs are estimated to be, respectively, \$46,500,000, \$7,900,000, and \$4,470,000 (Table 7.4.2).

As indicated in Table 7.4.3, the HDS type facility offers the lowest NPV.

7.4.4 Discussion

The estimated capital cost for the HDS facility is \$6,000,000 whereas the reported construction cost is \$10,400,000. As in case study 3.0, this variance is likely due to site-specific conditions and requirements such as overdesign capacity to handle peak flows.

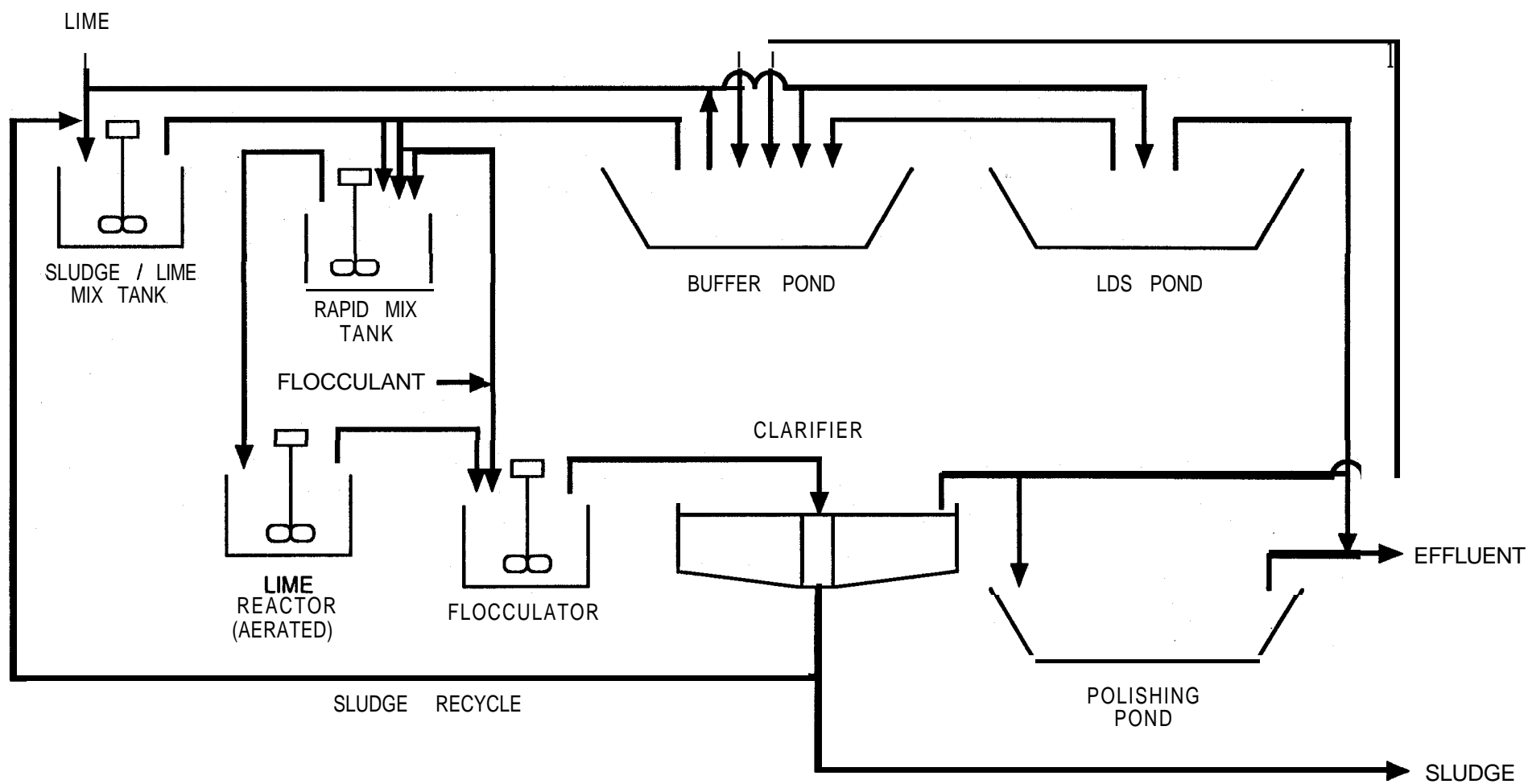
The preliminary cost comparison (Table 7.4.3) indicates that a HDS facility offers the lowest NPV at \$97,000,000. Capital cost represents only 7% of the NPV - compared to 86% for treatment, and 7% for sludge disposal.

If a conventional plant were developed the NPV would increase significantly to \$129,300,000. Capital cost would represent 3% of the NPV with treatment accounting for 61% and sludge disposal for 36%.

FIGURE 7.4

PROCESS FLOWSHEET FOR CASE STUDY No. 4
HIGH DENSITY SLUDGE TREATMENT OF AMD

AMD
AND OTHER FLOWS



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PART III

APPENDICES

APPENDIX A

SELECTED RESULTS OF LITERATURE REVIEW

APPENDIX A - SELECTED RESULTS OF LITERATURE REVIEW

Subsequent to award of this project, a key word search strategy was developed and a technology literature search was undertaken. Several databases were searched initially to identify how many potential references might be available through each source for the period spanning 1987 through 1993. In the end, three databases were accessed to obtain reference abstracts for review, namely, NTIS, Pollution Abstracts and Enviroline. The databases from these three sources were combined to reduce duplications prior to downloading the abstracts. Abstract listings were printed under two main subject areas; 1) mining/acid mine drainage treatment and 2) mining/sludge characterization/treatment/stabilization, etc.

The abstracts on over 300 references were received and subsequently reviewed to identify publications of interest.

Through contact with industry personnel and other organizations, numerous additional references were identified and obtained. Each document deemed applicable to this study was reviewed, assessed and summarized according to a standard research summary format.

The subject matter of each document is categorized according to mining sector, treatment technology and sludge management method. An overview of the pertinent facts is compiled along with useful data, charts, etc. Comments on data, the potential current or future use of the technologies or the reference are sometimes given. The literature reviews included in this appendix are sorted alphabetically by author. Table A.1 provides an index to the major topics covered in each reference.

Some good sources of general information identified include Environment Canada (1975), U.S.EPA design manual (1983), Kilborn best available treatment technology study (1991) and the Gionet (1987) report on sludges.

The information available on sludge management is quite limited. Current research trends are towards biological treatments and prevention and control of acid mine drainage (AMD). Some recent work, to a limited extent, has been geared towards metal recovery techniques. This includes CANMET development work on copper cementation units and selective precipitation.

Table A-1

TOPICAL INDEX TO SELECTED REFERENCES

	Conventional Treatment	Alternate Chemicals	Metals Removal	High Density Sludge	Sludge Management	Case Studies	Current Practice	Other
Ackman 1982					X		X	
Ackman et al. 1987	X							
Ackman and Kleinmann 1984	X							
Canadian Mining Journal 1980		X			X			
Dinardo et al. 1991a			X					
Dinardo et al. 1991b			X					
Environment Canada 1985	X			X			X	
Environment Canada 1975	X			X	X	X		
Everett and Du Plessis 1993								X
Gionet et al. 1987					X		X	
Hammack et al. 1993								X
Hauck and Masoonian 1990		X	X					
Higgs 1993	X			X			X	
Higgs 1990					X			
Huang and Liu 1993	X		X			X		
Kilborn 1991	X		X				X	

	Conventional Treatment	Alternate Chemicals	Metals Removal	High Density Sludge	Sludge Management	Case Studies	Current Practice	Other
Knocke and Kelley 1987				X				
Kuit 1980				X		X		
Kuyucak and St-Germain 1992								X
Lapakko and Antonson 1990								X
Lovett and Ziemkiewicz 1991		X						
Murdock et al. 1994				X	X	X		
Patterson 1990						X		
Reed et al. 1986					X			
Ritcey 1989	X	X	X					
Schiller et al. 1984		X						
SENES 1987					X		X	
Skousen 1991								X

Skousen et al. 1991	X							
Sprute et al. 1988					X			
SRK 1990	X				X			
SRK et al. 1989	X							
Stokowski et al. 1992	X							
Tetra				X				
Toor					X			
Twidwell et al. 1990			X		X			
U.S. EPA 1983	X		X	X	X			
Vos 1992		X						
Watzlaf and Casson 1990	X				X			
West 1988	X			X		X		
Wing 1983		X					X	
Yamabe 1990			X					

APPENDIX B

INDUSTRY CONTACTS

APPENDIX B - INDUSTRY CONTACTS

This Appendix summarizes contacts made regarding acid mine drainage (AMD) chemical treatment practices at selected mine sites. Information was obtained through a review of current and relevant technical literature (Appendix A), and discussions with contacts at:

1. mining companies
2. government ministries and agencies
3. industry associations
4. research organizations, consultants, and suppliers

B.1 Mining Companies

B.1.1 Initial Contacts

As a first step, general information about AMD chemical treatment and sludge disposal practices was obtained by contacting the mining companies listed in Table B.1. The list of initial contacts was designed to provide information on AMD treatment at:

- base metal, gold, uranium, and coal producers throughout Canada;
- both small mines (under 500 tpd ore production) and large mines;
- active and recently closed mines; and
- new mines either being developed or at the advanced feasibility stage.

