Review of Mine Drainage Treatment and Sludge Management Operations

MEND Report 3.43.1

This work was done on behalf of MEND and funded by The Mining Association of Canada and MEND

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CANMET Mining and Mineral Sciences Laboratories

Review of Mine Drainage Treatment and Sludge Management Operations

by Janice Zinck and Wesley Griffith

This work was done on behalf of MEND and sponsored by the Mining Association of Canada (MAC) and MEND

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EXECUTIVE SUMMARY

At the request of the Mine Environment Neutral Drainage (MEND) Program, Natural Resources Canada conducted a survey of mine drainage treatment and sludge management practices. A detailed survey was prepared which requested information such as site background and history, mine drainage characteristics, type of treatment and reagents used, treatment issues, sludge composition, sludge management practices and issues. The response from these questionnaires accounted for about 52% of the database. The remaining 48% of the data were extracted from technical papers, company press releases, website information, and public information. Data on treatment practices and sludge management were collected on over 100 sites. Most sites in the database are located in Canada, but other sites that populate the database are in the USA, UK, Australia, Mexico, Peru, China, South Africa, Germany, Brazil, New Zealand and Hungary. The majority of the mines surveyed were base metal mines (46%) followed by precious metal mines (23%), coal (7%), uranium (5%), and other (19%). Other types included molybdenum, antimony, diamond, tin and non-mining operations with acidic drainage issues.

The majority of sites surveyed reported that they expect to treat *in perpetuity* and as such, their choice of treatment is critical not only for economic but also for environmental reasons. Roughly thirty percent of the sites control their influent flow through water management practices. Active treatment processes were the most prevalent with chemical treatment more common than physical (membrane) and biological processes combined. Roughly the same number of basic (simple) treatment processes as high-density sludge (HDS) processes were recorded. Of the sites applying chemical treatment, lime was the most prominent reagent used. Flocculant was used in approximately 42% of the treatment operations and a range of flocculant types were recorded. Magnafloc 10 was the most common flocculant used.

Treatment issues recorded included the following:

- gypsum scaling,
- the control of total suspended solids (TSS) in the final effluent,
- managing high flows,
- algal blooms in collection ponds,
- poor settling,
- lime handling and mixing,
- polymer mixing during winter,
- difficulty in maintaining high density sludge,
- manganese and sulphate concentrations in the final effluent,
- inefficient mixing and acidity in water due to residual thiosulphate (S_2O_3) derived from mill processing.

Capital costs ranged considerably from \$0.02M to \$42M with the average of approximately \$7.5 M. The average cost to treat one cubic metre of mine drainage was \$1.54.

The majority of the sites surveyed utilized sludge ponds for dewatering and permanent sludge disposal. On average, sites produced about 9,500 tonnes of dry sludge per year with production ranging from 20 dry tonnes to 135,000 dry tonnes per year. Depending on the percent solids of the sludge, the volume factor ranged from approximately 2 to 70 times the sludge mass. Generally, sites reported having sufficient sludge storage capacity for an average of 25 years.

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À la demande des responsables du Programme de neutralisation des eaux de drainage dans l’environnement minier (NEDEM), Ressources naturelles Canada a mené un sondage sur les pratiques de traitement des eaux de drainage minier et de gestion des boues. Le sondage détaillé visait à obtenir des renseignements sur le contexte et l’historique des sites miniers, les caractéristiques des eaux de drainage minier, les types de traitement et de réactifs utilisés, les problèmes liés au traitement, la composition des boues ainsi que les pratiques et problèmes de gestion des boues. Les réponses aux questionnaires du sondage représentent environ 52 % des renseignements de la base de données, tandis les autres 48 % des données sont tirées de documents techniques, de communiqués de presse d’entreprises et de sites Web, ainsi que d’autres sources d’information publiques. Des données sur les pratiques de traitement et la gestion des boues ont ainsi été recueillies sur plus de 100 sites miniers. La plupart des sites se trouvent au Canada, mais d’autres sont situés aux États-Unis, au Royaume-Uni, en Australie, au Mexique, au Pérou, en Chine, en Afrique du Sud, en Allemagne, au Brésil, en Nouvelle-Zélande et en Hongrie. Quarante-six pour cent des mines sont des mines de métaux communs, 23 % des mines de métaux précieux, 7 % des mines de charbon, et 5 % des mines d’uranium, tandis que 19 % sont des sites d’un autre type (notamment des mines de molybdène, d’antimoine, de diamants ou d’étain, ainsi que des sites non miniers qui présentent des problèmes d’eaux de drainage acides).

Comme les responsables de la majorité des sites ont indiqué qu’ils prévoient traiter les eaux de drainage *à perpétuité*, leur choix du type de traitement est déterminant pour des raisons non seulement économiques, mais aussi environnementales. Dans environ 30 % des sites, l’influent est traité par des méthodes de gestion des eaux. Les procédés de traitement actif sont les plus courants, les procédés chimiques étant plus utilisés que les procédés physiques (membrane) et biologiques combinés. On a relevé à peu près le même nombre de procédés de traitement de base (simple) que de procédés à boues de haute densité. La chaux est le réactif le plus utilisé dans les traitements chimiques. Des floculants de divers types sont utilisés dans environ 42 % des opérations de traitement. Le Magnafloc 10 est le floculant le plus couramment utilisé.

Voici une liste de certains des problèmes de traitement signalés :

- l’entartrage causé par le gypse;
- la régulation des solides totaux en suspension dans l’effluent final;
- la gestion des débits élevés;
- la prolifération d’algues dans les bassins de stockage;
- une sédimentation inadéquate;
- la manutention de la chaux et son mélange;
- le mélange des polymères, en hiver;
- la difficulté d’assurer l’uniformité de boues à haute densité;
- les concentrations de manganèse et de sulfates de l’effluent final;
- un mélange inefficace et l’acidité de l’eau attribuable au thiosulfate (S_2O_3) résiduel provenant de l’usine.

Les coûts en capitaux varient beaucoup, soit de 0,02 à 42 M$, pour un coût moyen d'environ 7,5 M$. Le coût de traitement des eaux de drainage minier est en moyenne de 1,54 $\$/m^3$.

Des bassins sont utilisés dans la plupart des sites pour déshydrater les boues et les stocker en permanence. Les sites produisent de 20 à 135 000 tonnes de boues sèches par année, pour une moyenne d'environ 9500 t/a. Selon le pourcentage de solides dans les boues, le facteur de volume varie d'environ 2 à 70 fois la masse des boues. En général, les sites disposent d'une capacité de stockage des boues d'une durée moyenne de 25 ans.

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NOMENCLATURE / GLOSSARY

Acid drainage, acid mine drainage (AMD) or acid rock drainage (ARD) - A low pH, metal-laden, sulphate-rich drainage, which may occur during land disturbance such as mining activities, where sulphur or metal sulphides are exposed to atmospheric conditions and are oxidized. It forms under natural conditions from the oxidation of sulphide minerals and where the acidity exceeds the alkalinity. Non-mining exposures, such as highway road cuts, may produce similar drainage.

Active treatment - Systems that treat drainage with active addition of chemical/ biological reagents or the application of external energy (including manpower).

Armouring - The process of coating the surface of a material and reducing its performance.

Base metal - Industrial non-ferrous metals excluding precious metals. These include copper, lead, nickel and zinc.

Dissolved solids - The weight of matter, including both organic and inorganic matter, in solution in a stated volume of water. The amount of dissolved solids is usually determined by filtering water through a glass or 0.45 μm pore-diameter micrometer filter, weighing the filtrate residue remaining after the evaporation of the water, and drying the salts to constant weight at 180°C.

Effluent - A material, usually a liquid waste, that is emitted by a source, which is in this report industrial, such as a metallurgical or water treatment process.

Flocculant - A substance that causes suspended particles to aggregate or clump together. The higher mass causes the aggregated clumps to settle. Flocculants are used to reduce high concentrations of fine silt size and clay size suspended sediment, particles whose slow settling rate makes them otherwise very difficult to remove by settling. See also suspension and sediment/settling pond.

Hydrated Lime - Calcium hydroxide [$Ca(OH)_2$]. Produced from calcium oxide (CaO) or quick lime. Used as a neutralizing agent. See also lime, slaking.

Hydrolysis - The process of splitting the water molecule into separate components of hydrogen ions (H+) and hydroxide ions (OH-) that often react with other constituents present.

Lime - Calcium oxide (CaO). Also referred to as quick lime. Produced by heating limestone ($CaCO_3$) above 550°C in a kiln. Used to make calcium hydroxide [$Ca(OH)_2$] or hydrated lime (a cheap neutralizing agent) and to produce a slag from the impurities in metal ores.

Neutral mine drainage - A neutral pH, metal-laden, sulphate-rich drainage that may occur during land disturbance where sulphur or metal sulphides are exposed to atmospheric conditions. It forms under natural conditions from the oxidation of sulphide minerals and where the alkalinity equals or exceeds the acidity.

Neutralization potential (NP) - The amount of alkaline or basic material in rock or soil materials that is estimated by laboratory procedures of acid reaction followed by titration used to determine the capability of neutralizing acid from exchangeable acidity or pyrite oxidation. May also be referred to as acid neutralization potential (ANP).

Neutralization - A chemical reaction in which an acid and a base or alkali (soluble base) react to produce salt and water, which do not exhibit any of the acid or base properties.

Precious Metal - A general term applied to relatively more expensive metals, such as gold, silver and platinum, which based on cost, can be distinguished from base and the alkali and alkali earth metals. Sometimes called the noble metals.

Passive treatment - Systems that treat acid mine drainage without continual and active additions of chemicals/biological reagents or the application of external energy (including manpower), includes aerobic and anaerobic wetlands, anoxic limestone drains, successive alkalinity-producing systems, and open limestone channels.

Pit lake - Any perennial or ephemeral water body that occupies an excavation in the land surface created from the extraction of ore material.

Slaking - The process of reaction with water to hydrate a mineral. Slaked lime if formed from reacting quicklime with water.

Suspension and Sediment/Settling Pond - An open pond where process water is allowed to stand while suspended material settles out.

1.0 INTRODUCTION

Mine drainage treatment and sludge management are two important facets of mine site environmental control practices where acidic/neutral drainage occurs. Many sites with acidic or neutral drainage issues employ some form of chemical treatment to address acid drainage issues. The type of treatment implemented varies from site to site and depends on an array of factors including composition, climate, topography, other waste streams, and economics. Previously there was no single, comprehensive database containing treatment and sludge management information for mine sites. At the request of the Mine Environment Neutral Drainage (MEND) Program, CANMET-MMSL (Natural Resources Canada) conducted a survey of mine drainage treatment and sludge management practices used in Canada and abroad.

1.1 Data Collection Process

A detailed survey (Appendix A) was prepared which requested information such as site background and history, mine drainage characteristics, type of treatment and reagents used, treatment issues, sludge composition, sludge management practices and issues. The survey was reviewed by the MEND steering committee for content and completeness.

A list of contacts was developed including personnel from mining companies, associations, companies, federal, territorial and provincial governments, and consulting firms. Following this, introductory letters with attached survey questionnaires were sent to the various contacts. These initial letters were followed-up through emails and telephone calls. For some sites, despite repeated attempts, data were not provided and the site was not included in the database. The response from questionnaires accounted for about 52% of the database. The remaining 48% of the data were extracted from technical papers, company press releases, website information, and public information. The data were compiled into an interactive database, which was used to produce the data tables and graphs in this report. The database is planned to be maintained and regularly updated by CANMET-MMSL.

The data quality and degree of survey completion was variable. Some sites provided very detailed information, while for other sites the data were sparse. Some data, such as sludge leachate characteristics and to a lesser extent costing, were more difficult to obtain.

2.0 SITE INFORMATION

Data on treatment practices and sludge management were collected on over 100 sites. Site data collected included site contact, location, site status, operation type and receiving environment characteristics.

2.1 Site Location

Most sites in the database are located in Canada but other sites that populate the database are in USA, UK, Australia, Mexico, Peru, China, South Africa, Germany, Brazil, New Zealand and Hungary populate the database. Figure 1 and Tables 1 and 2 show the mine site locations. Most of the Canadian provinces and territories are represented in the database with the exception of Alberta, Nunavut and Prince Edward Island.

Figure 1: Location of sites surveyed.

Table 1: Survey site location by country

Country	Number Of Sites
Australia	3
Brazil	1
Canada	66
China	1
Germany	1
Hungary	1
Mexico	1
New Zealand	1
Peru	3
South Africa	2
United Kingdom	4
USA	24
Total Mine Sites	**108**

Table 2: Survey sites in Canada

Province	Number Of Sites
Alberta	0
British Columbia	11
Manitoba	2
New Brunswick	4
Newfoundland	3
Northwest Territories	2
Nova Scotia	4
Nunavut	0
Ontario	18
Prince Edward Island	0
Québec	13
Saskatchewan	2
Yukon	7

2.2 Mine Status and Type

The majority of the mines (Table 3) surveyed were base metal mines (46%), followed by precious metal mines (23%), coal (7%), uranium (5%), and other (19%). Other types included molybdenum, antimony, diamond, tin and non-mining operations with acidic drainage issues (such as highways and other construction activities).

Table 3: Mining operations surveyed

Type	Number of sites
Base Metal	50
Coal	8
Precious Metal	25
Uranium	5
Other	20

The majority of the sites surveyed were either operating or closed sites, with equal numbers of each surveyed. The remainder of the sites were orphaned or abandoned (Table 4).

Table 4: Status of sites surveyed

Status	Number of sites
Orphaned/Abandoned	10
Closed	49
Operating	49

2.3 Receiving Environment

The majority of the sites that reported gave detailed information on their receiving environment (Appendix B). The final effluent in most cases was discharged to sensitive aquatic environments including fish-bearing water courses and in some cases, the effluent was discharged into commercial and recreational fishing areas. For one site the discharge enters a receiving environment which is used to irrigate farm lands and in another case the receiving environment is the town's drinking water reservoir.

3.0 MINE DRAINAGE REQUIRING TREATMENT

3.1 Source and Composition

The primary sources of mine drainage that required treatment were identified as tailings, followed closely by waste rock and then mine workings (Figure 2). Other sources included heap leach pads, acid-generating rock from non-mining operations, contaminated soils, and historic mining operations. Several sites noted more than drainage source.

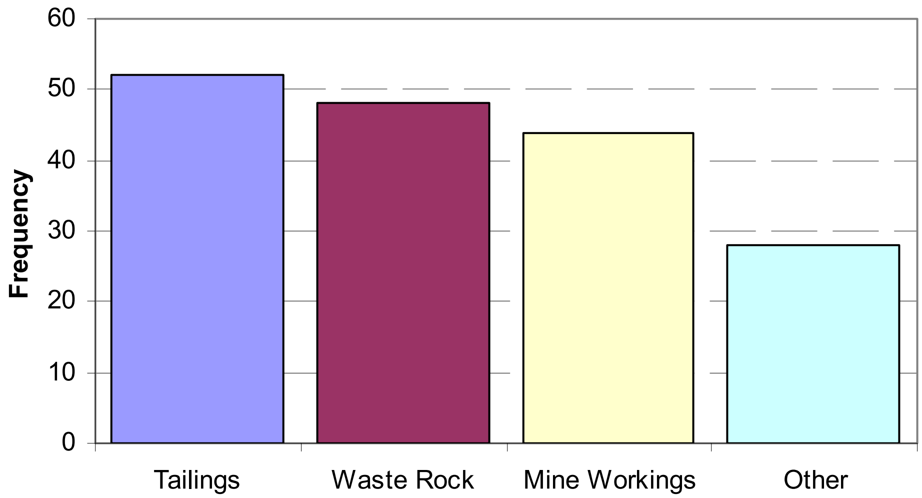

Figure 2: Sources of acidic and neutral drainage.

Respondents were asked to provide information on composition of the mine drainage that required treatment. Seventy-six percent of respondents provided drainage composition data, which are summarized in Appendix C. The AMD database is provided in Appendix D. In general, pH data were reported for most sites and are summarized in Figure 3. In addition, iron was reported for most sites and concentrations ranged greatly from 0.009 mg/L to 5,000 mg/L. Sulphate concentrations were variable ranging from 13.7 mg/L to 73,796 mg/L. With the potential for increased regulation of sulphate in the final effluent discharge, the need to develop effective sulphate removal technologies is becoming more important.

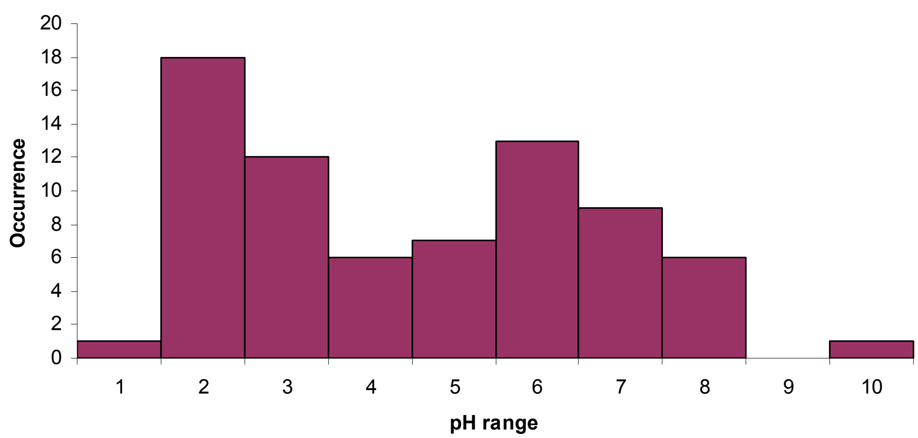

Figure 3: pH reported by site.
Note pH 1 = pH 1-2, pH 2 = pH 2-3, etc.

Fifteen sites reported co-treating other waste streams such as smelter effluent, contaminated groundwater, sewage treatment effluent, process effluent and wash water.

Treatment flow rates were variable. Figure 4 presents the average and maximum flows recorded in cubic metres per hour. It should be noted that, the highest flows were treated with basic neutralization processes, rather than high density sludge (HDS) processes.

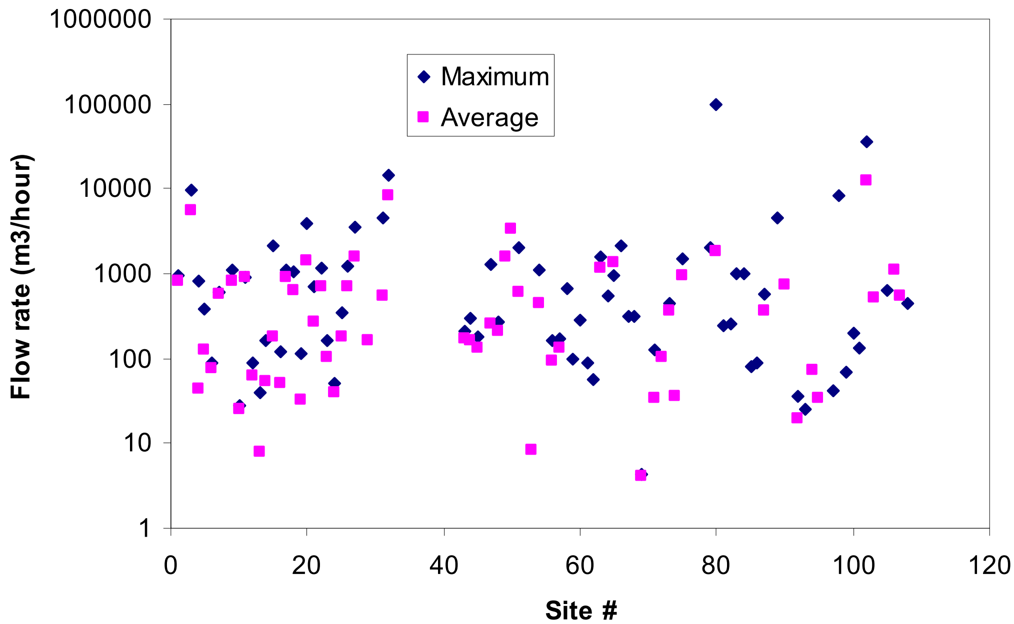

Figure 4: Average and maximum flow rate by site identification number.

4.0 TREATMENT PRACTICES

The majority of mine sites surveyed reported that they expect to treat *in perpetuity* and as such their choice of treatment technology is based on both economic and environmental reasons. There are a variety of treatment processes that can be applied either in isolation or in combination to remove metals and neutralize acidity (MEND, 2001; Aubé and Zinck, 2003). Most sites projected that treatment would be required for decades or longer and many predicted perpetual treatment (Figure 5). Treatment is generally site specific and what works for one site may not be advantageous for another.

4.1 Water Management

One of the keys to effective water management at a mine site is to treat only contaminated water and divert clean water. The water management system should be designed to handle high flood events – typically a 1:20, a 1:100 year event or higher. As a result of climate changes these extreme weather events are occurring more frequently. A water treatment plant typically cannot be economically designed to handle these types of events directly. Normally a large water storage system is put in place to handle peak flows associated with extreme events for later water treatment (Zinck and Aubé, 2010).

Roughly thirty percent of the sites control their influent flow through water management practices by diverting and managing various water sources to minimize the volume of water treated. Typical flow equalization options used include surge and holding ponds or reservoirs, pumps and level control (stop log), bulkheads, acid lake at the top of tailings dam, pits and underground mine workings.

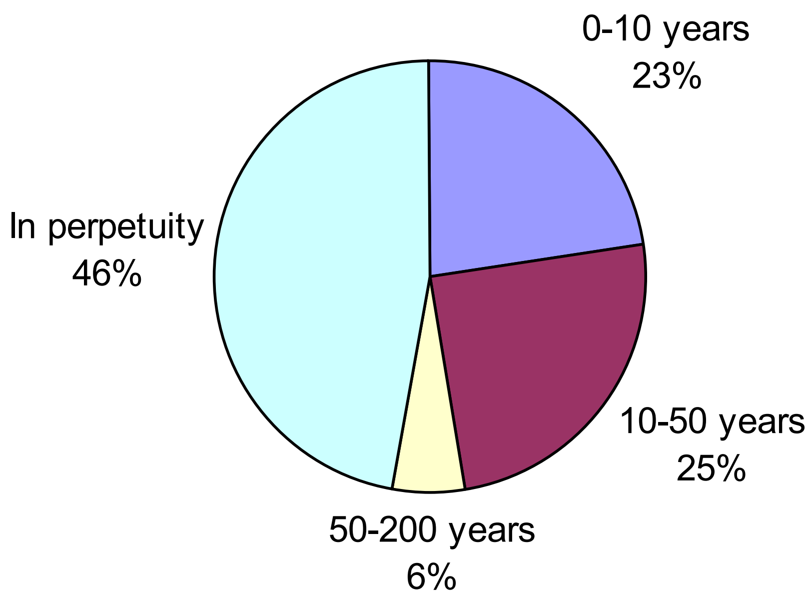

Figure 5: Predicted time treatment required.

4.2 Process Components

Survey respondents were asked to identify any, and all, applicable treatment processes used. While the survey focused primarily on active treatment processes, passive applications were also captured in the responses. Figure 6 presents the wide array of treatment processes that were reported in the survey. Active treatment processes are most prevalent, with chemical treatment more common than physical (membrane) and biological processes combined. Roughly the same number of basic (simple) treatment processes as high density sludge (HDS) processes were recorded. Many sites are moving towards HDS processes that employ mechanical agitation, flocculation, and sludge recycle to optimize treatment performance, increase sludge density and reduce reagent consumption. Alternately, other sites plan to modify their basic treatment systems to improve performance without investing in the added capital cost of a high density sludge treatment. For example, some sites will utilize reactors without sludge recycle to enhance mixing and precipitation, while others will add a simple sludge recycle line back to the start of their process. Between one and four reactors were reported to be used with the median being two. In Figure 6, "other" processes include the biosulphide process, pipe reactor, pit lake treatment, and Rotating Cylinder Treatment System™ RCTS technology. Approximately six percent of the operations surveyed were treating in batch mode which is assumed to be non-continuous operation. Treatment is generally site specific and what works for one site may not be applicable or advantageous at another. Factors that play into selecting which technology is applied include water quality, degree of treatment required, sensitivity of receiving environment, flow rate, cost, etc. An excellent tool to determine which treatment process should be selected is the Acid Drainage Decision Tree developed by Jack Adams (GARD Guide, Chapter 7). This reference also provides more information on the various treatment approaches discussed in this report.

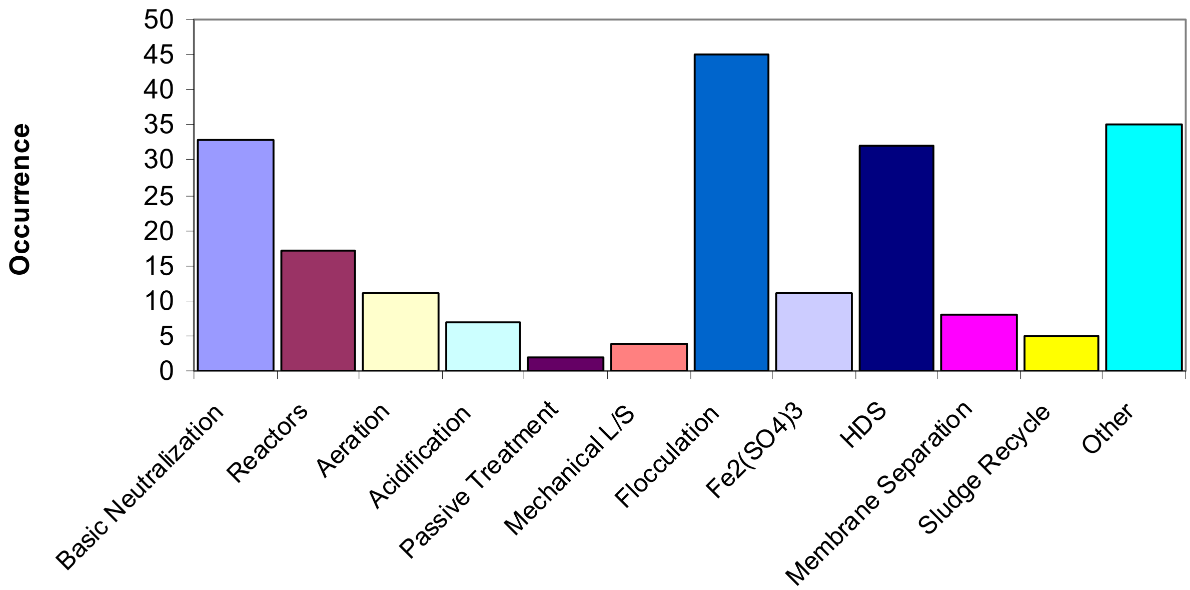

Figure 6: Range of treatment processes reported.

Membrane separation and biosulphide treatment were observed treatment practices at several sites. These treatment methods involve recovery/recycle of water and metals from mine effluent. Adoption of these relatively new technologies is increasing as lower effluent criteria and demand for 'zero discharge' are on the rise (e.g. membrane separation).

If ferrous concentrations are high (>100-200 mg/L) aeration is often required to oxidize the iron to a more stable form (Watzlaf and Casson, 1990). About 10% of the sites reported using aeration as an add-on to their processes. Aeration is a common component in HDS systems, where it is not considered an add-on technology for this survey.

4.3 Reagents

Of the sites applying chemical treatment, lime was the most used reagent. Lime was used in one of three forms: quicklime (CaO, without slaking) – 6%; hydrated lime ($Ca(OH)_2$) – 58%; and slaked lime ($Ca(OH)_2$ slaked on site) – 36%. Slaked lime can be prepared with a ball mill, paste or slurry slaker. In the database, slurry slakers were used three times more frequently than paste slakers. More information on lime slaking can be found in Zinck and Aubé (2000) and Hassibi (1999). Caustic soda (NaOH) is also used for hydrolysis and acidity neutralization. Caustic soda is very efficient and reacts rapidly however, it is almost ten times more expensive than lime and was used in 9% of the sites surveyed. Limestone is also used for hydrolysis and neutralization but its application is limited as it armours easily and can only neutralize to pH ~7. It was used at only 1% of the sites. Figure 7 shows the reagents used for treatment.

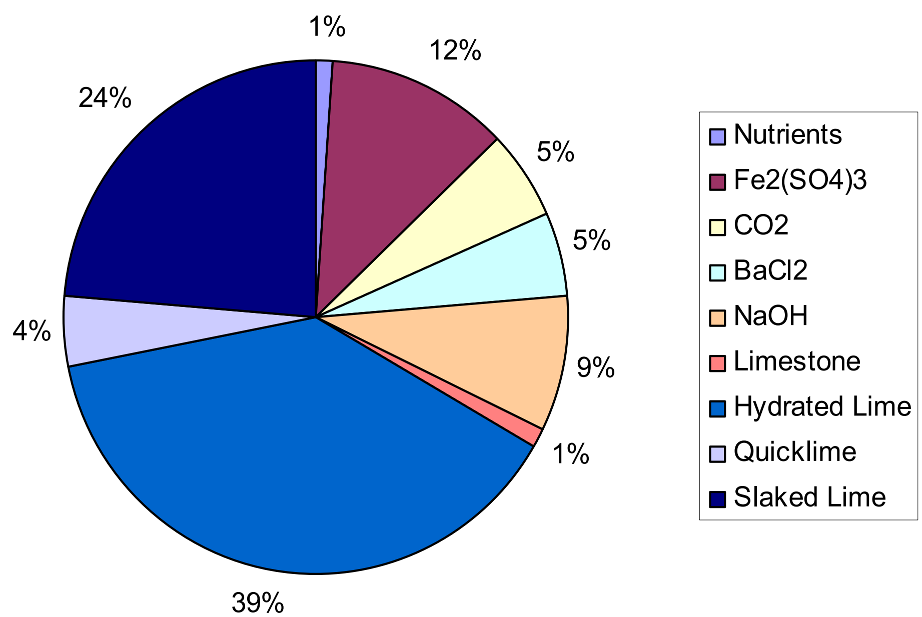

Figure 7: Type of reagents used for treatment.

To treat low strength mine drainage (low total dissolved solids (TDS)), sites will often apply a coagulant such as ferric sulphate to improve metal removal by surface adsorption and co-precipitation. The iron sulphate quickly dissolves and causes the iron to re-precipitate as ferric hydroxide/ferrihydrite. Ferric sulphate serves to agglomerate the precipitates and to adsorb any metals remaining in solution. Larger particles are formed by combining with the ferric hydroxide and settle much faster than the smaller particles. Twelve percent of the sites noted using ferric sulphate (Figure 7). Barium chloride is used for Radium-226 removal (5% of sites reporting). The principle of this method uses sulphate ions in liquid effluent, with the addition of barium chloride to form barium sulphate precipitate, then the radium provides isomorphous replacement with the $BaSO_4$ to form co-precipitation $Ba(Ra)SO_4$ (IAEA, 2004).

Depending on the contaminants to treat and the treatment pH set-point, the final effluent pH may require adjustment prior to discharge. Most sites sparge carbon dioxide to decrease the pH prior to discharge while fewer sites use sulphuric acid or a combination of both (Figure 7).

4.4 Flocculation

The primary purpose of flocculation is to agglomerate the finer particles and enhance settling in order to obtain a clear effluent. Flocculation aids in clarification by promoting the formation of flocs, or larger and denser particles, from the finer particles in solution, which settle more rapidly. The flocculant type and concentration have a major impact on sludge properties and typically account for 2-5% of treatment costs (Zinck and Aubé, 2000). Flocculants were used in approximately 42% of the treatment operations (Figure 6) and a range of flocculant types were recorded (Table 5). Magnafloc 10, which it is a non-toxic high molecular weight anionic polyacrylamide flocculant, was the most common flocculant used. The annual cost of flocculant usage varied from <$10k to >$1M. Figure 8 displays the observed relationship between flocculant cost and average flow rate on a log scale.

Table 5: Various types of flocculant used in mine water treatment

Name	Number of sites
Amerifloc 300	1
AN905MPM	1
Flomin SNF	1
Golden West 1883A	1
Magnafloc 10	10
Magnafloc 1011	4
Magnafloc 155	1
Magnafloc 156 (E10)	3
Magnafloc 24	2
Magnafloc 338	5
Percol	1
Percol E10	1
Polyclear 2748	1
Polyfloc 1103	1
Polyfloc AE 1125	1
Potassium Permangan	1
Powerfloc 3056 SH	1
Super Floc A110	1

4.5 Solid/Liquid Separation

Solid/liquid (S/L) separation is a critical part of any water treatment process whether it is simple gravity separation or more sophisticated mechanical separation. All sites with active treatment have some type of solid/liquid separation. The types of S/L separation used as recorded by the survey are shown is Figure 9. Over 50% of respondents used a conventional thickener/clarifier while six sites reported using lamella clarifiers. Settling ponds were also commonly used. For enhanced sludge dewatering some sites employ dewatering equipment, such as filter presses or centrifuges. To improve effluent quality and to reduce turbidity, polishing ponds and sand filters are typically used.