Persons contacted were also asked to comment on post closure AMD chemical treatment requirements (if any) and requirements for future research in the area of AMD chemical treatment.

B.1.2 Selected Sites

Information was compiled on AMD chemical treatment and sludge disposal practices at selected sites. Information was obtained from technical literature, or from in-house data, discussions and/or use of a survey questionnaire. Key information of interest at each of the sites included:

- AMD characteristics
- alkali used and consumption rate
- method of aeration (if used)

- flocculant used and consumption rate (if used)
- sludge characteristics and disposal practice
- capital cost (or estimated replacement cost)
- direct costs of treatment

B.2 GOVERNMENT MINISTRIES AND AGENCIES

Selected government ministries and agencies listed in Table B.2 were contacted in order to obtain information on:

- any research underway by government related to AMD treatment.
- plans for AMD treatment facilities at government owned sites producing AMD.

Table B.1

MINING COMPANIES CONTACTED

No.	Company	Location
1	Hemlo Gold Mines	Golden Giant
2	Muscocho Explorations	Magino, Magnacon
3	Williams Operating	Williams
4	Teck Corona Oper.	David Bell
5	Dickenson Group	Arthur White
6	Noranda Minerals	GECO
7	Falconbridge	Falconbridge
8	Noranda Minerals	Mattabi
9	Falconbridge	Kidd Creek
10	Royal Oak Mines	Head Office
11	Metall Mining	Quebec
12	Noranda Minerals	Mattagami
13	Noranda Minerals	Gaspe
14	Billiton	Selbaie
15	Audrey Resources	Mobrun
16	Teck	Head Office
17	Miramar Mining	Con
18	Echo Bay Mines	Lupin
19	Luscar Sterco	Coal Valley
20	North America Metals	Golden Bear
21	Teck	Bullmoose
22	Homestake Canada	Nickel Plate
23	Hillsborough Resources	Quinsam Coal
24	Gibraltar Mines	Gibraltar
25	Westmin Resources	Myra Falls
26	Westmin Resources	Premier Gold
27	Metall Mining	Winston Lake
28	Western Copper Holdings	Williams Creek

Table B.1

MINING COMPANIES CONTACTED (Cont'd)

	Company	Location
29	INCO	Thompson
30	Cape Breton Development	Head Office
31	Noranda Minerals	Head Office
32	Richmond Mines	Camflo
33	Noranda Minerals	Horne
34	Falconbridge	Onaping
35	Placer Dome	Head Office
36	Metall Mining	Izok Lake
37	HBM+S	Flin Flon
38	Brunswick M+S	Heath Steele
39	Brunswick M+S	Brunswick
40	Lac/Cambior	Doyon
41	Brunswick M+S	Brunswick
42	Noranda Sales	Head Office
43	Cominco	Kimberly
44	Cominco	Head Office

Table B.2

GOVERNMENT MINISTRIES AND AGENCIES CONTACTED

No.	Organization
1	British Columbia Ministry of Environment and Mines
2	Manitoba Department of Mines
3	Ontario Ministry of Northern Development and Mines
4	Nova Scotia Department of Natural Resources
5	U.S. EPA Office of Solid Waste

B.3 INDUSTRY ASSOCIATIONS

Industry associations contacted are listed in Table B.3.

Table B.3

INDUSTRY ASSOCIATIONS CONTACTED

No.	Organization
1	Ontario Mining Association
2	Coal Association of Canada
3	Mining Association of British Columbia
4	Quebec Mining Association

B.4 RESEARCH ORGANIZATIONS, CONSULTANTS, AND SUPPLIERS

Contacts made are summarized in Table B.4.

Table B.4

CONTACTS MADE WITH RESEARCH ORGANIZATIONS, CONSULTANTS, AND SUPPLIERS

No.	Organization
1	Lynton Gormley + Associates (Consultant involved in AMD chemical treatment of Britannia Mine AMD in British Columbia)
2	University of British Columbia (Biotechnology AMD treatment)
3	Triton Development Corp. (Biotechnology AMD treatment)
4	Koch Minerals of Canada (Lime Supplier)
5	Cominco Engineering Services Ltd. (HDS Technology Supplier)
6	Tetra Technologies Inc. (HDS Technology Supplier)
7	GL&V Ontario
8	Envirotech Canada
9	Lakefield Research
10	Golder Associates
11	BeachviLime Lime
12	Allied Colloids Ltd.

APPENDIX C

MODELLED COSTS

**by Richard C. Swider
Consulting Engineers Limited**

APPENDIX C: MODELLED COSTS

C.1 BASIS FOR PROCESS DESIGN, AND CAPITAL AND OPERATING COST ESTIMATES

PROCESS DESIGN

Acid Mine Drainage Solution

Solution Flow	55, 190, 820 m ³ /h
Solution Concentration	
Total as H ₂ SO ₄	50, 500, 5000 mg/L
H ₂ SO ₄	50%
Metals as Fe ₂ (SO ₄) ₃	50%
Precipitation	
CaSO ₄ .2H ₂ O	0, 0, 50%
Metal Hydroxides	100%

Neutralization

Neutralization (Flowsheet No.1)

Lime Reaction Tanks

Number	2
Retention Time - each	30 minutes

Neutralization (Flowsheet No.2 and No.3)

Slurry/Lime Mix Tank

Number	1
Retention Time	5 minutes

Rapid Mix Tank

Number	1
Retention Time	8 minutes

Lime Reaction Tank

Number	1 or 2
Retention Time - total	40 minutes

Reagent Selection

(Hydrated Lime, Bagged or Bulk;
or Bulk Quicklime)

Reagent selection is based on reagent costs, annual usage, storage life and operator requirements. The reagent selection for the three flowsheets is as follows:

Flow, m ³ /h	Concentration as H ₂ SO ₄ , mg/L		
	50	500	5000
55	Bagged Hydrated Lime	Bulk Hydrated Lime	Bulk Quicklime
190	Bagged Hydrated Lime	Bulk Hydrated Lime	Bulk Quicklime
820	Bulk Hydrated Lime	Bulk Quicklime	Bulk Quicklime

Thickening and Clarification

Solid Removal Pond (Flowsheet No.1)

Flocculent Dosage	3 gm/m ³
Settled Solids Density	5% solids
Pond Retention Time	48 hours

HDS Thickener (Flowsheets No.2 and No.3)

Flocculent Addition	
Dosage	3 gm/m ³
Mix Tank Retention Time	1 minute
Settled Solids Density	20% solids
Solids Recycle	500-2000%
Unit Loading Rate	1.0 m ³ /h/m ²

Solids Filtration (Flowsheet No.3)

Filter Type	Plate & Frame
Filter Cake Density	35% solids

Size and Operating Schedule

The filter size has been selected to provide the following operating schedule.

Flow, m ³ /h	Concentration as H ₂ SO ₄ , mg/L		
	50	500	5000
55	1 filter, 8h/day 5 cycles	1 filter, 8 h/day 5 cycles	1 filter, 24h/day 16 cycles
190	1 filter, 8h/day 5 cycles	1 filter, 8h/day 5 cycles	1 filter, 24h/day 16 cycles
820	1 filter, 8h/day 5 cycles	1 filter, 24h/day 16 cycles	2 filters, 24h/day 16 cycles each

Hydrated Lime or Lime Make-up and Storage Systems

Hydrated Lime Bagged

Slurry Make-up & Type
Number of Make-ups
Storage Tank Capacity
Slurry Density
Purity & Reactivity

Batch, Tank
1/week
7 days
10% solids
90%, 90%

Hydrated Lime Bulk

Bulk Storage
Capacity

Truck Unloading
Slurry Make-up & Type
Storage Tank Capacity
Slurry Density
Purity & Reactivity

Silo
1 truck loads
or 10 days
Pneumatic
Continuous, Tank
24 hours
10% solids
90%, 90%

Quicklime Bulk

Bulk Storage
Capacity

Truck Unloading
Lime Slaking
Storage Tank Capacity
Slurry Density
Purity & Reactivity

Silos
1 truck loads
or 10 days
Pneumatic
Rake type slaker
12 hours
10% solids
90%, 90%

Flocculent Make-up and Storage System

Flocculent Make-up System

Allied Colloids

Automatic

Storage Tank Capacity

24 hours

Solution Strength

0.5%

CAPITAL COST ESTIMATES

The capital cost estimates for the three flowsheet alternatives are based on the material balances calculated for the AMD flowrates and total acidity loadings. The material balances are based on the selected process design criteria.