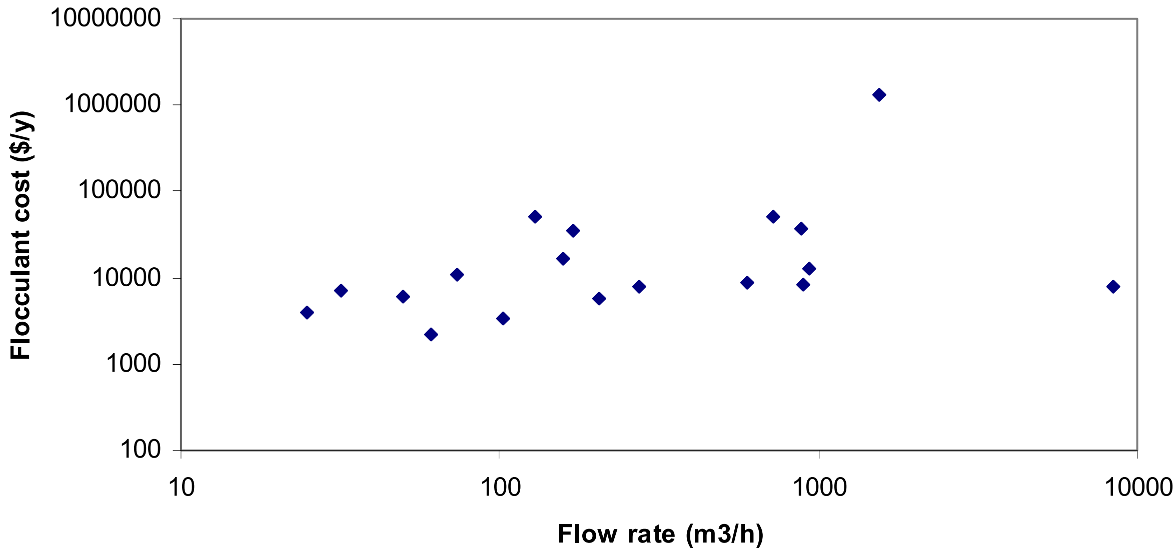

Figure 8: The relationship between flocculant cost and average flow rate (log scale).

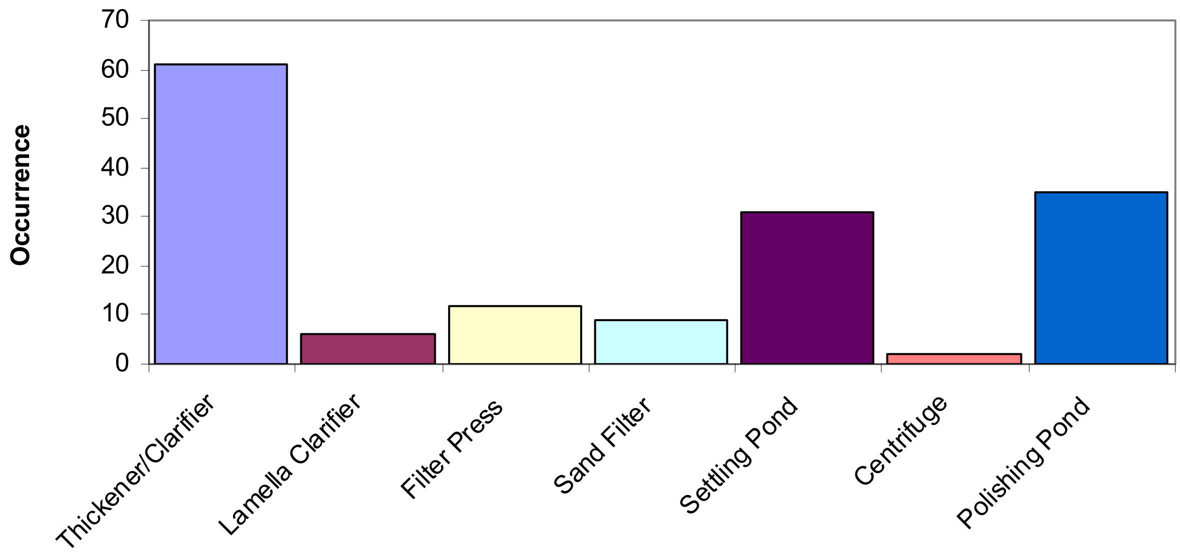

Figure 9: Solid/liquid separation methods used.

4.6 Effluent Quality

From the sites submitting final effluent data the minimum, maximum and average contaminant concentrations and physio-chemical characteristics of reported final effluent date are presented in Table 6. The average concentrations for arsenic, copper, nickel, lead and zinc were below Metal Mining Effluent Regulations (MMER, 2002).

Arsenic was the only contaminant that for all sites met discharge criteria. For the other metals at least two sites recorded concentrations exceeding regulatory limits. No single metal emerged as being most difficult to treat from the data, however slightly more exceedances were recorded for zinc than the other metals.

4.7 Treatment Issues

As part of the survey, respondents were invited to list treatment issues. Many respondents listed gypsum scaling of the process equipment and lime slurry lines as their main concern. Some noted that the application of sludge recycle/HDS treatment reduced scaling. Other issues included the control of total suspended solids (TSS) in the final effluent, managing high flows, algal blooms in collection ponds, poor settling, lime handling and mixing, polymer mixing during winter, difficulty in maintaining high density sludge, manganese and sulphate concentrations in the final effluent, inefficient mixing, and acidity in water due to residual thiosulphate (S_2O_3) derived from mill processing. Details of the treatment issues recorded in the survey are provided in Appendix E.

Table 6: Final effluent quality data

	As mg/L	**Cu mg/L**	**Fe mg/L**	**Ni mg/L**	**Pb mg/L**	**Zn mg/L**	**SO_4 mg/L**
min	0.001	0.0001	0.002	0.0015	0.00006	0.003	4
max	0.34	3.0	11	1.04	0.27	6.0	3340
average	0.03	0.13	0.76	0.11	0.02	0.23	1093
MMER*	0.5	0.3		0.5	0.2	0.5	
	Temp ºC	**TDS mg/L**	**TSS mg/L**	**Turbidity NTU**	**Conductivity µS**	**Eh mV**	**pH**
min	1.2	7	1	0.1	27.8	9	5.5
max	27	4808	65	15	13639	270	9.8
average	12.9	1479	5.9	2.2	2355	132	8.1
MMER*			15				6.0-9.5

*MMER - Metal Mining Effluent Regulation - Maximum Authorized Monthly Mean Concentration

5.0 SLUDGE MANAGEMENT

Most treatment processes will require some type of residue management whether it is for iron-metal-gypsum sludge from lime treatment, residue from treating membrane concentrate, uneconomic by-products from biosulphide treatment or the substrate from passive treatment systems.

5.1 Sludge Disposal Practices

Figure 10 presents the type of sludge management practices reported. Details on these and other sludge disposal and management options are described in MEND Report 3.42.3 (Zinck, 2005).

The majority of the sites surveyed utilize sludge ponds for dewatering and permanent sludge disposal. Disposal in a pond can minimize potential remobilization as the sludge is isolated from acidic waste. However many sites prefer to have one waste disposal area and choose disposal of the sludge with the mine tailings. There are several methods to co-dispose sludge with tailings. One method involves mixing the sludge with tailings (~ 2-5% sludge) before the mixture is sent to the tailings pond. More commonly, sites will either utilize the sludge as an alkaline rich cover over acidic tailings, or will simply dispose the sludge in the tailings pond. Some sites, such as NB Coal have had success disposing of their sludge in their waste rock dumps (Coleman and Butler, 2004).

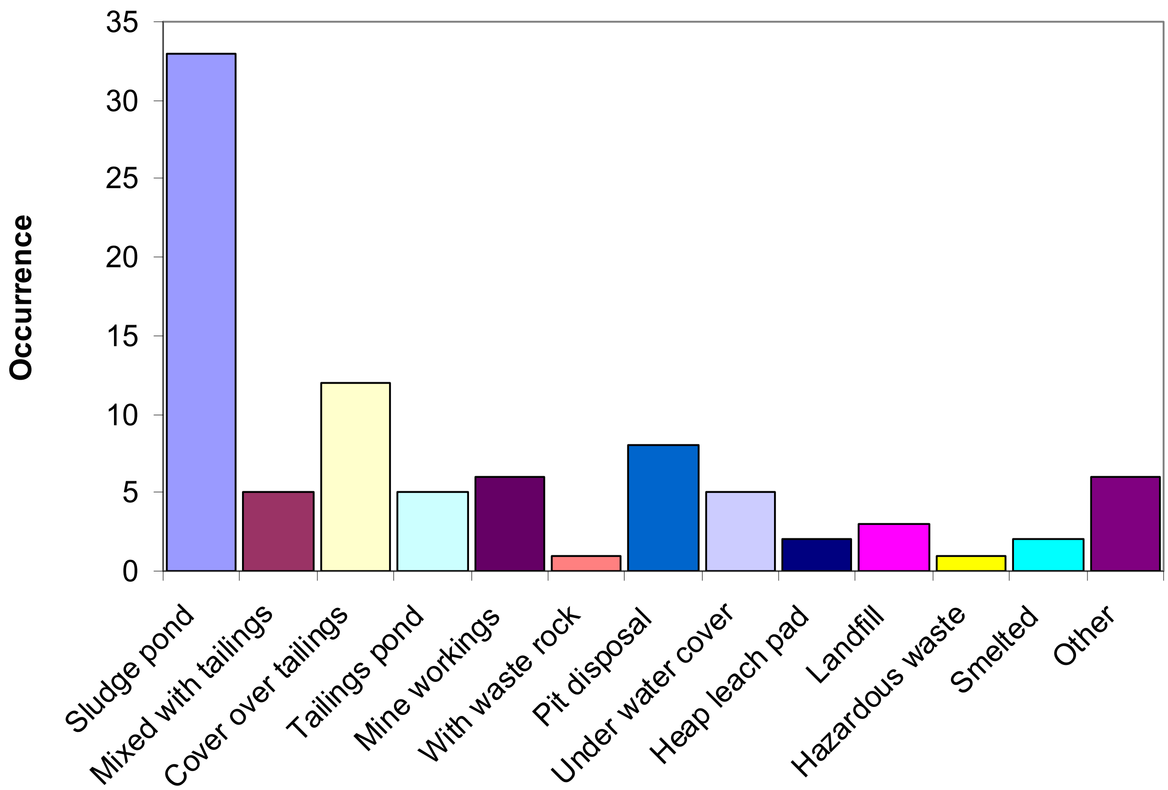

Figure 10: Sludge management practices reported.

Sludge disposal in mine workings offers an excellent sludge management strategy if site availability, mine capacity and configuration are appropriate (Zinck, 2005). Benefits of this option include the potential for the sludge to assist in mine water neutralization and minimization of surface reclamation requirements. This method is attractive from an economic and environmental standpoint, however, like most disposal options this is clearly site-specific (Zinck and Griffith, 2012a). Disposal in open pits is typically one of the most economical solutions for sludge storage, if the pit is within a reasonable pumping distance from the treatment plant. Many companies frequently take advantage of open pits available on site as an appropriate short or long-term sludge disposal option. McNee (2004) found that sludge disposal in a pit lake could cause increased suspended solids, productivity, dissolved oxygen and entrainment which ultimately resulted in whole-lake mixing. Eight sites reported using pits for sludge disposal.

Landfill disposal was necessary for some sites that did not possess sufficient area for on-site disposal or required specialized disposal for sludge declared hazardous by regulatory leachate tests. Some sites documented novel sludge disposal practices such as utilizing the sludge as a cover for refuse. No respondents recorded reprocessing the sludge, however two sites noted that their sludge was smelted to recover nickel.

5.2 Sludge Production and Storage Capacity

Roughly a quarter of the sites provided data on sludge production and storage capacity. To equalize the data, sludge production was reported in dry tonnes rather than cubic metres. On average, sites produce about 9,500 tonnes of dry sludge per year with production ranging from 20 dry tonnes to 135,000 dry tonnes annually. Depending on the percent solids of the sludge, the volume factor can range from approximately 2 to 70 times the sludge mass. While the volume in dry weight depends primarily on the drainage composition and strength the wet volume depends additional on the flow rate, treatment process and other factors.

Generally sites reported having sufficient sludge storage capacity for an average of 25 years. However, both extremes were reported with some sites having capacity for only another year while at least one site reported excessive capacity (mine workings).

5.3 Sludge Management Issues

Several issues associated with disposal and management of the treatment sludge were highlighted during the survey. Sludge desiccation, dusting of the sludge and the inability to drive machinery on the sludge for dust control were noted. Some sites noted that they were ‘running out of room’ to dispose of sludge and difficulty in dredging sludge ponds. High disposal costs and uncertainly regarding the long term chemical stability of the sludge were also highlighted as issues. Details of specific sludge management issues are listed in Appendix F.

6.0 COSTING

Cost data were collected on various treatment and sludge management aspects including capital, operating and disposal costs.

6.1 Capital

Capital cost data were collected for over half the reporting sites and the data were normalized to Canadian dollars for graphing and interpretation. Figure 11 shows the capital treatment plant costs for various treatment operation types. These data are summarized in Table 7.

Table 7: Minimum, maximum and average capital costs by treatment type

Cost ($M)	Treatment Process					
	Basic Neutralization	Passive Treatment	HDS	Membrane Separation	Other	All
Minimum	0.12	0.05	1.00	1.80	0.15	0.05
Maximum	42.00	1.49	23.88	37.40	5.54	42.00
Average	7.04	0.77	9.14	10.21	2.16	7.42

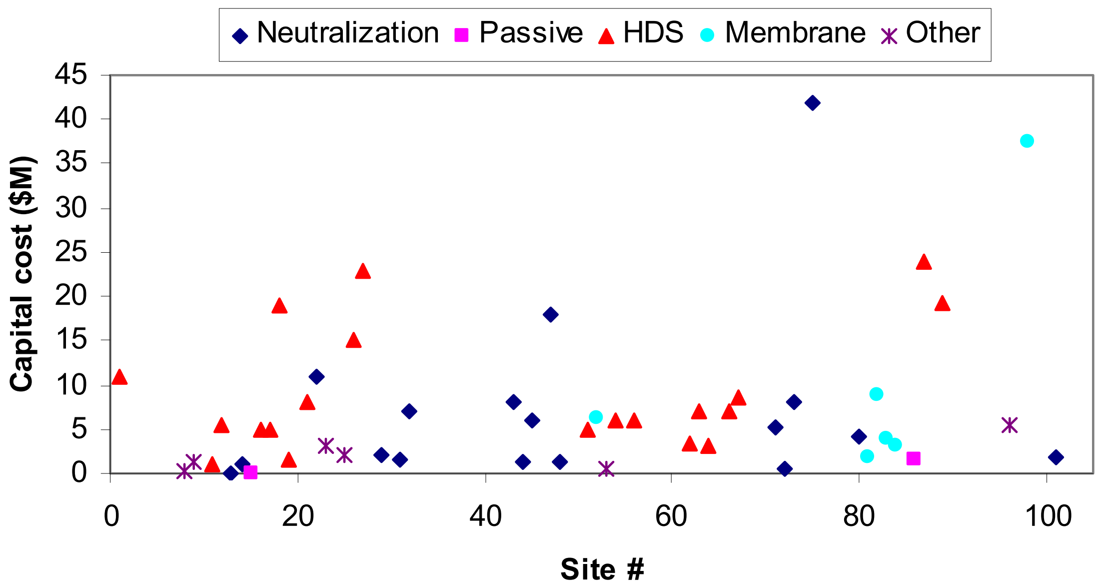

Figure 11: Capital costs for different types of treatment operations by site.

Capital costs ranged greatly from \$0.02M to \$42M with the average approximately \$7.5M. In general, membrane separation capital costs were roughly 10% higher than costs for HDS plants. Passive treatment systems were the least expensive treatment option in terms of capital outlay. The most expensive installation (\$42M) was for a basic treatment (neutralization) operation with recycle for a relatively high flow neutral drainage in a sensitive ecosystem.

The cost of the treatment plant accounted for approximately sixty percent of the total capital cost of the treatment system (Figure 12). Other capital cost components included waste management infrastructure, thickener/clarifier, and polishing ponds.

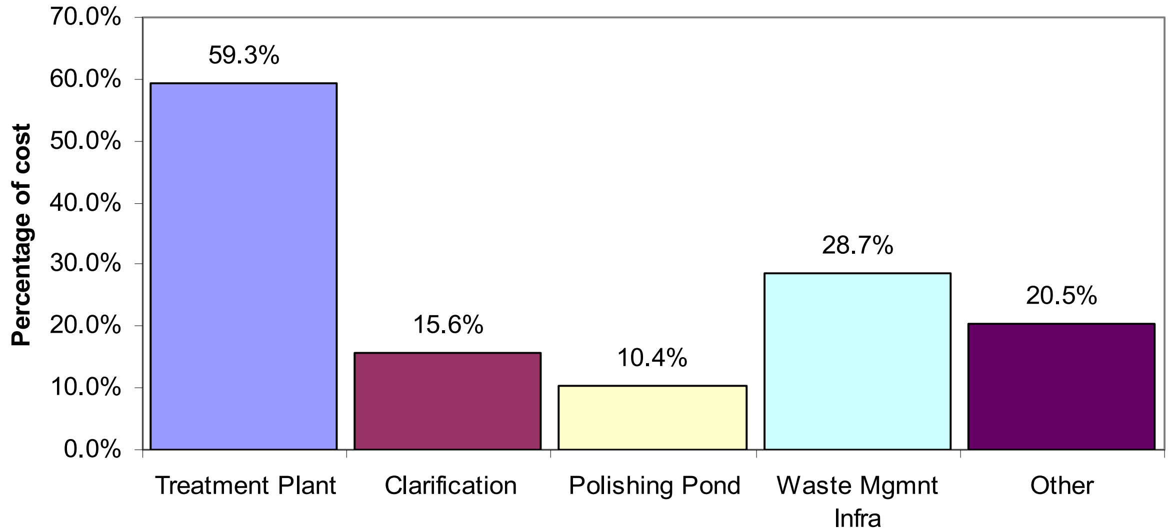

Figure 12: Capital cost breakdown as reported (i.e. total exceeds 100%).