The capital cost estimates are factored estimates based on new equipment costs for an engineered project. The equipment costs have been obtained as budget price estimates from manufacturers, or determined from cost information in our files. Installation, process piping, electrical, instrumentation and building costs have been calculated using factors that have been found to be suitable for this purpose for other projects of a generally similar nature. The factors have been adjusted as appropriate to reflect the specific requirements of the process flowsheet.

The capital costs are in current Canadian dollars with no provision for inflation or indirect costs.

OPERATING COST ESTIMATES

The operating cost estimates for the three flowsheet alternatives are based on the material balances calculated for the AMD flowrates and total acidity loadings. The material balances are based on the selected process design criteria.

Unit costs for reagents (and reagent transportation) were obtained from suppliers as budget prices. Costs for labour and electrical power are representative of general industry costs. The maintenance costs are based on factors found suitable for generally similar projects.

The operating costs are direct costs with a 10% indirect cost allowance. The operating costs are in current Canadian dollars with no allowance for inflation.

Unit costs used are as follows:

Bagged Hydrated Lime (F.O.B. Minesite)	\$0.26/kg
Bulk Hydrated Lime	" \$0.197/kg
Bulk Quicklime	" \$0.0902/kg
Flocculent	" \$4.55/kg
Electrical Power	
Usage Factor	80%
Cost	\$0.07/kWh
Operating Labour	
Hourly Rate	\$20.00
Burdens	35%

C.2 CAPITAL COST ESTIMATES - CASE I - CONVENTIONAL TREATMENT PROCESS

CAPITAL COST ESTIMATE (in 1,000's)

DESCRIPTION	FLOW,55m3/h						FLOW,190m3/h						FLOW,820m3/h					
	CONCENTRATION,mg/L						CONCENTRATION,mg/L						CONCENTRATION,mg/L					
	50.0		500.0		5000.0		50.0		500.0		5000.0		50.0		500.0		5000.0	
	Cost,\$	Op.,kW	Cost,\$	Op.,kW	Cost,\$	Op.,kW	Cost,\$	Op.,kW	Cost,\$	Op.,kW	Cost,\$	Op.,kW	Cost,\$	Op.,kW	Cost,\$	Op.,kW	Cost,\$	Op.,kW
NEUTRALIZATION CIRCUIT																		
2-Feed pumps	112	7.5	112	7.5	112	7.5	16.6	22.5	16.6	22.5	16.6	22.5	44.6	112.0	44.6	112.0	112.0	112.0
2-Lime reactor tank c/w agitator	24.0	15.0	24.0	15.0	24.0	15.0							136.8	52.5	136.6	52.5	136.6	52.5
1-Polishing pond	15.0		16.0		15.0	15.0	43.0	22.5	43.0	22.5	43.0		101.0		194.0		194.0	
2-Recycle water pumps	72	2.0	72	2.0	72	2.0	72	2.0	72	2.0	72	2.0	102	5.0	102	5.0	102	5.0
LIME OR HYDRATED LIME CIRCUIT																		
1 or 2-Lime bin c/w bin activator	-	-	39.1	0.7	23.3	0.7			39.1	0.7	55.6	3.5	39.1	0.7	23.3	0.7	166.0	6.0
1 or 2-Discharge screw conveyor	-	-	4.3	1.5	4.3	1.5			4.3	1.5	5.5	7.5	4.3	1.5	4.3	1.5	11.0	7.5
1-Pneumatic unloading system	-	-	15.0	7.5	15.0	7.6			15.0	7.5	15.0		15.0	7.5	15.0	7.5	15.0	7.5
1-Lime slaker or makeup tank	6.5	3.5	3.0	1.5	75.0	5.0	6.5	3.5	3.0	1.5	75.0	5.0	3.0	1.5	75.0	6.0	110.0	11.0
1-Lime storage tank c/w agitator	6.5	3.5	9.0	5.0	23.0	11.0	6.5	3.5	17.6	11.0	35.5	15.0	0.0	5.0	22.0	11.0	91.6	30.0
1 m	-	-			4.3	1.5					5.5	3.5			4.3	1.5	6.5	3.5
1-Transfer pump	3.6	1.5			4.6	3.5		1.5			4.6	3.5			4.8	3.5	6.1	7.5
2-Distribution pumps	7.2	1.5	72	1.5	9.6	3.5	3672	1.5	72	1.5	9.6	3.5	7.2	1.5	9.6	3.5	102	7.5
FLOCCULENT CIRCUIT																		
1-Flocculent makeup unit	27.0	3.5	27.0	3.5	27.0	3.5	27.0	3.5	27.0	3.5	27.0	1.5	27.0	3.5	27.0	3.5	27.0	3.5
1-Flocculent storage tank c/w agitator	2.2	0.7	2.2	0.7	2.2	0.7	3.2	1.5	3.2	1.5	3.2	0.7	6.6	2.5	6.6	2.5	6.6	2.5
2-Distribution pumps	6.4	0.7	5.4	0.7	6.4	0.7	5.4	0.7	5.4	0.7	5.4	0.7	7.6	1.5	7.6	1.5	7.6	1.5
SERVICES																		
1-Instrumentation compressor	39.4	30.0	39.4	30.0	39.4	30.0	39.4	30.0	39.4	30.0	39.4	30.0	39.4	30.0	39.4	30.0	39.4	30.0
2-Process/service compressors	99.0	75.0	99.0	75.0	99.0	75.0	99.0	75.0	99.0	75.0	99.0	75.0	174.6	150.0	174.6	150.0	174.6	150.0
TOTAL EQUIPMENT & POLISHING POND	254.2	144.4	508.0	152.1	389.7	166.6	307.6	167.7	311.0	161.4	490.3	202.2	716.6	374.7	660.3	391.2	1057.6	437.6
Total Process Equipment	239.2		293.0		374.7		264.6		327.0		447.3		524.6		606.3		863.8	
Equipment Installation,10%	23.0		29.3		37.5		26.5		32.7		44.7		52.5		60.6		86.4	
Process Piping,30%	71.6		87.9		112.4		79.4		98.1		134.2		157.4		161.9		259.1	
Electrical,20%	47.0		56.6		74.9		52.9		65.4		69.5		104.9		121.3		172.7	
Instrumentation,16%	38.3		46.9		60.0		42.3		52.3		71.6		83.9		97.0		139.2	
Building,37%	88.5		109.4		136.6		97.9		121.0		165.5		194.1		224.3		319.5	
Polishing Pond	15.0		15.0		16.0		43.0		43.0		43.0		194.0		194.0		194.0	
TOTAL DIRECT COST	524.5		639.1		613.1		605.6		739.5		995.7		1311.4		1485.4		2033.6	
Spare Parts,2%	10.5		12.6		16.3		121		14.6		19.9		26.2		29.7		40.7	
Construction Overheads,13%	66.2		63.1		105.7		76.9		96.1		129.4		170.5		193.1		264.4	
Eng. Proc.& Management,15%	76.7		95.0		122.0		91.0		110.5		149.4		196.7		222.6		305.0	
TOTAL INDIRECT COST	157.3		191.7		243.9		162.0		221.9		296.7		393.4		445.6		610.0	
TOTAL DIRECT & INDIRECT COST	661.6		630.6		1057.0		788.6		961.4		1294.5		1704.8		1931.0		2843.5	
CONTINGENCY,25%	170.5		207.7		264.3		191.1		240.3		323.6		426.2		462.6		660.9	
TOTAL ESTIMATED CAPITAL COST	652.3		1036.5		1321.3		985.7		1201.7		1616.1		2131.0		2413.6		3304.4	

CASE II - HIGH DENSITY SLUDGE PROCESS

CAPITAL COST ESTIMATE (in 1,000's)