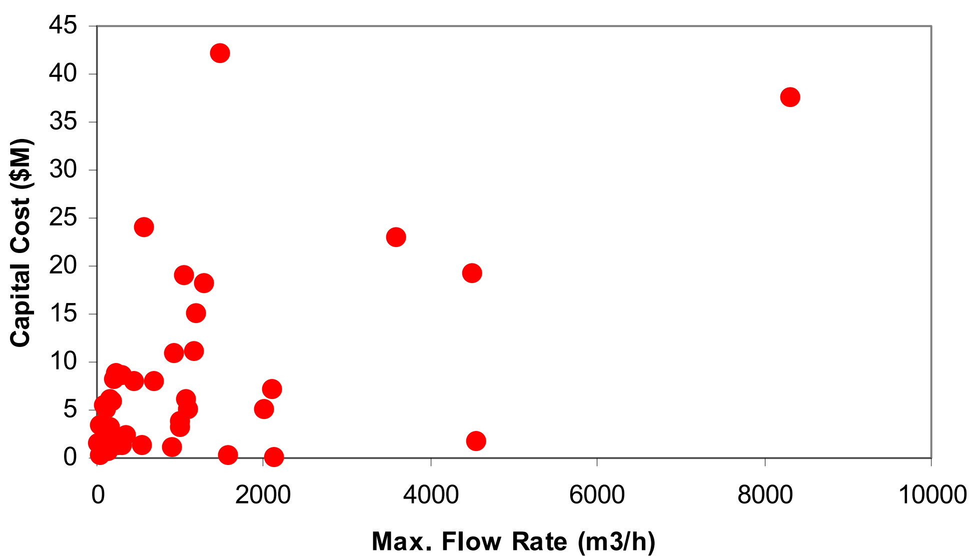

Figure 13: Capital cost versus flow rate for sites reporting data.

As noted by others (GARD Guide, 2012; Aubé, 2011) a relationship exists between flow rate and capital cost. Maximum flow rate was plotted versus capital cost (Figure 13) and a loose linear relationship was observed.

6.2 Operating Costs

An important factor in any treatment operation is the cost to treat one cubic meter of water. The data recorded for operating costs by treatment process are summarized in Table 8 and presented graphically in Figure 14. The average cost to treat one cubic metre of mine water was $1.54. The minimum cost recorded was $0.02 per m^3 for basic treatment and the highest cost was $8.55 per m^3 for a HDS plant that also treats arsenic and cyanide using caustic soda.

Table 8: Minimum, maximum and average operating costs by treatment type

Cost ($M)	Treatment Process					
	Basic Neutralization	Passive Treatment	HDS	Membrane Separation	Other	All
Minimum	0.02	0.03	0.04	0.76	0.25	0.02
Maximum	7.11	1.41	8.55	0.76	5.00	8.55
Average	1.52	0.72	1.54	0.76	2.63	1.54

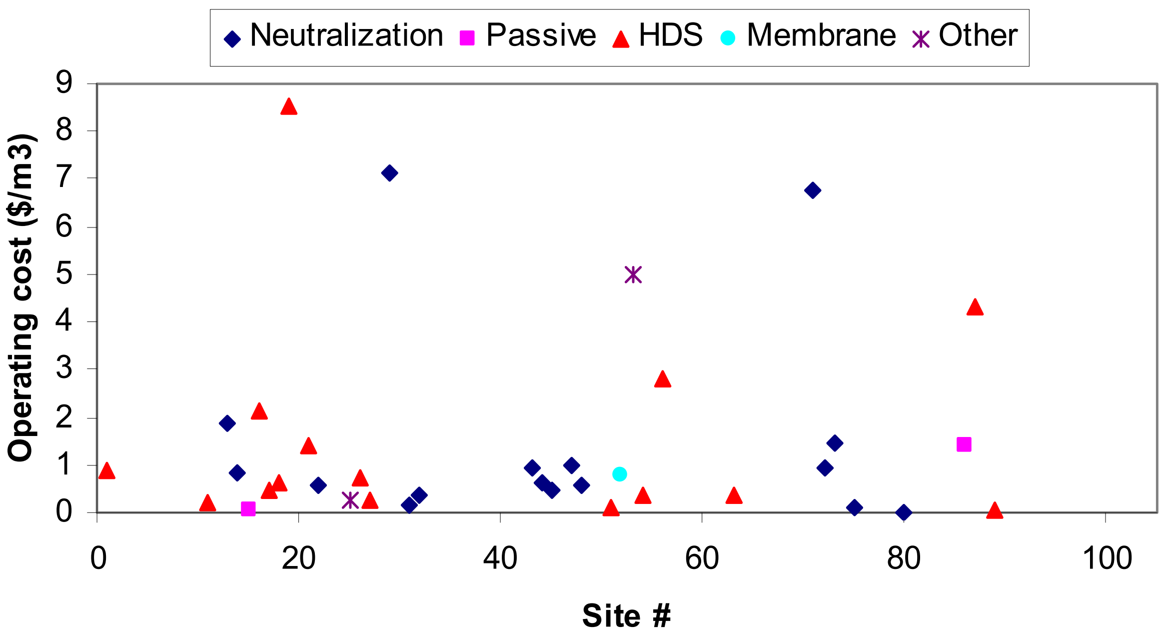

Figure 14: Operating costs for different types of treatment operations by site.

Sites were asked to provide a breakdown of annual operating costs (e.g. labour, reagents, power, etc.). The averaged breakdown for all sites reporting is depicted in Figure 15. The majority of the costs were notably for reagents and labour.

6.3 Disposal Costs

The costs associated with sludge disposal were not well reported. The survey found that only a fraction of sites had disposal cost data. Many items associated with disposal costs are often hidden within other treatment and operation costs (for example, pumping). Sludge management costs are frequently not separated and are often included in a range of treatment cost items. The annual costs recorded in the survey ranged from ~$10k to >$300k per annum (Figure 9). Some sites have been known to spend over $1M per annum on sludge dredging costs alone; however survey data for dredging costs was sparse ranging from $5 to $20 per cubic metre. This inconsistency in data highlights the need to better quantify the true costs associated with sludge and secondary waste disposal. Figure 15, showed that on average, sludge disposal accounts for approximately one tenth of the overall treatment cost.

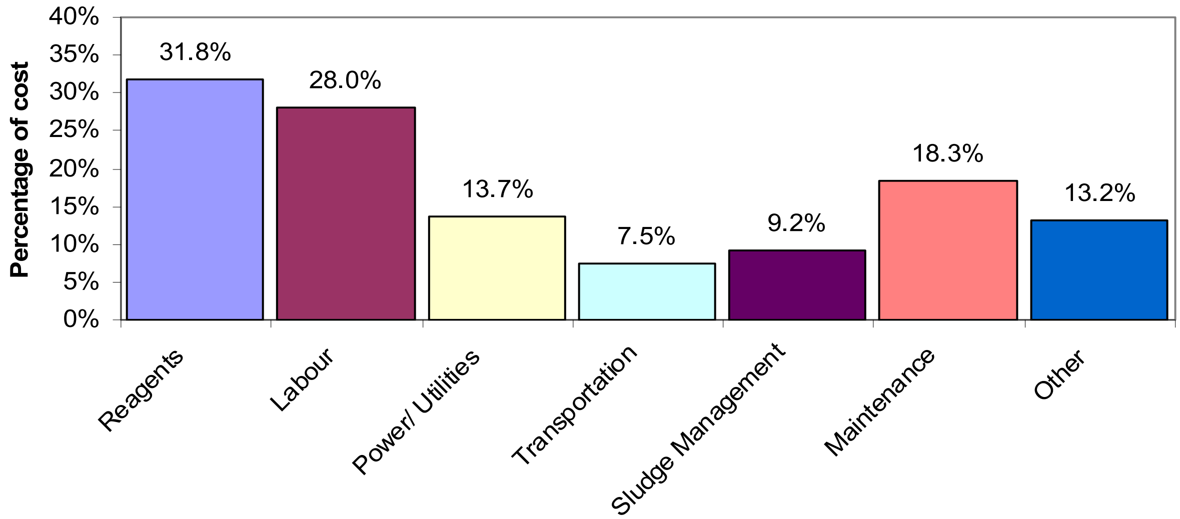

Figure 15: Operating cost breakdown.

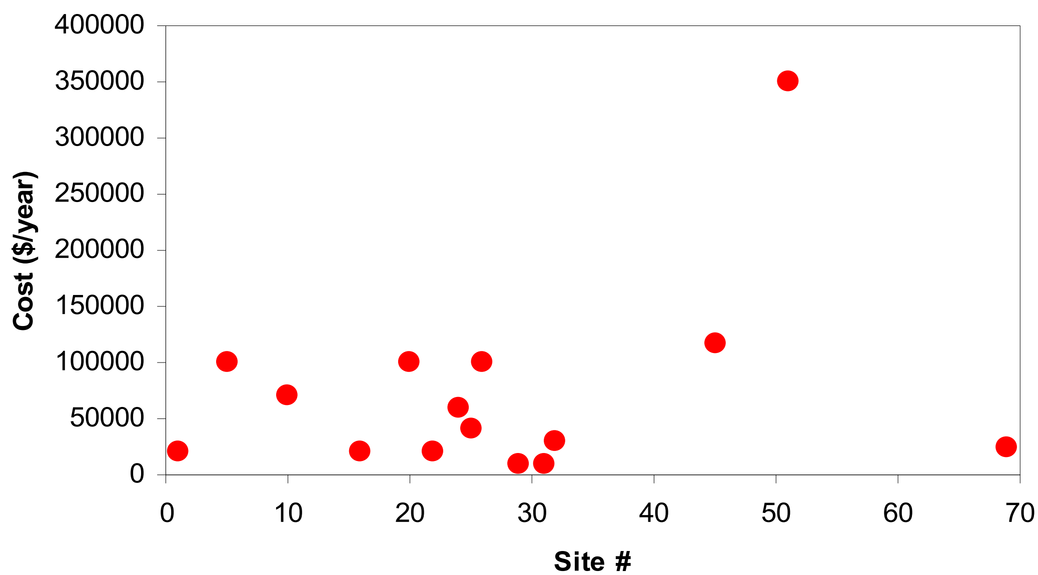

Figure 16: Sludge disposal costs by site.

7.0 CONCLUSIONS

The database developed for this project contains valuable information on various aspects related to mine water treatment and the management of the resultant sludge. The database will serve as a repository for relevant treatment information and will provide information on best practices and novel strategies. The data can be used to draw correlations between treatment parameters with the intent to improve economic and environmental treatment performance. The database will be continually updated with new site data and the electronic version of the database will continue to be managed by Natural Resources Canada. Opportunities exist to expand the database and to identify and study trends and relationships in the treatment data.

8.0 ACKNOWLEDGEMENTS

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The authors are indebted to the various site contacts, industrial personnel, and government officials for responding to the survey and providing treatment data (listed below).

Aboriginal Affairs and Northern Development Canada
(previously Indian and Northern Affairs Canada (INAC))
Aditya Birla Minerals
AMEC
Anglo Coal/BHP Billiton Energy Coal
Areva Resources Canada Inc.
Atlantic Richfield
Barge, Waggoner & Cannon Inc.
Barrick
Beaver Brook Antimony Mine Inc.
Billiton Metals Canada Inc.

Bioteq
Blue Note Mining
Breakwater Resources Ltd.
Bureau of Land Management
Cape Breton Development Corporation
Climax Molybdenum
Coal Authority
Columbia Metals
Complexo Minero-Industrial do Planalta de Poços de Caldas (CIPC)
Department of Primary Industries and Resources of South Australia (PIRSA)
Diavik Diamond Mines Inc.
EPCOR - Britannia Mine WTP Inc.
Falconbridge Limited – Bell Mine
First Nickel Inc.
Goldcorp.
Halifax International Airport (HIA)
HBC International
Highland Valley Copper
Huckleberry Mines Ltd.
Hudbay Minerals Inc.
Hungarian Ministry of Environment and Waters
Iamgold Corporation
Inmet Mining Corporation
Kennecott
Minera Yanacocha S.R.L.
Mines Richmont Inc.
Ontario Ministry of Northern Development and Mines (MNDM)
Molycorp Inc.
NB Coal Limited
Newmont Canada Limited
NVI Mining Ltd.
Ontario Ministry of the Environment (Eastern Region)
Peltrex (Pty) Ltd.
Peru Copper Inc.
Phelps Dodge
Rambler Metals and Mining Canada Limited
Rescan Environmental Services Ltd.
BHP Billiton
Rio Tinto
Solid Energy Ltd.
Teck
United Kingdom Coal Authority
United Kingdom Environment Agency
US Bureau of Reclamation
US EPA Superfund Records Center
Vale

Votorantim, SA Industrias
Wesdome Gold Mines
Williams Operating Corporation
Wismut GmbH
Xstrata Copper
Xstrata Ltd.
Xstrata Nickel
Xstrata Zinc
Yukon Government

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Additional papers completed by the authors that are relevant to this report are attached in Appendix G.

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APPENDIX A –
Mine Drainage Treatment and Sludge Management Practices - Survey

Mine Drainage Treatment and Sludge Management Practices

Contact Information		
Organization/Company		
	□ Company □ Government □ Association □ Consultant	
Contact Name	Name:	
	Address:	
	Phone:	
	Fax:	
	Email:	

Site Background Information	
Site Name	
Address / Location	
	Latitude:_______________ Longitude:____________________
Type of operation	□ Base metal □ Precious metal □ Uranium □ Coal □ Other_________________________
Mine status	□ Operating □ Closed Year:________________ □ Orphaned □ Abandoned
Receiving environment	Description of receiving environment (i.e. sensitive receptors, drinking water, fisheries etc.)

Raw Water Composition		
Treatment	Years of treatment since mine closure: ___________________ Expected years for treatment in future: ___________________	
Source of Acidic Drainage/ Neutral Drainage (AD / ND)	□ Tailings □ Waste rock □ Mine workings □ Other____________	
Composition of water to be treated (mg/L unless otherwise noted)	Al	Se
	As	U
	Ca	Zn
	Cd	Sulphate
	Cr	Temperature
	Co	Acidity
	Cu	TDS
	Fe total	TSS
	Fe – Ferrous	Turbidity (NTU)
	Mn	Eh (mV)
	Ni	Ec (µS)
	Pb	pH
	Ra	Other
Flow rates / Loadings	Minimum Flow: __________________________ m^3/hr Maximum Flow: __________________________ m^3/hr Average Flow: __________________________ m^3/hr Metal loadings:______________________________________ ____ ____	

<table>
<tr><th colspan="3">Treatment</th></tr>
<tr><td rowspan="3">Are other effluents/process waters treated with the AD/ND?</td><td colspan="2">□ Yes
□ No</td></tr>
<tr><td colspan="2">If yes, type of process water ____________________________
____</td></tr>
<tr><td colspan="2">Composition of process water: Metals, pH, etc. ___________
____</td></tr>
<tr><td>Type of treatment process</td><td>□ Basic neutralization
□ Reactors
□ Flocculation
□ Sludge recycle
□ Aeration
□ Acidification
□ $Fe_2(SO_4)_3$</td><td>□ Mechanical solid/liquid separation
□ High Density Sludge
□ Bio-sulphide precipitation
□ Passive treatment
□ Membrane separation
□ Other __________________</td></tr>
<tr><td>Process</td><td colspan="2">□ Continuous □ Batch
If Continuous,
Flow rate:
Average:___________ min____________ max ___________
Reactor size (s):___________________
If Batch,
Volume:_________________________
Frequency:_______________________
Method of flow equalization: __________________________
____</td></tr>
<tr><td>Capital Cost</td><td colspan="2">$ __________________________ (year _______)
Year of installation:__________________
Check which are included in this total cost:
□ Plant - % of total cost ______________________________
□ Clarifier - % of total cost ___________________________
□ Polishing Pond - % of total cost ______________________
□ Water Management Infrastructure - % of total cost _______
□ Other ____</td></tr>
</table>

Repairs / Upgrades	Are major repairs or upgrades planned for the next year: □ Yes □ No *If yes,* please provide details: ____________________________ ____ Estimated longevity of system if known:
Reagents	□ Hydrated Lime □ Quicklime □ Slaked lime Slaker Type: □ Paste, □ Slurry, □ ___________________ □ Limestone □ Barium Chloride □ Caustic Soda □ Ferrous Sulphate ($FeSO_4$) □ Nutrients (passive treatment) □ CO_2 for pH reduction post treatment □ Other ____
Reagent Usage	___________________ tonnes/year _______________ reagent ___________________ tonnes/year _______________ reagent
Flocculant	Type:____ Commercial name: ____________________________________ Dosage: ____ Cost:____ $/year
Solid/Liquid Separation	□ Settling pond □ Conventional (rake) clarifier/thickener Diameter__________________m Retention time:_____________minutes □ Lamellar clarifier □ Filter press
Grit Removal	□ Yes □ No
Polishing	□ Yes □ No *If yes,* □ Polishing pond Retention time:_________________days Size:___________________________m^2 □ Sand Filtration □ Final pH adjustment □ CO_2 addition □ Other____

<table>
<tr><td>Treatment Cost</td><td>____________________$/m³
Check which are included in this total cost:
□ Reagents - % of total cost ______________________________
□ Labour - % of total cost ______________________________
□ Power/utilities - % of total cost ________________________
□ Transportation - % of total cost ________________________
□ Sludge management - % of total cost ___________________
□ Maintenance - % of total cost
□ Other ____</td></tr>
<tr><td>Final Effluent</td><td>Typical effluent composition
pH ______________</td></tr>
<tr><td>Composition of treated water (mg/L unless otherwise noted)</td><td>
<table>
<tr><td>Al</td><td></td><td>Se</td><td></td></tr>
<tr><td>As</td><td></td><td>U</td><td></td></tr>
<tr><td>Ca</td><td></td><td>Zn</td><td></td></tr>
<tr><td>Cd</td><td></td><td>Sulphate</td><td></td></tr>
<tr><td>Cr</td><td></td><td>Temperature</td><td></td></tr>
<tr><td>Co</td><td></td><td>Acidity</td><td></td></tr>
<tr><td>Cu</td><td></td><td>TDS</td><td></td></tr>
<tr><td>Fe total</td><td></td><td>TSS</td><td></td></tr>
<tr><td>Fe – Ferrous</td><td></td><td>Turbidity (NTU)</td><td></td></tr>
<tr><td>Mn</td><td></td><td>Eh (mV)</td><td></td></tr>
<tr><td>Ni</td><td></td><td>Ec (µS)</td><td></td></tr>
<tr><td>Pb</td><td></td><td>pH</td><td></td></tr>
<tr><td>Ra</td><td></td><td>Other</td><td></td></tr>
</table>
</td></tr>
<tr><td>Treatment Issues</td><td>Describe any treatment issues (e.g. scaling, TSS, etc.)</td></tr>
</table>

Sludge Management		
Production	Annual production (dry tonnes per year):________________ Total sludge produced to date (dry tonnes): ________________ Estimated years producing sludge: ________________________ Storage capacity:________________________________m^3 Storage capacity remaining:_____________________years	
Sludge Disposal	□ Sludge pond □ With tailings □ Sludge mixed with tailings, discharged in tailings pond □ Sludge deposited on top of existing tailings □ Dredge sludge from pond disposed in tailings pond □ In mine working □ Landfill □ In waste rock pile □ In pit □ Other ____	□ Backfill □ Under water cover □ Reprocessed □ Smelted
Pond Disposal	If disposed in sludge pond, □ Approximate volume in pond:_________________________ □ Age of sludge in pond: ______________________________ □ Method of sludge relocation, if applicable:_______________ ____ □ Dredging frequency if applicable:______________________ □ Dredging costs: ___________________________________	
Disposal Costs	Costs of disposal (per year): _____________________________ Estimated long term disposal costs: _______________________	
Composition/ Properties	Al	Se
	As	U/Ra
	Ca	Zn
	Cd	Sulphate
	Cr	Ec
	Cu	% Solids
	Fe total	Settling rate
	Fe – Ferrous	NP
	Mn	pH
	Ni	Eh
	Pb	Ec

Sludge mineralogy/leachability	Is sludge mineralogy available? □ Yes □ No *If yes,* please provide composition:____________________ ____ Type of mineralogical data: □ X-ray diffraction (XRD) □ Scanning Electron Microscopy (SEM) □ Other ____ Have leach tests been performed on the sludge? □ Yes □ No *If yes,* □ TCLP or similar □ SPLP or similar □ Column testing □ Other ____
Sludge management issues	

Date of last update: ________________________________

Updated by: ______________________________________

Data entered: _____________________________________

APPENDIX B –
Details of Treatment Discharge Receiving Environment

Details of Treatment Discharge Receiving Environment

- Fisheries
- Fisheries waters– Lim Lake Watershed flows into White River through Pukaskwa National Park then Lake Superior and Cedar Creek Watershed flows into Black River into the Pic River (along Pic Heron Bay First Nations) then into Lake Superior
- Copper Cliff Creek to Junction creek, no sensitive receptors in immediate area
- Unknown marshes to fisheries in the Vermillion river
- Brook trout restocking in Junction Creek
- Whistle Creek to Post Creek
- Fisheries
- Effluent discharges to Miron Creek, First Lake, Eaglet Lake to the University River which empties into Lake Superior
- Nolin Creek to Junction Creek, no sensitive receptors in immediate area
- The Moira River runs through the site which is environmentally sensitive and is classified as a class 2 wetland
- Bell Creek/Sturgeon Lake
- Acid drainage from the Kam Kotia and Jameland Mine sites continues to impact the receiving creeks, rivers and fish habitat. The receiving environment affected is the Little Kamiskotia and Kamiskotia Rivers
- Lyon Creek– empties into Lyon Lake which empties into Sturgeon Lake
- Mine area is headwaters for Whitesand River– then empties into Lake Superior
- Rupert Inlet (Marine, active crab fishery)
- Johnson Creek– cattle and rainbow trout
- St Mary River, important for cutthroat trout and kokanee
- Howe Sound, Pacific Ocean
- Treated effluent is discharged into Hedley Creek, a tributary of the Similkameen River, which flows into Washington State
- The receiving environment is Myra Creek, located in Strathcona Provincial Park. The creek drains into Buttle Lake. There is a 5 km stretch of the creek that supports a limited population of cutthroat trout. The cutthroat are confined to this stretch by waterfalls upstream and downstream. Creek flows average 6 m^3/s, but range between 2 m^3/s and 20 m^3/s, depending on the season. Treated effluent from the mine's treatment system is discharged into the Creek approximately 2.5 km upstream of Buttle Lake. Buttle Lake is upstream of Campbell River's drinking water source
- Buck and Foxy Creeks– both fish bearing, closest resident is roughly 20 km away
- Fresh water creek. Creek is used to supply farm irrigation. It is also a potable water source for the community of Peachland
- Effluent is discharged into a natural water course
- Effluent is discharged into a natural water course
- Minor tributary which feeds into a slightly larger tributary 1 km away, several kilometers later, it empties into a larger seasonal canoeable and fishable river
- Fisheries

Details of Treatment Discharge Receiving Environment (cont'd)

- Little River: recipient water course of final treated effluent discharged from Water Treatment Plant located on site. Mine predicted to close in 2010
- Gander watershed
- The receiving water is South Brook. Following 45 years of mining in the area there is no aquatic life in the river system. South Brook sits downstream of an old mill and formed part of the receiving waters from the Mill tailings pond that was not managed to today's standards. Subsequently, the river system downstream of the mill has been polluted
- Small fish bearing brook called Gilles Pond Brook Tributary
- Sport fishing brook and river
- Recreational fish habitat– Northwest Brook and Lingan Bay. Also valued wetlands near site. Longer term the Cape Breton Regional Municipality (CBRM) consider developing groundwater resources nearby
- Atlantic Ocean– lucrative, lobster fishing grounds
- Goudreau Lake
- Petite Rivieré Héva
- Larder Brook
- Keriens Brook
- Babine Lake– fisheries
- Trojan Creek– Irrigation Water
- The Lockerby Mine FDP enters Zilch Creek which originates from the Lockerby Mine treatment pond system and empties into Zilch Lake. The primary receiver is considered Zilch Lake and the Zilch Lake watershed and as there are no physical barriers between Zilch Creek and the Vermilion River, the final receiver is the Vermilion River
- Yellowknife Bay– benthic- fish
- Treated water from McClean Lake Operations is ultimately discharged into the east basin of McClean Lake. The local area is comprised of upland and lowland terrestrial habitats interspersed with numerous small lakes and streams. Lakes and streams within the area are typical of the region with moderate productivity supporting a diversity of benthic invertebrates, phytoplankton, zooplankton, and fish species. The local area illustrates a predominance of immature and mature jack pine forest stands, interspersed with bogs and open fens that provide breeding and rearing areas for amphibians and reptiles. Lichens form a significant ground cover in mature upland jack pine and black spruce stands, which provides suitable forage habitat for caribou. Riparian zones contain a abundant food and cover for moose, beaver, snowshoe hares, small mammals, water birds, amphibians, and reptiles. These prey species provide a diversity of food for carnivores such as fisher, marten, lynx, wolves, eagles, falcons, hawks, and owls. All habitat types provide a broad range of niches for breeding songbirds

Details of Treatment Discharge Receiving Environment (cont'd)

- The site is located at the headwaters of several drainages. At the top of the drainage, aquatic habitat is limited due to naturally low pH and seasonal low flows. Fish occur lower in the drainages and site water quality criteria reflect their presence. In addition to fish, there are community irrigation canals, which are monitored for quality and quantity on a monthly basis. A risk-based approach has been used to establish protective water quality criteria
- No acid mine drainage
- Treated water is stored in an open pit, and overflow is expected by 2009. This water will then flow into the Wawagosic river, which is part of a 2,987km^2 watershed
- Water Treatment plant effluent is discharged to Hawk Inlet (seawater) per the mine's NPDES permit
- Vauze Creek– empties into Lac Dufault (the Northern part of the drinking water reservoir for Rouyn-Noranda)
- Kinojévis river
- Dome creek to Victoria Creek to Nisling River to Yukon River. Fisheries values from Victoria creek downstream. Traditional Little Salmon Carmacks First Nation hunting and food/medicine gathering area
- The receiving medium is the Bousquet river which runs in the Lake Chassignole. There is fishing and other recreational activities
- Lac De Montigny– fishing
- Untreated water from the Landusky mine site could affect well water downstream in the town of Landusky
- Untreated water for the Zortman mine site would flow into the Madison formation aquifer which can further affect Zortman town ground water downstream
- Treated water must meet stringent Peru class III irrigation standards. The effluent discharges to a local irrigation canal, where it is used by local farmers for irrigation and livestock watering
- Mine water flow path leads to Strawberry and Bear Butte Creeks, affecting aquatic life and wildlife. Downstream effect could be soil and well water contamination near the town of Sturgis
- Carnon River, Restronguet Creek and Falmouth Bay
- Permian Sandstone Aquifer– the water supply to 250,000 inhabitants
- Treated water flows to a restored and protected vegetated area, and then becomes the head water to Coniston creek
- The airport is the highest point in the area, therefore water could affect six main brooks (McDowell, Johnson, Leech, Black, Sandy Cole and Bennery, also in the vicinity is aquatic habitat in the Shubenacadie River
- Alamosa River– aquatic life, livestock and crops
- Sacramento River which is a salmon spawning grounds, fishery and other aquatic species of Keswick Reservoir
- Creek Duprat
- Dissolved metal contamination threatened the South Fork Coeur d'Alene River and its tributaries. Air emissions particulates affected surrounding vegetation

Details of Treatment Discharge Receiving Environment (cont'd)

- Impact Clear Creek– affecting the drinking water of near by town, and aquatic life
- Eagle River system affecting domestic, irrigation and recreational purpose
- Arkansas River watershed
- Water impacts Christal Creek
- Wildlife, drinking water
- Treated effluent flows into McCabe Lake, which is part of the Serpent River Watershed
- Ocoee River which is a whitewater recreational area
- Rivers in remote arctic region
- Contamination of the local area ground water and the Red River would impact local area, irrigation of gardens and crops, live stock watering, fishing, swimming and other recreational activities. Protection of the Rio Grande watershed is vital, since it's the drinking water supply for nearby towns
- Local area ground water and nearby farm land
- Local shallow alluvial aquifers and surface waters in the headwaters of the Upper Clark Fork River Basin
- Rivers in remote arctic region
- Pollution would flow into the Yauli River, then empties into the Mantaro River which is a source of irrigation for an important agricultural district, the Mantaro Valley
- A mine of such magnitude would impact the existence of all living beings in this area of Utah
- Direct flow to the Dawesley Creek would affect aquatic life and water supply used for irrigation and livestock
- ARD spills downstream to Leviathan and Bryant Creeks and the East Fort River, affects the historical habitat for the Lahontan cutthroat trout which is a federally listed endangered species
- Discharges into the Blue River affecting aquatic habitat
- Ecologically sensitive Blesbokspruit Ramsar wetland– sanctuary to the Marievale bird
- Untreated water could pose a threat to the Olifants River
- Potential contamination to nearby creek called Toka Creek
- Ebbw Fach River– could threaten aquatic life
- Fish habitat in the Ngakawau River and tributary streams, along with the South Pacific Ocean
- Blyth River which flows into the North Sea
- Antas River which is used for crop irrigation and cattle watering. And the Verde river used for irrigation
- Nearby aquifers, which are part of the community's drinking water supply. Also the Elbe river
- Surrounding ground water, and Silver Bow Creek
- Faro mine could affect the Ross River and the Pelly River, both of which flow through the traditional territory of the Kaska Nation and the Selkirk First Nation

APPENDIX C –
Raw Water Composition

Raw Water Composition

Al, As, Ca, Cd	Cr, Cu, Fe, Co	Mn, Ni, Pb, Ra	Se, U, Zn, SO_4	Temp	TDS	TSS	Turbidity	Conductivity	Eh	pH	Free Acid	Other 1			Other 2			Other 3		
mg/L	mg/L	mg/L	mg/L	°C	mg/L	mg/L	NTU	µS	mV		/ g/L H_2SO_4	ID	Value	Units	ID	Value	Units	ID	Value	Units
Al=15, As=0.001, Ca=450, Cd=0.03	Cr=0.01, Cu=1.61, Fe=2,000-5,000, Co=0.01	Mn=7, Ni=0.02, Pb=0.05, Ra=--	Se=0.001, U=--, Zn=18, SO_4=9360					1100-7100		2.5- 3.5	4900									
Al=0.102, As=0.002, Ca=82.1, Cd=0.0002	Cr=--, Cu=0.003, Fe=0.3, Co=--	Mn=--, Ni=0.004, Pb=0.001, Ra=--	Se=--, U=--, Zn=0.077, SO_4=134.2	6.8	659	2.9		922		7.7		Radium 226	<0.01	Bq/L	Molybdenum	0.07	mg/L	Antimony	0.013	mg/L
Al=0.997, As=0.0242, Ca=455, Cd=0.0005	Cr=0.0065, Cu=0.0624, Fe=19.3, Co=0.068	Mn=1.35, Ni=10.3, Pb=0.0209, Ra=--	Se=0.0142, U=--, Zn=0.121, SO_4=--							6.8										
Al=1.94, As=0.002, Ca=--, Cd=1.38	Cr=--, Cu=0.247, Fe=0.955, Co=0.193	Mn=--, Ni=5.869, Pb=0.003, Ra=--	Se=--, U=--, Zn=0.165, SO_4=--							5.9										
Al=0.02, As=0.02, Ca=322, Cd=0.0002	Cr=0.001, Cu=0.2, Fe=0.2, Co=0.02	Mn=0.2, Ni=0.2, Pb=0.001, Ra=--	Se=0.01, U=--, Zn=0.02, SO_4=--			6.13				7.7										
Al=--, As=<0.004, Ca=--, Cd=--	Cr=--, Cu=2.747, Fe=1.665, Co=--	Mn=--, Ni=0.194, Pb=<0.013, Ra=--	Se=--, U=--, Zn=0.41, SO_4=290			168		987		8.89	152	CN_{total}	3.423	ppm	NH_3	9.2	ppm	Hardness	50.8	ppm
Al=--, As=20-200, Ca=--, Cd=--																				
Al=36, As=0.06, Ca=170, Cd=0.3	Cr=0.02, Cu=10.2, Fe=149.9, Co=0.3	Mn=11, Ni=0.2, Pb=0.08, Ra=--	Se=--, U=0.003, Zn=84, SO_4=1728							2.9										
Al=44.4, As=0.01, Ca=435, Cd=0.145	Cr=0.013, Cu=14.5, Fe=1067, Co=3.99	Mn=53.1, Ni=0.395, Pb=0.0128, Ra=--	Se=0.023, U=--, Zn=160, SO_4=--			18				3.3	2410									
	Cr=--, Cu=0/035, Fe=0.604, Co=--		Se=--, U=--, Zn=6.2, SO_4=--			2.4				6.93	58									
Al=--, As=<0.01, Ca=225, Cd=--	Cr=--, Cu=0.008, Fe=0.2, Co=--	Mn=--, Ni=0.0025, Pb=0.005, Ra=--	Se=--, U=--, Zn=0.79, SO_4=--	4.1		< 4				8.9										
Al=24.2, As=0.00089, Ca=425, Cd=0.048	Cr=<0.0025, Cu=1.72, Fe=0.296, Co=0.155	Mn=6.24, Ni=0.116, Pb=0.0187, Ra=--	Se=0.0032, U=0.000421, Zn=8.1, SO_4=1602							4.47	891									
Al=0.2, As=0.002, Ca=400, Cd=0.01	Cr=0.002, Cu=0.05, Fe=1.7, Co=0.05	Mn=2.2, Ni=0.18, Pb=<0.0005, Ra=--	Se=0.01, U=0.01, Zn=1-6, SO_4=2,760-5,000		1,000-7,000	1-100	23			4-8	10									
Al=66.5, As=<0.05, Ca=277, Cd=0.162	Cr=0.016, Cu=0.198, Fe=367, Co=0.139	Mn=38.5, Ni=0.244, Pb=0.25, Ra=--	Se=<0.03, U=--, Zn=157, SO_4=3030							2.8										
Al=23.5, As=<0.002, Ca=373, Cd=0.094	Cr=<0.005, Cu=18.2, Fe=3.6, Co=0.065	Mn=4.45, Ni=0.036, Pb=0.063, Ra=--	Se=<0.002, U=--, Zn=21.4, SO_4=1510	13		4				4	237									
Al=0.05, As=0.3, Ca=385, Cd=0.005	Cr=0.001, Cu=0.01, Fe=0.446, Co=0.67	Mn=3.2, Ni=0.01, Pb=0.01, Ra=--	Se=0.025, U=0.003, Zn=0.01, SO_4=1100	0-15	2325	9.3	10-20	2.5		7.86		CN_{sad}	0.52	ppm	CN_{wad}	0.17	ppm	NH_3	15	ppm
Al=4.2, As=0.193, Ca=143.8, Cd=0.043	Cr=0.0097, Cu=2.526, Fe=11.41, Co=0.0167	Mn=2.8111, Ni=0.049, Pb=0.177, Ra=--	Se=0.193, U=0.0004, Zn=11.44, SO_4=--			160	23.1			7.09	17									
Al=1071, As=9.6, Ca=381, Cd=1.2	Cr=0.35, Cu=78.8, Fe=1663, Co=5.12	Mn=168.3, Ni=10.6, Pb=<0.05, Ra=--	Se=--, U=--, Zn=167.3, SO_4=12500					6200		2.5	11766									