DESCRIPTION	FLOW,55m3/h						FLOW,190m3/h						FLOW,820m3/h					
	CONCENTRATION,gm/L						CONCENTRATION,gm/L						CONCENTRATION,gm/L					
	50.0		500.0		5W0.0		50.0		500.0		5W0.0		50.0		500.0		5W0.0	
	Cost,\$	Op.,kW	Cost,\$	Op.,kW	Cost,\$	Op.,kW	Cost,\$	Op.,kW	Cost,\$	Op.,kW	Cost,\$	Op.,kW	Cost,\$	Op.,kW	Cost,\$	Op.,kW	Cost,\$	Op.,kW
NEUTRALIZATION CIRCUIT																		
2-Feed pumps	112	7.5	112	7.5	112	7.5	16.6	22.5	15.6	22.5	16.6	22.5	44.6	112.0	44.6	112.0	44.6	112.0
1-Sludge/lime mix tank c/w agitator	5.3	3.5	5.3	3.5	5.3	3.5	3.5	102	7.7	102	7.7	102	7.7	24.6	15.0	24.6	15.0	24.6
1-Rapid mix tank c/w agitator	7.3	3.5	7.3	3.5	7.3	3.5	17.6	11.0	17.6	11.0	17.6	11.0	35.5	15.0	35.5	15.0	35.5	15.0
1 or 2-Lime reactor tank c/w agitator	24.0	15.0	24.0	15.0	24.0	15.0	43.0	22.5	43.0	22.5	43.0	22.5	136.8	52.5	136.8	52.5	136.8	52.5
1-HDS Thickener c/w floc tank	107.6	5.0	107.6	5.0	107.6	5.0	169.0	7.5	189.0	7.5	189.0	7.5	452.0	9.0	452.0	9.0	452.0	9.0
1-Polishing pond	15.0	-	15.0	-	15.0	-	43.0	-	43.0	-	43.0	-	194.0	-	194.0	-	194.0	-
2-Underflow pumps	102	7.5	102	7.5	102	7.5	102	7.5	102	7.5	102	7.5	102	7.5	102	7.5	102	7.5
2-Recycle water pumps	72	2.0	72	2.0	72	2.0	72	2.0	72	2.0	72	2.0	102	5.0	102	5.0	102	5.0
LIME OR HYDRATE LIME CIRCUIT																		
1 or 2-Lime bin c/w bin activator	-	-	39.1	0.7	23.3	0.7	-	-	39.1	0.7	55.6	3.0	39.1	0.7	23.3	0.7	166.0	6.0
1 or 2-Discharge screw conveyor	-	-	4.3	-	4.3	-	-	-	4.3	-	5.5	-	4.3	-	4.3	-	11.0	-
1-Pneumatic unloading system	-	-	15.0	-	15.0	-	-	-	15.0	-	7.5	-	15.0	-	15.0	-	7.5	-
1-Lime slaker or makeup tank	6.5	3.5	3.0	1.5	75.0	5.0	6.5	3.5	3.0	1.5	75.0	6.0	3.0	1.5	75.0	5.0	110.0	11.0
1-Lime storage tank c/w agitator	6.5	3.5	9.0	5.0	23.0	11.0	6.5	3.5	17.6	11.0	35.5	15.0	9.0	5.0	23.0	11.0	91.6	30.0
1-Reject conveyor	-	-	-	-	4.3	1.5	-	-	-	-	5.5	3.5	-	-	4.3	1.5	5.5	3.5
1-Transfer pump	3.6	1.5	-	-	4.0	3.5	3.6	1.5	-	-	4.0	3.5	-	-	4.0	3.5	5.1	7.5
2-Distribution pumps	72	1.5	72	1.5	9.6	3.5	72	1.5	72	1.5	9.6	3.5	72	1.5	9.6	3.5	102	7.5
FLOCCULENT CIRCUIT																		
1-Flocculent makeup unit	27.0	3.5	27.0	3.5	27.0	3.5	27.0	3.5	27.0	3.5	27.0	3.5	27.0	3.5	27.0	3.5	27.0	3.5
1-Flocculent storage tank c/w agitator	22	0.7	22	0.7	22	0.7	32	1.5	32	1.5	32	1.5	6.6	2.5	6.6	2.5	6.6	2.5
2-Distribution pumps	5.4	0.7	5.4	0.7	5.4	0.7	5.4	0.7	5.4	0.7	5.4	0.7	7.6	1.5	7.6	1.5	7.6	1.5
SERVICES																		
1-Instrumentation compressor	39.4	30.0	39.4	30.0	39.4	30.0	39.4	30.0	39.4	30.0	39.4	30.0	39.4	30.0	39.4	30.0	39.4	30.0
2-Process/service compressors	99.0	75.0	99.0	75.0	99.0	75.0	99.0	75.0	99.0	75.0	99.0	75.0	174.6	150.0	174.0	150.0	174.8	150.0
TOTAL EQUIPMENT & POLISHING POND	384.8	163.9	438.6	171.6	520.3	166.1	534.6	201.4	597.0	215.1	717.3	235.9	1241.1	421.2	1322.8	437.7	1580.1	484.0
Total Equipment	369.8		423.6		505.3		491.6		554.0		674.3		1047.1		1128.0		1386.1	
Equipment Installation,10%	37.0		42.4		50.5		49.2		55.4		67.4		104.7		112.9		136.6	
Process Piping,30%	110.9		127.1		151.8		147.5		165.2		202.3		314.1		338.6		415.6	
Electrical,20%	74.0		64.7		101.1		96.3		110.6		134.9		209.4		225.8		277.2	
Instrumentation,16%	592		67.8		80.8		76.7		66.6		107.9		167.5		180.8		221.6	
Building,37% (excluding thickener)	136.6		158.7		167.0		161.9		206.0		249.5		367.4		417.7		512.9	
Polishing Pond	15.0		15.0		15.0		43.0		43.0		43.0		194.0		194.0		194.0	
TOTAL DIRECT COST	602.7		917.3		1091.3		1090.1		1223.0		1479.3		2424.3		2596.3		3146.4	
Spare Parts,2%	16.1		10.3		21.8		21.8		24.5		29.6		48.5		52.0		62.9	
Construction Overheads,13%	104.3		119.2		141.9		141.7		159.0		192.3		315.2		337.8		409.0	
Eng.,Proc.& Management,15%	120.4		137.6		163.7		163.5		163.5		221.9		363.6		389.8		472.0	
TOTAL INDIRECT COST	240.6		275.2		327.4		327.0		366.9		443.8		727.3		779.5		943.9	
TOTAL DIRECT & INDIRECT COST	1043.5		1192.4		1416.7		1417.1		1569.9		1923.0		3151.8		3377.8		4090.3	
CONTINGENCY,25%	260.9		298.1		354.7		354.3		397.5		480.8		787.9		644.5		1022.6	
TOTAL CAPITAL COST ESTIMATE	1304.3		1490.6		1773.3		1771.4		1967.4		2403.6		3939.6		4222.3		5112.9	

CASE III - ENHANCED HIGH DENSITY SLUDGE PROCESS

CAPITAL COST ESTIMATE (in 1,000's)