Al, As, Ca, Cd	Cr, Cu, Fe, Co	Mn, Ni, Pb, Ra	Se, U, Zn, SO_4	Temp	TDS	TSS	Turbidity	Conductivity	Eh	pH	Free Acid	Other 1			Other 2			Other 3		
mg/L	mg/L	mg/L	mg/L	ºC	mg/L	mg/L	NTU	µS	mV		/ g/L H_2SO_4	ID	Value	Units	ID	Value	Units	ID	Value	Units
Al=--, As=--, Ca=98, Cd=--	Cr=--, Cu=0.004, Fe=--, Co=--	Mn=0.08, Ni=--, Pb=--, Ra=--	Se=--, U=--, Zn=--, SO_4=332	8	644	<1	0.5			8.2		Mo	2.4	ppm						
Al=--, As=0.002, Ca=--, Cd=--	Cr=--, Cu=0.168, Fe=1.624, Co=--	Mn=1.927, Ni=0.053, Pb=0.077, Ra=--	Se=--, U=--, Zn=42.336, SO_4=--	13				6928		6.46-8.02										
Al=--, As=--, Ca=--, Cd=0.01	Cr=--, Cu=0.17, Fe=3.67, Co=--	Mn=1.29, Ni=--, Pb=0.06, Ra=1.07	Se=--, U=--, Zn=4.5255, SO_4=--	14		18.44				6.1-7.8										
Al=48.4, As=0.002, Ca=216, Cd=0.0021	Cr=<0.001, Cu=0.015, Fe=9.38, Co=0.253	Mn=23.2, Ni=0.32, Pb=0.0005, Ra=--	Se=0.009, U=0.0021, Zn=0.86, SO_4=1220					22.5		3.42	550									
Al=--, As=--, Ca=140, Cd=--	Cr=--, Cu=7, Fe=250, Co=--	Mn=--, Ni=--, Pb=0.4, Ra=--	Se=--, U=--, Zn=170, SO_4=1200			30-50				2.7-3.1										
Al=--, As=--, Ca=55, Cd=--	Cr=--, Cu=1.45, Fe=418.3, Co=--	Mn=--, Ni=--, Pb=1.9, Ra=--	Se=--, U=--, Zn=100, SO_4=3000							3.5-5		Mg	94.4	ppm						
Al=0.002-0.004, As=0.001, Ca=252-457, Cd=0.0012-0.0107	Cr=<0.001, Cu=0.002-0.01, Fe=0.02-7.88, Co=0.086-0.113	Mn=5.19-6.81, Ni=0.041-0.066, Pb=<0.0001, Ra=--	Se=<0.001, U=<0.0001-0.0011, Zn=2.47-5.55, SO_4=--							6-6.65										
Al=15.5, As=--, Ca=84, Cd=--	Cr=--, Cu=6.05, Fe=36, Co=--	Mn=9.88, Ni=0.044, Pb=0.004, Ra=--	Se=--, U=--, Zn=42, SO_4=426							3.1	280									
Al=4.8, As=<0.006, Ca=290, Cd=0.00097	Cr=<0.01, Cu=<0.02, Fe=220, Co=0.18	Mn=57, Ni=0.21, Pb=<0.01, Ra=--	Se=<0.01, U=<0.0015, Zn=0.54, SO_4=2300		3550	34	61	3700		3.53	370									
Al=--, As=0.28, Ca=--, Cd=<0.001	Cr=--, Cu=0.002, Fe=0.48, Co=--	Mn=--, Ni=0.728, Pb=<0.002, Ra=3.55 Bq/L	Se=0.003, U=0.184, Zn=<0.005, SO_4=--		1730	3		1838		7.2		Pb-210	0.26	Bq/L	Po	0.03	Bq/L	Th-230	0.12	Bq/L
Al=--, As=2.91, Ca=--, Cd=<0.001	Cr=--, Cu=0.001, Fe=0.35, Co=--	Mn=--, Ni=0.218, Pb=0.004, Ra=0.82Bq/L				25		301		10.5		Pb-210	0.26	Bq/L	Po-210	0.03	Bq/L	Th-210	0.12	Bq/L
Al=106-0.8, As=2.7-0.003, Ca=2,4311-4.52, Cd=0.396-0.004	Cr=0.129-0.02, Cu=145-0.094, Fe=1243-0.426, Co=0.461-0.002	Mn=18.46-0.202, Ni=0.182-0.005, Pb=4.582-0.043, Ra=--	Se=0.016-0.002, U=--, Zn=25.81-0.05, SO_4=3,190-38.9							4-3.2										
	Cr=--, Cu=194, Fe=449, Co=--		Se=--, U=--, Zn=1.549, SO_4=11990							2.85	6570									
Al=--, As=0.004, Ca=206, Cd=0.001	Cr=0.002, Cu=0.003, Fe=<0.05, Co=--	Mn=0.4, Ni=0.01, Pb=0.014, Ra=--	Se=0.2, U=--, Zn=0.12, SO_4=835	10.8	978	38	71	1391	260	8.1	0.107	S_2O_3	50	mg/l						
Al=--, As=--, Ca=--, Cd=4.9	Cr=--, Cu=--, Fe=8.9, Co=--	Mn=--, Ni=--, Pb=2.5, Ra=--	Se=--, U=--, Zn=388, SO_4=--		4300					4.4										
Al=--, As=--, Ca=--, Cd=4.9	Cr=--, Cu=--, Fe=8.9, Co=--	Mn=--, Ni=--, Pb=2.5, Ra=--	Se=--, U=--, Zn=388, SO_4=--		4300					4.4										
	Cr=--, Cu=3.42, Fe=118.73, Co=--		Se=--, U=--, Zn=8.5, SO_4=--					798		2.74	692									
Al=--, As=0.17, Ca=696, Cd=--	Cr=--, Cu=8.04, Fe=584, Co=--	Mn=11.6, Ni=0.2, Pb=0.2, Ra=--	Se=--, U=--, Zn=133, SO_4=--			3.6					1145									

Al, As, Ca, Cd	Cr, Cu, Fe, Co	Mn, Ni, Pb, Ra	Se, U, Zn, SO_4	Temp	TDS	TSS	Turbidity	Conductivity	Eh	pH	Free Acid	Other 1			Other 2			Other 3		
mg/L	mg/L	mg/L	mg/L	ºC	mg/L	mg/L	NTU	µS	mV		/ g/L H_2SO_4	ID	Value	Units	ID	Value	Units	ID	Value	Units
Al=<0.01, As=0.04, Ca=278, Cd=0.0013	Cr=<0.001, Cu=3.7, Fe=1.1, Co=0.058	Mn=2.54, Ni=0.025, Pb=0.017, Ra=--	Se=<0.02, U=--, Zn=0.057, SO_4=1230		1680	14		2080		8.42		CN_{wad}	0.677	mg/l						
	Cr=--, Cu=4.2, Fe=660, Co=--		Se=--, U=--, Zn=--, SO_4=4500		8500					2.5	3500									
Al=--, As=0.15, Ca=--, Cd=0.04	Cr=--, Cu=0.11, Fe=18.8, Co=--	Mn=7.6, Ni=--, Pb=0.004, Ra=--	Se=0.004, U=--, Zn=1.72, SO_4=991			20				5										
Al=--, As=0.227, Ca=--, Cd=0.218	Cr=--, Cu=6.95, Fe=40, Co=--	Mn=35, Ni=--, Pb=0.005, Ra=--	Se=0.012, U=--, Zn=7.02, SO_4=3000			20				3.7										
		Mn=200, Ni=--, Pb=--, Ra=--	Se=--, U=--, Zn=10, SO_4=--																	
Al=--, As=--, Ca=--, Cd=10.6	Cr=--, Cu=8.1, Fe=450, Co=--	Mn=380, Ni=0.9, Pb=--, Ra=--	Se=0.9, U=--, Zn=1230, SO_4=--							1.5		Hg	0.25	mg/L						
Al=--, As=--, Ca=--, Cd=6	Cr=--, Cu=--, Fe=28, Co=--	Mn=142, Ni=--, Pb=--, Ra=--	Se=--, U=--, Zn=475, SO_4=--																	
Al=23, As=3, Ca=--, Cd=--	Cr=--, Cu=0.8, Fe=180, Co=--	Mn=5, Ni=0.55, Pb=0.15, Ra=--	Se=--, U=--, Zn=45, SO_4=--			10				3.5										
Al=0.37, As=--, Ca=1630, Cd=--	Cr=--, Cu=--, Fe=27.1, Co=--	Mn=2.06, Ni=--, Pb=--, Ra=--	Se=--, U=--, Zn=--, SO_4=3500							5.9		Mg	1020	mg/L	Na	21822	mg/L	K	2020	mg/L
										6.9										
										~3.0										
Al=624.1, As=14.66, Ca=186.5, Cd=3.76	Cr=--, Cu=137.5, Fe=7532, Co=0.554	Mn=9.45, Ni=0.83, Pb=2.87, Ra=--	Se=--, U=--, Zn=517, SO_4=28300							1-3	28975	Fe^{2+}	5545	mg/L						
	Cr=--, Cu=0.87, Fe=13.7, Co=--		Se=--, U=--, Zn=3.57, SO_4=--							3.1										
										2-3										
Al=15-35, As=0.02-0.3, Ca=--, Cd=0.05-0.3	Cr=--, Cu=4.0-7.0, Fe=75-200, Co=--	Mn=65-150, Ni=0.15-0.35, Pb=0.005-0.15, Ra=--	Se=--, U=--, Zn=25-50, SO_4=1,000-3,000							2-3										
Al=--, As=--, Ca=--, Cd=0.25	Cr=--, Cu=1.08, Fe=320, Co=--	Mn=300, Ni=--, Pb=0.07, Ra=--	Se=--, U=--, Zn=130, SO_4=4000			70				5.1										
Al=--, As=--, Ca=--, Cd=0.02	Cr=--, Cu=--, Fe=1.4, Co=--	Mn=1.8, Ni=--, Pb=--, Ra=--	Se=--, U=--, Zn=3.6, SO_4=370							5.9										
	Cr=--, Cu=0.007, Fe=--, Co=--	Mn=--, Ni=0.355, Pb=0.069, Ra=--	Se=--, U=--, Zn=124, SO_4=--							6.3										
Al=0.03, As=0.0042, Ca=21.8, Cd=<0.0001	Cr=<0.0004, Cu=0.0015, Fe=0.009, Co=0.0002	Mn=0.019, Ni=0.0108, Pb=<0.0001, Ra=--	Se=0.0009, U=0.0074, Zn=0.005, SO_4=13.7		261	13	31.7	505		8.1										
Al=--, As=0.07, Ca=44.9, Cd=0.002	Cr=--, Cu=0.002, Fe=1.73, Co=--	Mn=--, Ni=0.25, Pb=0.01, Ra=--	Se=--, U=--, Zn=8-10, SO_4=1085							7.03		Mg	37.6	mg/L						
			Se=--, U=--, Zn=2, SO_4=--																	

Al, As, Ca, Cd	Cr, Cu, Fe, Co	Mn, Ni, Pb, Ra	Se, U, Zn, SO_4	Temp	TDS	TSS	Turbidity	Conductivity	Eh	pH	Free Acid	Other 1			Other 2			Other 3		
mg/L	mg/L	mg/L	mg/L	ºC	mg/L	mg/L	NTU	µS	mV		/ g/L H_2SO_4	ID	Value	Units	ID	Value	Units	ID	Value	Units
			Se=--, U=--, Zn=10, SO_4=--																	
	Cr=--, Cu=--, Fe=0.09, Co=0.0007	Mn=0,356, Ni=--, Pb=0.0007, Ra=0.52	Se=0.0003, U=<0.005, Zn=0.003, SO_4=244							6.9		Ba	0.029	mg/L						
	Cr=--, Cu=--, Fe=10, Co=--									5	23									
Al=0.08475, As=<0.001, Ca=66.12, Cd=0.0003	Cr=< 0.001, Cu=0.04156, Fe=0.065, Co=0.11475	Mn=0.2435, Ni=14.82, Pb=< 0.001, Ra=--	Se=--, U=--, Zn=0.0112, SO_4=237.75	1-12	323.75	2.5		529		7.22										
	Cr=--, Cu=300, Fe=500, Co=35	Mn=--, Ni=10, Pb=--, Ra=--																		
	Cr=--, Cu=250, Fe=--, Co=--											Fe^{3+}	725	mg/L						
	Cr=--, Cu=220-360, Fe=--, Co=--																			
Al=1.2, As=--, Ca=--, Cd=--	Cr=--, Cu=1.2, Fe=23.9, Co=--	Mn=10.8, Ni=1.98, Pb=--, Ra=--	Se=--, U=--, Zn=3, SO_4=3205	31	12447			12.24	101	5.63										
Al=122, As=0.018, Ca=--, Cd=0.116	Cr=--, Cu=282, Fe=17.9, Co=--	Mn=16.5, Ni=6.95, Pb=0.092, Ra=--	Se=--, U=--, Zn=29.9, SO_4=2131		3366					3.4-4.0										
Al=0.1996, As=0.00667, Ca=376, Cd=<0.0001	Cr=0.001883, Cu=0.0192, Fe=0.1667, Co=0.02874	Mn=0.3221, Ni=0.2032, Pb=<0.001, Ra=--	Se=--, U=--, Zn=0.01817, SO_4=905	1-12	1525	7.02		2366		7.48										
Al=4.4, As=1.5, Ca=--, Cd=0.24	Cr=--, Cu=13.7, Fe=151, Co=--	Mn=42.4, Ni=--, Pb=0.15, Ra=--	Se=--, U=--, Zn=59, SO_4=1716							2.7		NO_3	9.6	mg/L						
Al=--, As=--, Ca=438, Cd=--			Se=--, U=--, Zn=--, SO_4=1291		2355					6.7		Mg	144	mg/L	Cl	157	mg/L	Na	74	mg/L
Al=5959, As=--, Ca=488, Cd=--	Cr=--, Cu=153, Fe=420, Co=--	Mn=472, Ni=--, Pb=--, Ra=--	Se=--, U=--, Zn=228, SO_4=73796		92000					2.9		Mg	9910	mg/L						
Al=50, As=--, Ca=450, Cd=--	Cr=--, Cu=--, Fe=4000, Co=--	Mn=150, Ni=--, Pb=--, Ra=--	Se=--, U=--, Zn=15, SO_4=8000							2.3	7000	Mg	300	mg/L	Cl	250	mg/L			
Al=50, As=--, Ca=450, Cd=--	Cr=--, Cu=--, Fe=4000, Co=--	Mn=150, Ni=--, Pb=--, Ra=--	Se=--, U=--, Zn=15, SO_4=8,240-14,000					6,970-11,800		2.5 -2.9	7000	Mg	300	mg/L	Cl	250	mg/L			
Al=2-490, As=--, Ca=--, Cd=--	Cr=--, Cu=0.1-5, Fe=1-600, Co=--	Mn=--, Ni=0.3-7.0, Pb=--, Ra=--	Se=--, U=--, Zn=0.06-1.5, SO_4=--	5-9				750		4.5-7.7		Fe^{2+}	600	mg/L						
Al=--, As=--, Ca=--, Cd=1			Se=--, U=--, Zn=270, SO_4=--																	
	Cr=--, Cu=200, Fe=--, Co=--																			
Al=0.3, As=--, Ca=422, Cd=--	Cr=--, Cu=--, Fe=135, Co=--	Mn=4.1, Ni=--, Pb=--, Ra=--	Se=--, U=--, Zn=0.02, SO_4=1383	26.7	2879			322		6.4		Mg	197	mg/L	Cl	184	mg/L			