DESCRIPTION	FLOW,55m3/h						FLOW,190m3/h						FLOW,820m3/h					
	CONCENTRATION,mg/L						CONCENTRATION,mg/L						CONCENTRATION,mg/L					
	50.0		500.0		5000.0		50.0		500.0		5000.0		50.0		500.0		5000.0	
	Cost,\$	Op.,kW	Cost,\$	Op.,kW	Cost,\$	Op.,kW	Cost,\$	Op.,kW	Cost,\$	Op.,kW	Cost,\$	Op.,kW	Cost,\$	Op.,kW	Cost,\$	Op.,kW	Cost,\$	Op.,kW
NEUTRALIZATION CIRCUIT																		
2-Feed pumps	112	7.5	112	7.5	112	7.5	16.6	22.5	16.6	22.5	16.6	22.5	44.8	112.0	U.6	1120	44.8	1120
1-Sludge/lime mix tank c/w agitator	5.3	3.5	5.3	3.5	5.3	3.5	10.2	7.7	10.2	7.7	10.2	7.7	24.8	15.0	24.6	15.0	24.8	15.0
1-Rapkl mix tank c/w agitator	7.3	3.5	7.3	3.5	7.3	3.5	17.0	11.0	17.6	11.0	17.6	11.0	35.5	15.0	35.6	16.0	35.5	15.0
1 or 2-Lime reactor tank c/w agitator	24.0	15.0	24.0	15.0	24.0	15.0	43.0	22.5	43.0	22.5	43.0	22.5	136.6	52.5	136.8	52.6	136.6	52.5
1-HDS Thickener c/w flocc tank	107.8	5.0	107.6	5.0	107.6	5.0	169.0	7.5	160.0	7.5	169.0	7.5	452.0	9.0	452.0	0.0	452.0	0.0
1-Polishing pond	15.0		15.0		15.0		43.0		43.0		43.0		194.0		194.0		194.0	
2-Underflow pumps	102	7.5	102	7.5	102	7.5	102	7.5	102	7.5	102	7.5	102	7.5	102	102	102	7.6
2 or 4-Pressure filter feed pumps	8.0	1.5	12.4	3.5	15.0	5.0	6.0	1.5	12.4	3.5	24.4	11.0	12.4	3.5	15.0	X:X	77.6	30.0
1 or 2-Pressure filters c/w bin	32.0	0.7	115.0	0.7	197.0	0.7	32.0	0.7	115.0	0.7	456.0	0.7	115.0	0.7	101.0	0.7	1975.0	1.5
2 or 4-Filter cake pumps	8.0	1.5	12.4	3.5	15.0	5.0	8.0	1.6	12.4	3.5	24.4	11.0	12.4	3.5	15.0	5.0	77.6	30.0
2-Recycle water pumps	7.2	2.0	7.2	2.0	7.2	2.0	7.2	2.0	7.2	2.0	7.2	2.0	102	5.0	102	5.0	102	5.0
LIME OR HYDRATED LIME CIRCUIT																		
1 of 2-Lime bin c/w bin activator			39.1	0.7	23.3	0.7			39.1	0.7	55.6	3.0	39.1	0.7	23.3	0.7	158.0	6.0
1 or 2-Discharge screw conveyor			4.3	1.5	4.3	1.5			4.3	1.5	5.5	3.5	4.3	1.5	4.3	1.5	11.0	7.5
1-Pneumatic unloading system			15.0	7.5	15.0	7.5			15.0	7.5	15.0	7.5	15.0	7.5	15.0	7.5	15.0	7.6
1-Lime slaker or makeup tank	6.5	3.5	3.0	1.5	75.0	5.0	6.5	3.5	3.0	1.6	75.0	5.0	3.0	1.5	75.0	5.0	110.0	11.0
1-Lime storage tank c/w agitator	6.5	3.5	9.0	5.0	23.0	11.0	6.5	3.5	17.6	11.0	35.5	15.0	9.0	5.0	23.0	11.0	01.6	30.0
1-Reject conveyor					4.3	1.5					5.5	3.5			4.3	1.5	5.5	3.5
1-Transfer pump	3.6	1.5			4.6	3.5	3.6	1.5			4.6	3.5			4.6	3.5	5.1	7.5
2-Distribution pumps	7.2	1.5	7.2	1.5	9.6	3.5	7.2	1.5	7.2	1.5	9.6	3.5	7.2	1.5	9.6	3.5	102	7.5
FLOCCULENT CIRCUIT																		
1-Flocculent makeup unit	27.0	3.5	27.0	3.5	27.0	3.5	27.0	3.5	27.0	3.5	27.0	3.5	27.0	3.6	27.0	3.5	27.0	3.5
1-Flocculent storage tank c/w agitator	2.2	0.7	2.2	0.7	2.2	0.7	3.2	1.5	3.2	1.6	3.2	1.5	6.6	2.5	6.6	2.5	6.6	2.6
2-Distribution pumps	5.4	0.7	5.4	0.7	5.4	0.7	5.4	0.7	5.4	0.7	5.4	0.7	7.6	1.5	7.6	1.5	7.6	1.5
SERVICES																		
1-Instrumentation compressor	39.4	30.0	39.4	30.0	39.4	30.0	39.4	30.0	39.4	30.0	39.4	30.0	39.4	30.0	39.4	30.0	39.4	30.0
2-Process/service compressors	99.0	75.0	09.0	75.0	99.0	75.0	174.6	150.0	174.6	150.0	174.6	150.0	258.6	225.0	256.6	225.0	256.6	225.0
TOTAL EQUIPMENT & POLISHING POND	432.6	167.6	576.4	179.3	747.3	196.6	656.4	260.1	612.6	297.6	1297.0	333.6	1464.7	503.9	1633.6	523.4	3795.1	621f.5
Total Equipment	417.6		563.4		732.3		615.4		769.6		1254.9		1270.7		1439.6		3501.1	
Equipment Installation,10%	41.0		56.3		73.2		61.5		77.0		125.5		127.1		144.0		360.1	
Process Piping,30%	125.3		169.0		219.7		164.6		230.9		376.5		361.2		431.9		1080.3	
Electrical,20%	03.6		112.7		146.5		123.1		153.9		251.0		254.1		267.9		720.2	
Instrumentation,16%	66.8		90.1		117.2		96.5		123.1		200.8		203.3		230.3		576.2	
Building,37% (excluding thickener)	114.7		166.6		231.1		157.6		214.6		394.4		302.9		365.4		1165.2	
Polishing Pond	15.0		15.0		15.0		43.0		43.0		43.0		194.0		194.0		194.0	
TOTAL DIRECT COST	865.0		1175.2		1534.9		1263.9		1612.3		2646.0		2733.4		3003.1		7697.1	
Spare Parts,2%	17.3		23.5		30.7		25.7		32.2		52.9		54.7		61.9		153.9	
Construction Overheads,13%	112.5		152.6		190.5		166.9		209.6		344.0		355.3		402.1		1000.6	
Eng.,Proc.& Management,15%	129.8		176.3		230.2		192.6		241.8		396.9		410.0		454.0		1154.6	
TOTAL INDIRECT COST	259.5		352.5		460.5		365.2		463.7		793.6		920.0		927.9		2309.1	
TOTAL DIRECT & INDIRECT COST	1124.5		1527.7		1995.4		1669.0		2095.0		3439.6		3653.4		4021.0		10006.2	
CONTINGENCY,25%	261.1		361.9		496.6		417.3		524.0		860.0		666.3		1005.3		2501.6	
TOTAL ESTIMATED CAPITAL COST	1405.7		1909.6		2454.2		2066.3		2520.0		4299.8		4441.7		5026.3		12507.8	

C.3 OPERATING COST ESTIMATES

OPERATING COST ESTIMATE (in 1,000's)

FLOW,55m3/h

FLOW,190m3/h

DESCRIPTION	CONCENTRATION,mg/L			CONCENTRATION,mg		
	50	500	5000	50	500	5000
	Cost,\$/y	Cost,\$/y	Cost,\$/y	Cost,\$/y	Cost,\$/y	Cost,\$/y
CASE No.1,FLWSHEET No.1						
Hydrated Lime or Lime	5.8	44.2	202.6	20.2	152.8	699.8
Flocculent	8.8	6.8	6.8	22.7	22.7	22.7
Operating Labour	22.5	22.5	78.6	22.5	22.5	78.6
Maintenance (labour & supplies)	29.8	36.3	46.2	34.5	42.1	56.6
Electrical Power	70.8	74.6	82.7	82.3	89.0	99.2
Total Direct Cost	135.7	184.4	416.9	182.1	329.1	956.9
Indirect Cost,10%	13.8	18.4	41.7	18.2	32.9	95.7
Contingency,1 0%	13.8	18.4	41.7	18.2	32.9	95.7
TOTAL OPERATING COST ESTIMATE	182.9	221.3	500.3	218.5	394.9	1148.3
CASE No.2,FLWSHEET No.2						
Hydrated Lime or Lime	5.8	44.2	202.6	20.2	152.8	699.8
Flocculent	8.8	6.8	6.8	22.7	22.7	22.7
Operating Labour	22.5	22.5	78.8	22.5	22.5	78.6
Maintenance (labour & supplies)	45.7	52.2	62.1	62.0	69.6	84.1
Electrical Power	80.4	84.2	92.3	98.8	105.5	115.7
Total Direct Cost	181.1	209.8	442.3	226.1	373.1	1001.0
Indirect Cost,10%	16.1	21.0	44.2	22.6	37.3	100.1
Contingency,10%	16.1	21.0	44.2	22.6	37.3	100.1
TOTAL OPERATING COST ESTIMATE	193.4	251.8	530.8	271.4	447.7	1201.2
CASE No.3,FLWSHEET No.3						
Hydrated Lime or Lime	5.8	44.2	202.8	20.2	152.8	899.8
Flocculent	6.8	6.8	6.8	22.7	22.7	22.7
Operating Labour	78.6	78.6	235.9	78.8	78.6	314.5
Maintenance (labour & supplies)	49.2	66.8	87.3	73.0	91.7	150.5
Electrical Power	82.2	88.0	97.5	137.4	146.1	163.7
Total Direct Cost	222.7	284.4	630.0	331.9	492.0	1351.1
Indirect Cost,10%	22.3	28.4	63.0	33.2	49.2	135.1
Contingency,1 0%	22.3	28.4	63.0	33.2	49.2	135.1
TOTAL OPERATING COST ESTIMATE	267.2	341.3	756.0	398.3	590.4	1821.3

APPENDIX D

**CASE STUDIES 1 TO 4
PRELIMINARY COST CALCULATIONS**

APPENDIX D.1 - CASE STUDY 1

CONVENTIONAL TREATMENT PRELIMINARY COST CALCULATIONS

CAPITAL COST

- inflow rate = 6,000 m³/day (4,200 L/min)
- equivalent acidity = 2,000 mg/L
- loading = 500 kg solids/hr

From Figure 6.1, the capital cost is \$1,500,000.

OPERATING COST

Basis	Solids Loading	Flowrate
Case 1: 250 m ³ /hr @ 2,000 mg/L	500 kg/hr	250 m ³ /hr
Modelled: 190 m ³ /hr @ 5,000 mg/L	950 kg/hr	190 m ³ /hr

Adjust selected modelled operating costs shown in Appendix C as follows:

Lime \$699,800 x	$\frac{500}{950}$ (prorate loadings)	=	\$368,300/yr
Flocculant \$22,700 x	$\frac{500}{950}$ (prorate loadings)	=	\$ 12,000
Operating labour, remains at		=	\$ 78,600
Mtce @ 3.5% of capital cost above		=	\$ 52,500
Electrical power \$ 99,200 x	$\frac{250}{190}$ (prorate flows)	=	<u>\$130,500</u>
Subtotal			\$641,900
Plus 10% indirects			64,200
Plus 10% contingency			<u>64,200</u>
Total			\$770,300/yr
Use			\$770,000

APPENDIX D.1 - CASE STUDY 1

HDS TREATMENT PRELIMINARY COST CALCULATION

CAPITAL COST

- inflow rate = 6,000 m³/day (4,200 L/min)
- equivalent acidity = 2,000 mg/L
- loading = 500 kg solids/hr

From Figure 6.2, the capital cost is \$2,300,000.