Al, As, Ca, Cd	Cr, Cu, Fe, Co	Mn, Ni, Pb, Ra	Se, U, Zn, SO_4	Temp	TDS	TSS	Turbidity	Conductivity	Eh	pH	Free Acid	Other 1			Other 2			Other 3		
mg/L	mg/L	mg/L	mg/L	°C	mg/L	mg/L	NTU	µS	mV		/ g/L H_2SO_4	ID	Value	Units	ID	Value	Units	ID	Value	Units
Al=--, As=--, Ca=660, Cd=--	Cr=--, Cu=--, Fe=210, Co=--		Se=--, U=--, Zn=--, SO_4=3090		4800					2.7		Mg	230	mg/L						
	Cr=--, Cu=30, Fe=--, Co=--		Se=--, U=--, Zn=450, SO_4=--							2.3										
Al=0.167, As=--, Ca=0.034, Cd=0.034	Cr=--, Cu=--, Fe=65, Co=--	Mn=4.4, Ni=--, Pb=--, Ra=--	Se=--, U=--, Zn=17, SO_4=890		1625					6.23	200	Solid content	56	mg/L						
Al=--, As=--, Ca=195, Cd=--	Cr=--, Cu=--, Fe=48, Co=--	Mn=1.29, Ni=--, Pb=--, Ra=--	Se=--, U=--, Zn=--, SO_4=1460			90		3424		6.8		Mg	153	mg/L	Fe^{2+}	36.2	mg/L			
Al=54, As=--, Ca=1, Cd=--	Cr=--, Cu=--, Fe=26, Co=--		Se=--, U=--, Zn=--, SO_4=398							3	432	Fe^{2+}	11	mg/L						
	Cr=--, Cu=--, Fe=60, Co=--																			
Al=1.0-9.8, As=--, Ca=--, Cd=--	Cr=--, Cu=--, Fe=0.5-2.0, Co=--	Mn=1-15, Ni=--, Pb=--, Ra=--	Se=--, U=--, Zn=--, SO_4=20-370							2.7-6.7		U (dissolved)	0.1-4.21	Bq/L	Ra (dissolved)	0.02-0.2	Bq/L			
Al=21.9, As=--, Ca=--, Cd=--	Cr=--, Cu=--, Fe=112, Co=--	Mn=6, Ni=--, Pb=--, Ra=--								2.6		U(total)	13.7	mg/L	Ra	8980	mB/L			
Al=270, As=0.7, Ca=--, Cd=2.1	Cr=--, Cu=180, Fe=900, Co=--	Mn=--, Ni=1.2, Pb=--, Ra=--	Se=--, U=0.7, Zn=620, SO_4=--							2.7										
			Se=--, U=--, Zn=65-98, SO_4=--																	

APPENDIX D –
AMD Database

Note: To maintain confidentially, the sites are not identified.

Entry Number	Mine Status	Type of Operation	Principal Metal	Province/State	Country	Is Effluent Treated?	Raw Water: Al, As, Ca, Cd (mg/L)
IDNo							
1	Closed 1995	Base Metal		ON	Canada	Yes	Al=15, As=0.001, Ca=450, Cd=0.03
2	Closed 2006	Precious Metal		ON	Canada	No	Al=0.102, As=0.002, Ca=82.1, Cd=0.0002
3	Operating	Base Metal		ON	Canada	Yes	
4	Closed 2002	Base Metal		ON	Canada	Yes	
5	Operating	Base Metal		ON	Canada	Yes	Al=0.997, As=0.0242, Ca=455, Cd=0.0005
6	Closed 1997	Base Metal		ON	Canada	Yes	Al=1.94, As=0.002, Ca=--, Cd=1.38
7	Operating	Gold		ON	Canada	Yes	Al=0.02, As=0.02, Ca=322, Cd=0.0002
8	Operating	Precious Metal		ON	Canada	Yes	Al=--, As=0.004, Ca=--, Cd=--
9	Operating	Base Metal		ON	Canada	Yes	
10	Abandoned 1961	Precious Metal		ON	Canada	Yes	Al=--, As=20-200, Ca=--, Cd=--
11	Closed 1991	Base Metal		ON	Canada	Yes	Al=36, As=0.06, Ca=170, Cd=0.3
12	Orphaned 1972	Base Metal		ON	Canada	Yes	Al=44.4, As=0.01, Ca=435, Cd=0.165
13	Closed 1980	Base Metal		ON	Canada	Yes	
14	Closed 1998	Base Metal		ON	Canada	Yes	Al=--, As=0.01, Ca=225, Cd=--
15	Closed 1995	Base Metal		BC	Canada	Yes	Al=24.2, As=0.00089, Ca=435, Cd=0.048
16	Closed 1992	Base Metal		BC	Canada	Yes	Al=0.2, As=0.002, Ca=400, Cd=0.01
17	Closed 2001	Base Metal		BC	Canada	Yes	Al=66.5, As=0.05, Ca=377, Cd=0.162
18	Closed 1974	Base Metal		BC	Canada	Yes	Al=23.5, As=0.002, Ca=373, Cd=0.094
19	Closed 1996	Precious Metal		BC	Canada	Yes	Al=0.05, As=0.3, Ca=085, Cd=0.005
20	Operating	Base Metal		BC	Canada	Yes	Al=4.2, As=0.193, Ca=143.8, Cd=0.043
21	Closed	Precious Metal		BC	Canada	Yes	Al=1071, As=6.6, Ca=381, Cd=1.2
22	Closed 1990	Base Metal		BC	Canada	Yes	Al=--, As=--, Ca=98, Cd=--
23	Operating	Base Metal		MB	Canada	Yes	Al=--, As=0.002, Ca=--, Cd=--
24	Operating	Base Metal		MB	Canada	Yes	Al=--, As=--, Ca=--, Cd=0.01
25	Closed 1986	Coal		NB	Canada	Yes	Al=68.4, As=0.002, Ca=219, Cd=0.0021
26	Closed 1999	Base Metal		NB	Canada	Yes	Al=--, As=--, Ca=140, Cd=--
27	Operating	Base Metal		NB	Canada	Yes	Al=--, As=--, Ca=65, Cd=--
28	Operating	Other	Antimony	NL	Canada	Yes	
29	Abandoned	Base Metal		NL	Canada	Yes	Al=0.002-0.006, As=0.001, Ca=252-457, Cd=0.0012-0.0107
30	Operating	Base Metal		NL	Canada	No	
31	Closed 1982	Base Metal		NS	Canada	Yes	Al=15.5, As=--, Ca=84, Cd=--
32	Closed 1998	Coal		NS	Canada	Yes	Al=4.8, As=0.006, Ca=290, Cd=0.00097
33	Closed 1984	Coal		NS	Canada	No	
34	Operating	Precious Metal		ON	Canada	No	
35	Operating	Precious Metal		QC	Canada	No	
36	Operating	Precious Metal		QC	Canada	No	
37	Operating	Precious Metal		QC	Canada	No	
38	Closed 1992	Base Metal		BC	Canada	No	
39	Operating	Base Metal		BC	Canada	No	
40	Operating	Base Metal		BC	Canada	No	
41	Operating	Base Metal	Nickel	ON	Canada	No	
42	Abandoned	Precious Metal		NWT	Canada	Yes	
43	Operating	Uranium		SK	Canada	Yes	Al=--, As=0.28, Ca=--, Cd=0.001
44	Operating	Uranium		SK	Canada	Yes	Al=--, As=2.91, Ca=--, Cd=0.001
45	Operating	Precious Metal			Peru	Yes	Al=108-0.8, As=2.7-0.003, Ca=2,4211-4.02, Cd=0.398-0.004
46	Operating	Base Metal		QC	Canada	No	
47	Closed 2004	Base Metal		QC	Canada	Yes	
48	Operating	Precious Metal		AK	USA	Yes	Al=--, As=0.004, Ca=206, Cd=0.001
49	Operating	Base Metal		AK	USA	Yes	Al=--, As=--, Ca=--, Cd=4.8
50	Operating	Base Metal		AK	USA	Yes	Al=--, As=--, Ca=--, Cd=6.9
51	Closed 1995	Base Metal		QC	Canada	Yes	
52	Closed 2005	Base Metal		QC	Canada	Yes	Al=--, As=0.17, Ca=686, Cd=--
53	Abandoned	Precious Metal			Canada	Yes	Al=0.01, As=0.04, Ca=278, Cd=0.0013
54	Operating	Precious Metal		QC	Canada	Yes	
55	Operating	Precious Metal		QC	Canada	No	
56	Closed 1998	Precious Metal		MT	USA	Yes	Al=--, As=0.15, Ca=--, Cd=0.04
57	Closed 1998	Precious Metal		MT	USA	Yes	Al=--, As=0.227, Ca=--, Cd=0.218
58	Closed	Other	Molybdenum & Uranium	CO	USA	Yes	
59	Operating	Other	Zinc Refinery		Peru	Yes	Al=--, As=--, Ca=--, Cd=10.6
60	Operating	Other	Zinc Refinery	QC	Canada	Yes	Al=--, As=--, Ca=--, Cd=6
61	Operating	Precious Metal		AK	USA	Yes	
62	Abandoned	Precious Metal		SD	USA	Yes	
63	Closed 1998	Other	Tin		United Kingdom	Yes	Al=23, As=2, Ca=--, Cd=--
64	Closed 1986	Coal			United Kingdom	Yes	Al=0.37, As=--, Ca=1630, Cd=--
65	Operating	Base Metal		ON	Canada	Yes	
66	Operating	Other		NS	Canada	Yes	
67	Abandoned	Precious Metal		Co	USA	Yes	
68	Abandoned	Other	precious metals, copper, zinc, pyrite	Ca	USA	Yes	Al=424.1, As=14.66, Ca=186.5, Cd=3.76
69	Closed	Base Metal		QC	Canada	Yes	
70	Operating	Other	Lead, Zinc, Silver	ID	USA	Yes	
71	Closed 1997	Precious Metal		Co	USA	Yes	Al=15-35, As=0.02-0.3, Ca=--, Cd=0.05-0.3
72	Closed 1984	Other	Zinc, lead and precious metals. Also famous for pyrite, barite, rhodochrosite, galen and sphalerite specimens.	Co	USA	Yes	Al=--, As=--, Ca=--, Cd=0.25
73	Closed 1984	Other	Precious metals, copper, zinc, manganese, and lead	Co	USA	Yes	Al=--, As=--, Ca=--, Cd=0.02
74	Abandoned	Other	Silver, lead, zinc	YT	Canada	Yes	
75	Operating	Other	Diamonds	NWT	Canada	Yes	Al=0.33, As=0.0042, Ca=21.8, Cd=0.0001
76	Closed	Other	Silver, Lead, Zinc	YT	Canada	Yes	Al=--, As=0.07, Ca=44.8, Cd=0.002
77	Closed	Other	Silver, Lead, Zinc	YT	Canada	Yes	

Entry Number	Mine Status	Type of Operation	Principal Metal	Province/State	Country	Is Effluent Treated?	Raw Water: Al, As, Ca, Cd (mg/L)
78	Closed	Other	Silver, Lead, Zinc	YT	Canada	Yes	
79	Closed 1996	Uranium		ON	Canada	Yes	
80	Abandoned 1987	Base Metal	Cu	TN	USA	Yes	
81	Operating	Base Metal		QC	Canada	Yes	Al=0.08475, As=<0.001, Ca=66.12, Cd=0.0003
82	Operating	Base Metal	Copper	Queensland	Australia	Yes	
83	Operating	Base Metal	Copper	Jiangxi	China	Yes	
84	Closed 1975	Base Metal	Copper	AZ	USA	Yes	
85	Operating	Other	Molybdenum	NM	USA	Yes	
86	Operating	Precious Metal		MT	USA	Yes	Al=1.2, As=--, Ca=--, Cd=--
87	Operating	Base Metal	Copper	NM	USA	Yes	Al=122, As=0.018, Ca=--, Cd=0.116
88	Operating	Base Metal		QC	Canada	Yes	Al=0.1986, As=0.00667, Ca=376, Cd=<0.0001
89	Operating	Base Metal		Junin	Peru	Yes	Al=4.4, As=1.5, Ca=--, Cd=0.24
90	Operating	Base Metal	Copper	UT	USA	Yes	Al=--, As=--, Ca=438, Cd=--
91	Operating	Base Metal	Copper	UT	USA	Yes	Al=6869, As=--, Ca=488, Cd=--
92	Closed 1972	Other	Sulphur to produce sulphuric acid used in fertilizer production.	SA	Australia	Yes	Al=50, As=--, Ca=450, Cd=--
93	Closed 1972	Other	Sulphur to produce sulphuric acid used in fertilizer production.	SA	Australia	Yes	Al=50, As=--, Ca=450, Cd=--
94	Closed 1962	Other	Copper sulfate for processing silver ore.	CA	USA	Yes	Al=0-490, As=--, Ca=--, Cd=--
95	Closed 1970	Other	Zinc and silver	Co	USA	Yes	Al=--, As=--, Ca=--, Cd=1
96	Operating	Precious Metal			Mexico	Yes	
97	Operating	Precious Metal		Gauteng	South Africa	Yes	Al=0.3, As=--, Ca=422, Cd=--
98	Operating	Coal			South Africa	Yes	Al=--, As=--, Ca=660, Cd=--
99	Operating	Base Metal		NB	Canada	Yes	
100	Closed 1986	Base Metal			Hungary	Yes	Al=0.167, As=--, Ca=0.034, Cd=0.034
101	Closed 1988	Coal			United Kingdom	Yes	Al=--, As=--, Ca=195, Cd=--
102	Operating	Coal			New Zealand	Yes	Al=54, As=--, Ca=1, Cd=--
103	Closed 1986	Coal			United Kingdom	Yes	
104	Closed 1997	Uranium			Brazil	Yes	Al=1.0-9.8, As=--, Ca=--, Cd=--
105	Closed 1997	Uranium			Germany	Yes	Al=21.8, As=--, Ca=--, Cd=--
106	Closed 1982	Base Metal	Cu	Montana	USA	Yes	Al=370, As=0.7, Ca=--, Cd=2.1
107	Closed 1998	Base Metal		YT	Canada	Yes	
108	Closed 1998	Base Metal		YT	Canada	Yes	
109	Closed	Gold		Colorado	USA	Yes	Al=--, As=--, Ca=--, Cd=0.36
110	Closed 1962	Other	Iron	Minnesota	USA	Yes	

APPENDIX E –
Treatment Issues Recorded

Treatment Issues Recorded

- Gypsum scaling is evident however the HD water treatment has helped the situation.
- Algal blooms in collection ponds, poor settling, dredging sludge and disposal from treatment ponds.
- Lime handling and mixing, Polymer mixing during winter.
- Scaling of the process equipment and lime slurry lines. Periodic cleaning and replacement of equipment and lines were necessary.
- Elevated suspended solids in the final effluent discharge. A re-design of the floc system was undertaken in 2005. Adjustments to the floc addition rates were required on a regular basis.
- Poor retention time during maximum flow output of the clarifier thickener. Additional baffles in the feed launder to the thickener had to be installed to improve settling time.
- Lime make-up and supply to the reaction tanks. Plugging of the hydrated lime feeder system to the slurry makeup tank. The feeder and delivery system were modified.
- Mn dissolves in polishing pond during the winter if we lower the pond to ice (i.e. reducing conditions).
- With high sludge production it's difficult to maintain high density.
- Treated effluent is discharged into Hedley Creek, a tributary of the Similkameen River, which flows into Washington State.
- Scaling is an issue if sludge density is not high enough. For a good year we have to descale the first reaction tanks and agitators in both reaction tanks. For a bad year with low sludge density the whole circuit including the clarifier needs to be descaled. Still much better and the LDS plant that would gain over 30 cm of gypsum/year in the first reaction tank.
- Maintaining sludge density is an issue, it takes time to build up the density but can be lost quickly with process upset such as increasing the flow rate too quickly.
- TSS would be a problem at high flows if we were not pumping to the main Zone pit before discharging to the receiving environment.
- Related to scale, we have to clean the pH probes daily or else the scale can give us false readings (high or low).
- Scaling
- Scaling on probes, gypsum precipitation, and thiosalts
- Not in production
- It is anticipated scaling of the pipeline is likely to take place and that will have to be cleaned out periodically.
- Final Effluent is used as industrial water and if it is going to be discharged to the environment it is mixed with excess treated water in the Carachugo buffer pond to reach appropriate pH level.
- Scaling of the probe of measurement of the pH causes a potential variation of the pH of the water treated with the exit of the factory.