OPERATING COST

Basis	Solids Loading	Flowrate
Case: 250 m ³ /hr @ 2,000 mg/L	500 kg/hr	250 m ³ /hr
Modelled: 190 m ³ /hr @ 5,000 mg/L	950 kg/hr	190 m ³ /hr

Adjust modelled operating costs shown in Appendix C as follows:

Lime \$699,800 x	$\frac{500}{950}$ (prorate loadings)	=	\$368,300/yr
Flocculant \$22,700 x	$\frac{500}{950}$ (prorate loadings)	=	\$ 12,000
Operating labour, remains at		=	\$ 78,600
Mtce @ 3.5% of capital cost above		=	\$ 80,500
Electrical power \$115,700 x	$\frac{250}{190}$ (prorate flows)	=	<u>\$152,200</u>
Subtotal			\$691,600
Plus 10% indirects			69,200
Plus 10% contingency			<u>69,200</u>
Total			\$830,000/yr
Use			\$830,000

APPENDIX D.1 - CASE STUDY 1

ENHANCED HDS TREATMENT PRELIMINARY COST CALCULATION

CAPITAL COST

- inflow rate = 6,000 m³/day (4,200 L/min)
- equivalent acidity = 2,000 mg/L
- loading = 500 kg solids/hr

From Figure 6.3, the capital cost is \$3,200,000.

OPERATING COST

Basis	Solids Loading	Flowrate
Case: 250 m ³ /hr @ 2,000 mg/L	500 kg/hr	250 m ³ /hr
Modelled: 190 m ³ /hr @ 5,000 mg/L	950 kg/hr	190 m ³ /hr

Adjust modelled operating costs shown in Appendix C as follows:

Lime \$699,800 x	$\frac{500}{950}$ (prorate loadings)	=	\$368,300/yr
Flocculant \$22,700 x	$\frac{500}{950}$ (prorate loadings)	=	\$ 12,000
Operating labour, use		=	\$ 78,600
Mtce @ 3.5% of capital cost above		=	\$112,000
Electrical power \$163,700 x	$\frac{250}{190}$ (prorate flows)	=	<u>\$215,400</u>
Subtotal			\$786,300
Plus 10% indirects			78,600
Plus 10% contingency			<u>78,600</u>
Total			\$943,500/yr
Use			\$940,000

APPENDIX D.2 - CASE STUDY 2

CONVENTIONAL TREATMENT PRELIMINARY COST CALCULATIONS

CAPITAL COST

- inflow rate = 2,200 m³/day (1,500 L/min)
- equivalent acidity = 5,000 mg/L
- loading = 460 kg solids/hr

From Figure 6.1, the capital cost is \$1,400,000.

OPERATING COST

Basis	Solids Loading	Flowrate
Case: 92 m ³ /hr @ 5,000 mg/L	460 kg/hr	92 m ³ /hr
Modelled: 55 m ³ /hr @ 5,000 mg/L	275 kg/hr	55 m ³ /hr

Adjust selected modelled operating costs shown in Appendix C as follows:

Lime \$202,600 x	$\frac{460}{275}$ (prorate loadings)	=	\$338,900/yr
Flocculant \$6,800 x	$\frac{460}{275}$ (prorate loadings)	=	\$ 11,400
Operating labour, assume 0.5 m.s./day (no clarifier)		=	\$ 39,300
Mtce @ 3.5% of capital cost above		=	\$ 49,000
Electrical power \$ 82,700 x	$\frac{92}{55}$ (prorate flows)	=	<u>\$138,300</u>
Subtotal			\$576,900
Plus 10% indirects			\$ 57,700
Plus 10% contingency			<u>\$ 57,700</u>
Total			\$692,300/yr
Use			\$690,000

APPENDIX D.2 - CASE STUDY 2

HDS TREATMENT PRELIMINARY COST CALCULATION

CAPITAL COST

- inflow rate = 2,200 m³/day (1,500 L/min)
- equivalent acidity = 5,000 mg/L
- loading = 460 kg solids/hr

From Figure 6.2, the capital cost is \$1,900,000.

OPERATING COST

Basis	Solids Loading	Flowrate
Case: 92 m ³ /hr @ 5,000 mg/L	460 kg/hr	92 m ³ /hr
Modelled: 55 m ³ /hr @ 5,000 mg/L	275 kg/hr	55 m ³ /hr

Adjust modelled operating costs shown in Appendix C as follows:

Lime \$202,600 x	$\frac{460}{275}$ (prorate loadings)	=	\$338,900/yr
Flocculant \$6,800 x	$\frac{460}{275}$ (prorate loadings)	=	\$ 11,400
Operating labour, remains at		=	\$ 78,600
Mtce @ 3.5% of capital cost above		=	\$ 66,500
Electrical power \$ 92,300 x	$\frac{92}{55}$ (prorate flows)	=	<u>\$154,400</u>
Subtotal			\$649,800
Plus 10% indirects			\$ 65,000
Plus 10% contingency			<u>\$ 65,000</u>
Total			\$779,800/yr
Use			\$780,000

APPENDIX D.2 - CASE STUDY 2

ENHANCED HDS TREATMENT PRELIMINARY COST CALCULATION

CAPITAL COST

- inflow rate = 2,200 m³/day (1,500 L/min)
- equivalent acidity = 5,000 mg/L
- loading = 460 kg solids/hr

From Figure 6.3, the capital cost is \$2,800,000.

OPERATING COST

Basis	Solids Loading	Flowrate
Case: 92 m ³ /hr @ 5,000 mg/L	460 kg/hr	92 m ³ /hr
Modelled: 55 m ³ /hr @ 5,000 mg/L	275 kg/hr	55 m ³ /hr

Adjust modelled operating costs shown in Appendix C as follows:

Lime \$202,600 x	$\frac{460}{275}$ (prorate loadings)	=	\$ 338,900/yr
Flocculant \$6,800 x	$\frac{460}{275}$ (prorate loadings)	=	\$ 11,400
Operating labour, use		=	\$ 235,900
Mtce @ 3.5% of capital cost above		=	\$ 98,000
Electrical power \$ 97,500 x	$\frac{92}{55}$ (prorate flows)	=	<u>\$ 163,000</u>
Subtotal			\$ 847,200
Plus 10% indirects			\$ 84,700
Plus 10% contingency			<u>\$ 84,700</u>
Total			\$1,016,600/yr
Use			\$1,020,000

APPENDIX D.3 - CASE STUDY 3

CONVENTIONAL TREATMENT PRELIMINARY COST CALCULATIONS

CAPITAL COST

- inflow rate = 18,760 m³/day (13,000 L/min)
- equivalent acidity = 1,000 mg/L
- loading = 780 kg solids/hr

From Figure 6.1, the capital cost is \$2,500,000.

OPERATING COST

Basis	Solids Loading	Flowrate
Case: 780 m ³ /hr @ 1,000 mg/L	780 kg/hr	780 m ³ /hr
Modelled: 820 m ³ /hr @ 500 mg/L	410 kg/hr	820 m ³ /hr

Adjust modelled operating costs shown in Appendix C as follows:

Lime \$302,000 x $\frac{780}{410}$ (prorate loadings)	=	\$ 574,500
Flocculant, remains at	=	\$ 98,400
Operating labour, remains at	=	\$ 78,600
Mtce @ 3.5% of capital cost above	=	\$ 87,500
Electrical power \$191,900 x $\frac{780}{820}$ (prorate flows)	=	\$ <u>182,500</u>
Subtotal		\$1,021,500
Plus 10% indirects		102,200
Plus 10% contingency		<u>102,200</u>
Total		\$1,225,900/yr
Use		\$1,230,000

APPENDIX D.3 - CASE STUDY 3

HDS TREATMENT PRELIMINARY COST CALCULATION

CAPITAL COST

- inflow rate = 18,760 m³/day (13,000 L/min)
- equivalent acidity = 1,000 mg/L
- loading = 780 kg solids/hr

From Figure 6.2, the capital cost is \$4,400,000.

OPERATING COST

Basis	Solids Loading	Flowrate
Case: 780 m ³ /hr @ 1,000 mg/L	780 kg/hr	780 m ³ /hr
Modelled: 820 m ³ /hr @ 500 mg/L	410 kg/hr	820 m ³ /hr

Adjust modelled operating costs shown in Appendix C as follows:

Lime \$302,000 x $\frac{780}{410}$ (prorate loadings)	=	\$ 574,500/yr
Flocculant, remains at	=	\$ 98,400
Operating labour, remains at	=	\$ 78,600
Mtce @ 3.5% of capital cost above	=	\$ 154,000
Electrical power \$214,700 x $\frac{780}{820}$ (prorate flows)	=	\$ <u>204,200</u>
Subtotal		\$1,109,700
Plus 10% indirects		111,000
Plus 10% contingency		<u>111,000</u>
Total		\$1,331,700
Use		\$1,330,000

APPENDIX D.3 - CASE STUDY 3

ENHANCED HDS TREATMENT PRELIMINARY COST CALCULATION

CAPITAL COST

- inflow rate = 18,760 m³/day (13,000 L/min)
- equivalent acidity = 1,000 mg/L
- loading = 770 kg solids/hr

From Figure 6.3, the capital cost is \$7,000,000.

OPERATING COST

Basis	Solids Loading	Flowrate
Case: 780 m ³ /hr @ 1,500 mg/L	780 kg/hr	780 m ³ /hr
Modelled: 820 m ³ /hr @ 500 mg/L	410 kg/hr	820 m ³ /hr

Adjust modelled operating costs shown in Appendix C as follows:

Lime \$302,000 x $\frac{780}{410}$ (prorate loadings)	=	\$ 574,500/yr
Flocculant, remains at	=	\$ 98,400
Operating labour, remains at	=	\$ 235,900
Mtce @ 3.5% of capital cost above	=	\$ 245,000
Electrical power \$256,800 x $\frac{780}{820}$ (prorate flows)	=	\$ <u>244,300</u>
Subtotal		\$1,398,100
Plus 10% indirects		139,800
Plus 10% contingency		<u>139,800</u>
Total		\$1,677,700/yr
Use		\$1,700,000

APPENDIX D.4 - CASE STUDY 4

CONVENTIONAL TREATMENT PRELIMINARY COST CALCULATIONS

CAPITAL COST

- inflow rate = 25,200 m³/day (17,500 L/min)
- equivalent acidity = 2,000 mg/L
- loading = 1,575 kg solids/hr

Apply 6/10ths rule to capital cost data:

$$\left(\frac{1,050}{820} \right)^{0.6} \times \$3,304,000 = \$3,800,000$$

OPERATING COST

Basis	Solids Loading	Flowrate
Case: 1,050 m ³ /hr @ 2,000 mg/L	2,100 kg/hr	1,050 m ³ /hr
Modelled: 820 m ³ /hr @ 5,000 mg/L	4,100 kg/hr	820 m ³ /hr

Adjust modelled operating costs shown in Appendix C as follows:

Lime \$3,020,000 x	$\frac{2,100}{4,100}$ (prorate loadings)	=	\$1,546,800/yr
Flocculant \$98,400 x	$\frac{2,100}{4,100}$ (prorate loadings)	=	\$ 50,400
Operating labour, remains at		=	\$ 78,600
Mtce @ 3.5% of capital cost above		=	\$ 133,000
Electrical power <u>\$214,600</u> x $\frac{1,050}{820}$ (prorate flows)		=	\$ <u>274,800</u>
Subtotal			\$2,083,600
Plus 10% indirects			208,000
Plus 10% contingency			<u>208,000</u>
Total			\$2,499,600/yr
Use			\$2,500,000

APPENDIX D.4 - CASE STUDY 4

HDS TREATMENT PRELIMINARY COST CALCULATION

CAPITAL COST

- inflow rate = 25,200 m³/day (17,500 L/min)
- equivalent acidity = 2,000 mg/L
- loading = 1,575 kg solids/hr

Apply 6/10ths rule to capital cost data:

$$\left(\frac{1,050}{820} \right)^{0.6} \times \$5,112,000 = \$6,000,000$$

OPERATING COST

Basis	Solids Loading	Flowrate
Case: 1,050 m ³ /hr @ 2,000 mg/L	2,100 kg/hr	1,050 m ³ /hr
Modelled: 820 m ³ /hr @ 5,000 mg/L	4,100 kg/hr	820 m ³ /hr

Adjust modelled operating costs shown in Appendix C as follows:

Lime \$3,020,000 x	$\frac{2,100}{4,100}$ (prorate loadings)	=	\$1,546,800/yr
Flocculant \$98,400 x	$\frac{2,100}{4,100}$ (prorate loadings)	=	\$ 50,400
Operating labour,		=	\$ 78,600
Mtce @ 3.5% of capital cost above		=	\$ 210,000
Electrical power <u>\$237,600</u> x $\frac{1,050}{820}$ (prorate flows)		=	\$ <u>304,000</u>
Subtotal			\$2,189,800
Plus 10% indirects			219,000
Plus 10% contingency			<u>219,000</u>
Total			\$2,627,800/yr
Use			\$2,630,000

APPENDIX D.4 - CASE STUDY 4

ENHANCED HDS TREATMENT PRELIMINARY COST CALCULATION

CAPITAL COST

- inflow rate = 25,200 m³/day (17,500 L/min)
- equivalent acidity = 2,000 mg/L
- loading = 1,575 kg solids/hr

Apply 6/10ths rule to capital cost data:

$$\left(\frac{1,050}{820} \right)^{0.6} \times \$12,508,000 = \$15,000,000$$

OPERATING COST

Basis	Solids Loading	Flowrate
Case: 1,050 m ³ /hr @ 2,000 mg/L	2,100 kg/hr	1,050 m ³ /hr
Modelled: 820 m ³ /hr @ 5,000 mg/L	4,100 kg/hr	820 m ³ /hr

Adjust modelled operating costs shown in Appendix C as follows:

Lime \$3,020,000 x	$\frac{2,100}{4,100}$ (prorate loadings) =	\$1,546,800/yr
Flocculant \$98,400 x	$\frac{2,100}{4,100}$ (prorate loadings) =	\$ 50,400
Operating labour,	=	\$ 471,700
Mtce @ 3.5% of capital cost above	=	\$ 525,000
Electrical power \$304,400 x	$\frac{1,050}{820}$ (prorate flows) =	\$ <u>389,800</u>
Subtotal		\$2,983,700
Plus 10% indirects		298,400
Plus 10% contingency		<u>298,400</u>
Total		\$3,580,500/yr
Use		\$3,600,000

APPENDIX E

DISCUSSION AND FUTURE RESEARCH NEEDS

APPENDIX E: DISCUSSION AND FUTURE RESEARCH NEEDS

E.1 OVERVIEW

Chemical treatment technology for the control of acid mine drainage is well developed. Major advances made to automated and highly efficient systems to produce high quality effluents and dense sludges have occurred over the past 20 years. New developments regarding mechanical clarifier design, polymer applications, dewatering equipment etc. will continue but these developments will only serve to optimize existing systems.

The real issue regarding chemical treatment technology relates to sludge production and disposal.

In some cases, the volumes of sludges which can be produced from an acid generating waste will exceed the volume of waste. Furthermore, sludges may have both physical and chemical properties which are undesirable for long-term management. Some sludges are gelatinous fluids and many sludges have the potential to produce contaminated leachates.

The following review highlights the findings of this study and identifies key areas where there are future research needs.

E.2 CHEMICAL TREATMENT TECHNOLOGY

Chemical treatment technologies are well advanced. The selection of a treatment method is very site-specific. The review of existing systems in Canada has demonstrated.

- Virtually all installed systems can meet effluent criteria.
- Systems installed cover a wide range from batch addition systems which require minimal attention (1-2 days/mo) to highly automated high density sludge (HDS) circuits with routine operator attention.
- Lime feeding systems range from direct pneumatic addition of lime to ponds to sophisticated automated pH control systems. By far the most common system is manual lime slurry addition.
- Implementation costs for construction of the treatment plant have ranged from <\$100,000 to more than \$10,000,000. A key finding is that capital costs are not often a major component

of the total cost. A summary of the capital and operating costs (see Table E.1) for the 4 case studies reviewed in Chapter 7 assuming 100 years of treatment indicate that capital costs represent only 1 to 11 percent of the total cost for acid mine drainage (AMD) treatment. Routine operating costs range from 55 to 91 percent of the total costs while sludge disposal costs can range from 1 to 45 percent of the total cost.

- Of the case studies reviewed, the most cost effective solutions were batch treatment at one plant, conventional treatment at one plant and HDS at two plants. As a matter of record, each facility for which the comparison was based upon had adopted the most cost effective option estimated in this study.
- Operating costs are the most expensive component for AMD treatment. Typical relative costs for lime, flocculant, labour, maintenance and power (% of total operating) is provided in Table E.2. From the table it is clear that lime costs are the most significant item. Obviously, any effort directed towards at source reduction of the acidity could have a dramatic impact on the overall operating costs.
- There are several rules of thumb for chemical addition rates, reactor retention times, thickener overflow rates, filter loadings, etc. The industry experience indicates that these factors may be suitable for comparing alternatives but are not suitable for design. Pilot testing is recommended to optimize design parameters. This is not to say that a plant cannot be built and successfully operated without laboratory testing. However, if this were to be done, a conservative (i.e. more costly) design would likely be adopted.
- Treatment at remote sites where labour is not generally present represents a major challenge. Conventional continuous treatment technologies are normally not suitable. Passive treatment with alkaline drains could be considered but performance is almost impossible to predict. For these systems where practical, AMD storage reservoirs with seasonal or batch treatment offer simple cost effective solutions.
- The trend in modern AMD plants is to install HDS systems. These systems have performed well for more than 20 years producing sludges at more than 20% solids. For systems producing HDS sludge at 20% as compared with low density sludges at 2 to 5% solids, sludge volumes are reduced by a factor of 5 to 10.
- Limestone is widely available and has major cost advantages. For a typical system, reagent

Table E.1

**COMPARISON OF COSTS
(PERCENT OF TOTAL COST)**

	Batch Plant	Conventional Plant	HDS Plant	Enhanced HDS
CASE 1				
Capital	<1	4	8	9
Operating NPV	55	66	86	87
Sludge Disposal NPV	45	30	6	4
Total Cost (10⁶ \$)	24.6	36.9	30.4	34.0
CASE 2A (IMPOUNDMENT)				
Capital	-	4	7	8
Operating NPV	-	57	85	88
Sludge Disposal NPV	-	39	8	4
Total Cost (10⁶ \$)	-	38.4	29.1	36.5
CASE 2B (PIT DISPOSAL)				
Capital	-	5	7	8
Operating NPV	-	81	91	91
Sludge Disposal NPV	-	14	2	1
Total Cost (10⁶ \$)	-	27.0	27.2	35.4
CASE 3				
Capital	-	5	9	11
Operating NPV	-	81	88	88
Sludge Disposal NPV	-	14	3	1
Total Cost (10⁶ \$)	-	48.3	47.6	61.4
CASE 4				
Capital	-	3	6	11
Operating NPV	-	61	86	85
Sludge Disposal NPV	-	36	8	4
Total Cost (10⁶ \$)	-	129.3	97.0	133.2

Notes:

Capital costs based upon model results.

Operating costs calculated - NPV discount rate 3%, 100 years.

Sludge disposal costs assume \$4/m³ for engineered storage except option 2b which assumes sludge disposal in a pit at \$1/m³.

sludge disposal NPV discount rate 3%, 100 years.

Table E.2

**OPERATING COST ANALYSIS
(PERCENT OF TOTAL OPERATING COST⁽¹⁾)**

	Batch Plant	Conventional Plant	HDS Plant	Enhanced HDS
Lime	90%	74%	71%	52%
Flocculant	0%	2%	2%	2%
Operating Labour	5%	4%	4%	16%
Maintenance	5%	6%	10%	18%
Electrical Power	<1%	14%	13%	12%

Note:

⁽¹⁾ Before indirect support costs.

cost for limestone is about the cost of lime. For a high volume lime user (case study 4), if limestone could be used to neutralize 80% of the acidity, potential saving (NPV) at this location would be about \$30 million.

The primary drawback to limestone is related to problems with chemical feeding and the inability to raise pH levels above about 5 to 6. Under these conditions ferrous iron and many metals will not precipitate. However, as stage one of a two-stage neutralization process, a substantial potential cost savings exists.

From the standpoint of metals recovery, two-stage precipitation has been suggested to create an upgraded second stage metals precipitate. Limestone has potential as the first stage alkali.

E.3 SLUDGE DISPOSAL TECHNOLOGY

The long term management and disposal of sludges represents a major area of concern for AMD treatment technology. Sludge production data for the industry as a whole are not available and the data available are difficult to compare as sludges have broad ranges of densities and chemical characteristics.

The review of the current situation in Canada has indicated that:

- The production of low density sludges is the most prominent practice. Historically, the costs associated with long term sludge disposal have not been a major consideration in AMD treatment plant selection at many locations.
- Sludge disposal costs may be substantial. At some locations, basins or pits exist to manage sludges for the long term. At most locations, the production of large volumes of sludge will necessitate the design and construction of engineered sludge storage basins. Using a cost at \$4/m³, sludge disposal costs could represent upwards of 10 to 50% of long term costs.
- There is some potential that AMD sludges could be classified as hazardous wastes. If so, costs for disposal would escalate enormously. Should this occur, the economic benefits of recycle, enhanced HDS, etc. would become much more favourable.
- Sludge volumes can be substantial. In some cases sludge production from AMD waste can exceed the volume of the waste source (e.g. tailings mass).

- Limited data are available on long-term stability of sludges. Much of the data are anecdotal. Several chemical stability tests have been performed on a broad range of sludges. The results of this work demonstrate that under alkaline conditions most metals are relatively insoluble. However, under marginally acidic to acidic conditions many metals in the form of oxides, carbonates and hydroxides are readily mobilized.
- Some metals and radionuclides in AMD sludges are precipitated as co-precipitates. These metals include arsenic, molybdenum and radium-226. Under alkaline conditions, molybdenum sludges are not chemically stable while arsenic and radium-226 are relatively stable.

Arsenic is normally precipitated at a high pH as arsenate and is geochemically unstable. Over geological time, iron may convert to oxyhydroxides and result in arsenic mobility. At low iron to arsenic ratios, the arsenic solubility is enhanced while at high iron to arsenic ratios, arsenic mobility is minimized. This is attributed to adsorption on iron flocs.

Radium is co-precipitated with metal sulphates, all of which are believed to be equilibrium solubility controlled. Over time, sulphate levels in the precipitate pore water may drop and result in the dissolution of some radium. This does not appear to be a major issue.

- There have been several investigations into the enhanced recovery of metals both pre and post sludge production. For the high volume, low metals content wastewaters typical of AMD, little potential exists for recovery of metals prior to AMD treatment. Potential does exist to implement staged precipitation to recover a primarily iron/gypsum sludge and a secondary metals concentrate. Costs are not likely to be favourable; however, the recycle potential of the metals precipitate would be greatly enhanced.
- Smelting of sludges for metal recovery offers the greatest potential. Technology currently exists to produce and dewater sludges to adequate levels for smelter feeds. The major impediment to recycling to smelters are low metals values and contaminants in the sludge.
- Most tailings contain sludges with characteristics similar to AMD sludges. These sludges arise from mine water treatment, disposal of sludges in the tailings pond, precipitation of oxide minerals during milling and presence of oxide in the ore. As a general comment, long-term metals mobility from tailings is probably as significant or greater a concern as long-term

metals mobility from sludges.

- There are no definitive studies which indicate how sludges should be managed in the long term. Options being used today include disposal in pits, disposal in landfills, disposal in tailings basins or disposal in water filled basins. In selected cases, some residual alkalinity is added to provide better long-term stability. A better understanding of factors which affect chemical stability would assist in assessing if there are preferred management options.

E.4 RESEARCH NEEDS

The chemical treatment of AMD is well advanced. Virtually all plants meet effluent criteria and technology adopted at Canadian facilities is at the leading edge. There is no requirement to further investigate treatment technologies for conventional metals removal. As a result of this review, three potential areas were identified as warranting some level of future effort. These include the use of limestone, recycling of sludges for metals recovery, and investigations regarding sludge stability. Each of these items is briefly reviewed below.

1) *Limestone*

Limestone has potential as a cost effective substitute for lime for treatment of AMD. With the limited use in Canada, further study may be warranted to confirm or develop:

- applicability and cost benefits of limestone;
- simple methods for feeding, mixing and optimizing use;
- effects on sludge production/stability;
- limitations in metals precipitation;
- application as a stage 1 alkali in a two stage treatment system with second stage metals recovery.

2) *Sludge Recycling*

At present, circumstances few sludges are recycled. The prime reasons are low metals contents, contamination levels and poor economics. In the future, recycling could become more attractive especially if these sludges are subjected to hazardous waste regulations. We see no rationale for such a designation but should this occur, current costs for hazardous waste disposal which are on the order of \$100's/m³ would encourage recycling.

Several recycling options have been reviewed by CANMET and others. Of the technologies reviewed (ion exchange, solvent extraction, concentration etc.), sequential precipitation offers perhaps the best potential at this time for sludges with poor economic value or contamination problems. For these cases, two-stage precipitation could produce a bulk precipitate of iron and gypsum and a metals concentrate. Possibly limestone could be used as the first stage alkali. Cost savings from limestone use may offset increased costs for two-stage sludge removal and handling.

3) *Sludge Stability*

There is, at best, only a minor data file on the stability of sludges. If the industry can demonstrate that sludges are chemically stable over the long term and that the factors affecting stability are known, a rational case can be developed to offset any need to reclassify sludges as hazardous waste. The types of studies required to develop this case could include:

- field monitoring of old sludge storage basins;
- accelerated weathering tests;
- investigation of factors affecting sludge chemical stability such as method of sludge production, availability of excess buffering, levels of iron and gypsum, sludge age, etc.