Treatment Issues Recorded (cont'd)

- Quoted treatment cost includes labour, reagents, maintenance and sludge disposal. Acidity in water is due to residual thiosulphate (S_2O_3) derived from mill processing. Raw and treated water compositions represent the dissolved fraction for most constituents and were derived from averaging results from several samples. The data therefore, do not show the overall removal efficiency of the treatment process. Average total concentrations for influent and effluent samples are as follows: Total zinc influent 0.69 mg/l, effluent 0.09 mg/l; total copper influent 0.03 mg/l, effluent 0.01mg/l, total lead influent 0.29 mg/l, effluent 0.1 mg/l.
- WTP#1 provides process water after treating tailings impoundment water, no polishing step. Flotation tailings report to the tailings impoundment. WTP sludges report to the tailings impoundment. High TDS (gypsum) in clarifier overflow solutions. Implicated in scaling in the plant and in limiting environmental discharge.
- WTP#2 treats water reclaimed from the tailings impoundment for discharge. Sand filter polishing step. Sulphide addition for polishing metals. Flotation tailings report to the tailings impoundment. WTP sludges report to the tailings impoundment. High TDS (gypsum) in clarifier overflow solutions. Implicated in scaling in the plant and in limiting environmental discharge.
- Treatment plant designed for remote operation without full-time operator.
- The treatment plant runs twice per year.
- A little scaling but it is not a major problem. That requires an annual maintenance.
- WTP treats slightly acidic and slightly elevated levels of dissolved metals by lime addition with the addition of hydrated lime. No ferric sulphate addition is required, and a portion of the sludge is recycled back to the first reactor.
- WTP-Hydrated lime is used to neutralize ARD acidity and remove metals, ferric sulphate is also used to aid in arsenic removal; in -addition, a portion of the sludge is recycled back to the first reactor.
- The treatment plant treats water contains high Mn concentration from the mine, in addition to seepage from a decommissioned uranium mine.
- Treatment of high strength variable feed containing elevated levels of Mn, SO_4 and Zn. HDS process require multi-stage lime addition for efficient metal removal and "smart" pH control system.
- Multi-media filters and sludge press is used to dewater sludge.
- Almost a decade ago, this US EPA superfund site was left with 150 million gallons of acidic, heavy metal laden water in three open pits, as well as millions of cubic yards of acid-generating waste rock.
- The Unipure HDS process not only effectively removed dissolved metals, but surprisingly able to reduce TSS in the final effluent below regulated limits without a sand filter.
- The Unipure treatment is a modular design making it portable, so it can be moved to other sites in the future.

Treatment Issues Recorded (cont'd)

- The high flowrate was selected for this WTP to quickly drain the holding ponds to reduce their attractiveness to the birds and thus improve safety for aircraft. This feature does increase the complexity of operating the WTP at peak efficiency.
- Gypsum scaling of the Thickener.
- Since sodium hydroxide sludge is more difficult to dewater, polymer is added to the clarifier to enhance flocculation. Then the clarifier overflow is routed to a gravity filter to remove unsettled solids.
- Since lime treatment of AMD often result in gypsum scaling, soda ash is added in a second stage of the precipitation process. The soda ash reduces gypsum formation by removing some calcium with carbonate.
- The treatment process involves CO_2 stripping followed by sodium hydroxide precipitation then clarification.
- Hydrated lime is mixed at a central mixing facility and delivered to the mine portal via a lime truck. The lime slurry is stored in a retrofitted propane tank and continuously added to the portal drainage. The treated effluent is then carried by pipeline a settling pond before discharged.
- Algae in the summer months.
- Hydrated lime is mixed at a central mixing facility and delivered to the mine portals via a lime truck. The slurry lime is stored at each site in retrofitted propane tanks and continuously added to mine portal drainages. Once treated the effluent is then diverted through settling pond(s) before discharge to the environment. Treatment issues involve plugged and broken lime feed pumps and lines, plugged valves and erratic pH changes from manual administering of lime. Also inefficient mixing of lime and raw water is a problem.
- The current WTP is, outdated technology, prone to high power consumption and have no capacity to contain effluent in the event of an upset. Plan to build a new WTP to address these issues.
- Acidic effluent from the North Potato Creek is combined with acidic effluent from the bottom layer of the historic South Mine Pit and treated by the North Potato Creek water treatment plant. The treatment process consists of treating very high flows of AMD in a rapid mix tank with hydrated lime, which then overflows back to South Mine Pit for settling, with final effluent being discharged to Ocoee River. *Reference: Faulkner, B.B., Griff Wyatt, E., Chermak, A., Miller, F.K., 2005. "The Largest Acid Mine Drainage Treatment Plant In the World."*
- The BioSulphide process recovers copper , cobalt and nickel. Annual production expected to be 1.4M lbs Cu and 135K lbs cobalt/nickel.
- Up to copper 4.4M lbs recovered annually.
- This process recovered 1.4 million lbs copper in 2007.
- The UNR passivation process is aimed at reducing AMD generation by treating the pit walls. Please note- the feed composition represents AMD composition produced from untreated sections of the pit wall. While the final effluent composition represents drainage generated from the treated sections of the pit wall.

Treatment Issues Recorded (cont'd)

- Unlike most processes, this treatment system utilizes nanofiltration as an up-front treatment method (as opposed to a polishing method) while the concentrate is treated by HDS process and the effluent is of high quality and ready for discharge.
- Even though high sulphate and manganese concentration do not pose a health risk, they seem to affect the aesthetic qualities of drinking water.
- The feed for the Reverse Osmosis system is a sulphate plume water. A portion of the permeate is recycled back into the process, while the remainder is conditioned for drinking water.
- Gypsum scaling would be a major treatment issue.
- Process leach water combined with contaminated ground water is treated by this membrane filtration system. A major treatment issue is gypsum scaling of pressure vessels. In this treatment system the final effluent is called the permeate, which is recycled in the membrane filtration system.
- During periods of high flows thickener efficiency is reduced resulting in higher TSS in the clarifying pond.
- This process is design to recover zinc as a saleable product to offset treatment cost. No zinc production numbers are available since the treatment plant was just recently commissioned.

APPENDIX F –
Sludge Management Issues Recorded

Sludge Management Issues Recorded

- In the summer months, sludge cells dry up quickly into fine dust that is blown by wind.
- Annual sludge removal "spikes" the pH of the settling pond to pH 10-12, this water is then used to treat and settle fresh run-off.
- Site is running out of room to dispose the sludge, will have to dispose off site on the future.
- Difficulty in dredging sludge lagoon and high disposal cost.
- Due to arsenic content in sludge a quarterly sample is taken to maintain a status of “non” special waste and therefore not requiring approval for storage under the provincial Waste Management Act.
- Once the lined ponds are filled, a HPDE liner will be fused over top the sludge and the liner will be covered with till and topsoil and re-vegetated.
- With the new HDS plant we do not have many sludge problems. Pumping the sludge to open pit is now quite easy from the clarifier. When we still operated the LDS plant and used sludge ponds, we expended a lot of energy of pumping the sludge to open pit. Work in the open pit and the sludge is showing that the sludge is quite stable in the pit lake. Would like to find a use for the sludge so that the metals do not have to go into a landfill (pitfil). Long term we will be looking for other places to store sludge if we can not find a use for it (once the pit is full).
- Sludge is dredged back into waste rock in pit since 1992. Changes in mine water quality include higher mine water pH, lower metal concentrations, lower lime consumption (75% reduction), no additional environmental or liability costs associated with building new ponds as the same 10 ponds have been used/dredged and reused since 1991.
- The only issue we have is with dusting during the dry season and when there is no snow cover during winter. We are now in the process of covering most of the old sludge ponds. We seeded approximately 4 acres last year as trial with different seed mixes and it has grown well.
- When dry sludge becomes difficult to manage due to availability for remobilization (dusting), and inability to drive machinery on the sludge for dust control.
- The amount of sludge produced in the WTP is not monitored. The underflows of the hydroxide, radium arsenic and radium polishing clarifiers are periodically pumped into the sludge tank (25.5 m^3) when the clarifier torque begins to increase or the slime levels of the clarifier begins to rise quickly. When the sludge tank reaches capacity (approximately every 3 days), the plant operator will pump the sludge to the tailings neutralization circuit. The chemical assay of the sludge is not documented nor is the solids mineralogy.
- The amount of sludge produced in the WTP is not monitored. The WTP plant was shut down for approximately one month to allow sludge removal from the settling ponds. The sludge is deposited in the landfill for chemically and radiologically contaminated materials at the perimeter of the Tailings Management Facility for eventual disposal with the tailings.

Sludge Management Issues Recorded (cont'd)

- Water treatment plant sludge is dewatered in a plate frame press and mixed with dewatered tailings in the mine's dry stack tailings pile, which is a permitted landfill. Some reductive dissolution of ferric oxyhydroxide sludge likely occurs but has not been quantified.
- Minimal sludge produced. The main reason for water treatment at site was to reduce cyanide in tailings pore water. Metals not a large concern, therefore not too much attention paid to sludge management.
- No particular problem.
- This process produces coarse, self-draining, pumpable sludge at 40%, which dewaters to over 55% solids in the pond.
- Sludge leaves the plant at 4-8% solids and is further concentrated to 25-30% after the filter press.
- Sludge leaves HDS plant at ~30% solids and is placed on drying beds to dewater to 65-70% solids. Then is finally stored in landfill.
- We transport sludge in the winter.
- Sludge produced at the thickener underflow contains approximately 3% solids, which is then routed to holding tanks. The sludge is then pumped to a filter press to increase solids to 18%.The cost of sludge disposal $45US/ton.
- Plate and frame filter presses are used to dewater the sludge from 4-8% solids to a solids content of 50%. Sludge disposal cost is $23US/ton
- Clarifier overflow goes to a gravity filter to remove residual solids and then discharged. Sludge from the Clarifier underflow contains a 3-5% solids content is further dewatered to 35- 40% using plate and frame filter presses. Finally the sludge is transported to a landfill approx. 150 miles away. A closer disposal facility would reduce sludge disposal costs which are at $75US/ton.
- Sludge produced is gelatinous and therefore difficult to settle. Settling pond must be dredged every 4-6 weeks in-order for the final effluent to meet regulated metal discharge limits.
- Residue is sent to smelter to recover nickel to off set treatment cost.
- In this Reverse Osmosis process, instead of sludge a concentrate is produced and the concentrate composition is in ppm units.
- Sludge produced from the CSIR process is combined with the brine from the RO process and disposed in evaporation ponds (330,000 cubic meter capacity).
- The solid content of the sludge after centrifuge is approximately 40%. The sludge is regarded as a hazardous waste because of its arsenic content (1000 g/t).
- Periodically the settling ponds are drained and the sludge is removed and disposed elsewhere.
- Metal remobilization issues since sludge is disposed in acidic mine pit.
- Sludge is centrifuged to 48% solids then disposed on site.
- Sludge from clarifier underflow is pumped to the Berkeley Pit.

APPENDIX G –
Relevant Publications

(separate attachment files entitled)

Disposal, Reprocessing and Reuse Options for Acidic Drainage Treatment Sludge
by Janice Zinck

International ARD Treatment and Sludge Management Survey
by Janice Zinck and Wesley Griffith

Evaluation of Sludge Management Options
by Janice Zinck and Wesley Griffith

DISPOSAL, REPROCESSING AND REUSE OPTIONS FOR ACIDIC DRAINAGE TREATMENT SLUDGE[1]

Janice Zinck[2]

Abstract: Sludge management is an escalating concern as the inventory of sludge continues to grow through perpetual "pump and treat" of acidic waters at mine sites. Current sludge management practices, in general, are ad hoc and frequently do not address long-term storage, and in some cases, long-term stability. While a variety of sludge disposal practices have been applied, many have not been fully investigated and monitoring data on the performance of these technologies is limited and not readily available. This paper discusses options for treatment sludge management including conventional disposal technologies, reprocessing options for metal recovery, novel sludge reuse technologies and options for reclamation of sludge areas.

Additional Key Words: lime treatment, high density sludge process, co-disposal, sludge stability, pond disposal, backfill, leaching, mine reclamation

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[2] CANMET-MMSL, Natural Resources Canada, 555 Booth Street, Ottawa, ON, Canada, K1A 0G1, 613-995-4221, jzinck@nrcan.gc.ca

Introduction

Sludge management is an escalating concern as the inventory of sludge continues to increase and the stability of the sludge under various disposal conditions is poorly understood. As such, the management and disposal of these mining wastes requires careful consideration and planning.

Sludge management considerations

To design the most appropriate sludge management strategy for a site, several factors need to be considered. The principle considerations are the mass of sludge produced, whether the mine is operating or closed, dewatering ability of the sludge, sludge density (moisture content), sludge volume, chemical and physical stability, sludge composition, disposal location availability and economics.

The ability of sludge to dewater may limit the options available. Sludge that can dewater without mechanical assistance will not only reduce the area required for disposal, it also makes it more attractive for reuse options. The ability of sludge to dewater depends on its particle size, morphology and surface charge. As a particle deviates from a spherical shape, the surface area per unit volume increases, resulting in reduced settleability and decreased dewatering rate (Vachon et al., 1987). These characteristics are linked directly to the water treatment process that generates the sludge and to the raw water chemistry (see Zinck, 2005, for further discussion).

Sludge Disposal

Storage and disposal of wastewater treatment sludge is not problem unique to acidic drainage or lime treatment. Pulp and paper, tannery, municipal, and acidic drainage sludges all face similar issues. Economics and land availability usually determine what sludge disposal strategy is adopted (Vachon et al., 1987). Sludge disposal constitutes a significant proportion of the overall treatment costs. Various options available for sludge disposal are reviewed below.

Pond disposal

Sludge management involves three principle steps, namely solid-liquid separation, sludge dewatering and disposal. Many sites utilize settling ponds as an efficient sludge management option. The sludge is pumped to a settling pond where solid-liquid separation, dewatering and in many cases disposal occur simultaneously. While settling and disposal in the same pond requires large land areas, this approach is simple and requires only minimal design and construction considerations (Lovell, 1973). Pond disposal refers to long-term disposal of the sludge in an impoundment. Examples of pond disposal are presented in Fig. 1.

Issues associated with pond disposal are minimal. Wind resuspension and dusting present problems at some sites, particularly in arid or northern regions. Due to the large requirement for space, land use can be a challenge for some sites. Disposal space is not a present concern at most Canadian sites, but with perpetual chemical treatment it may become an issue. Due to the thixiotropic nature of sludges (viscosity decreases as shear strength increases), pond failure could present some concerns although not to the same extent as with tailings impoundments. However, in a pond environment, either with or without a water cover, the degree of metal leaching is expected to be minimal, as the excess alkalinity available in the sludge is enough to sustain a moderate pH for decades, even centuries (Zinck et al., 1997).

Figure 1: Examples of pond disposal for sludge.

Sludge disposal in a pond environment can be either subaerial or subaqueous. In a subaerial environment, the sludge is exposed to weathering conditions. Sludge cracking due to moisture loss at the surface is prevalent, causing an increase in surface water infiltration. Under these conditions, sludge dewatering occurs at the surface while the majority of the sludge at depth is still very moist. The desiccated surface may be reclaimed. Sludge pond reclamation is discussed later in the paper.

The cost of pond sludge disposal depends on the production rate and the stability of the sludge. However, this method of disposal is relatively inexpensive. Unfortunately, ponds are often under designed to meet sludge management requirements and frequently fill-up prematurely. Mechanical sludge removal can cost approximately \$5 to as much \$30 per tonne for removal with a truck and backhoe.

For example, Kidd Creek Metallurgical Site (Timmins, Ontario) spends upwards of \$1 million per year on dredging costs (Scott, 2004). Ackman (1982) evaluates sludge removal techniques in terms of storage capacity, economics, maintenance and versatility. Due to the high long-term maintenance costs of dredging, it is best if the sludge can be disposed of long-term in the pond in order to avoid frequent and costly sludge removal from the pond. If long-term pond disposal is not an option, the sludge must be removed and disposed of in a more suitable, site-specific location (e.g. in underground workings).

In general, sludge disposal in ponds exhibits minimal metal leaching. Where sludge leaching is a concern, the application of a water cover (subaqueous) proves to be effective in reducing metal mobility. In a laboratory study (CANMET, 2004), sludge was found to be more chemically stable when a water cover was applied to a pond disposal scenario. In this case, the amount of Cd, Cu, Mg and Zn mobilized was significantly lower with a water cover compared to without. The presence of a water cover over the sludge provided better distribution of the alkalinity and buffering capacity resulting in better pH control and lower metal mobility. Water covers may reduce metal mobility (e.g. Zn) by as much as 10%. Zn and Cd are frequently the metals that mobilize readily and as such are problematic. Liners may also be required if sludge leaching is problematic. The cost for liners can range from \$4-\$12/m^2 for a synthetic liner and more than double that amount for a clay liner.

Codisposal with Tailings

Many mine sites dispose of treatment sludge with mill tailings to reduce the waste management resources required to dispose tailings and sludge separately. While there is some perception that the addition of lime treatment sludge to a tailings impoundment area may provide buffering capacity, this has yet to be validated. Moreover, the long-term stability of acidic drainage treatment sludge disposed with tailings is generally unknown and requires considerable further investigation.

The practice of co-mixing tailings with treatment sludge for disposal involves injecting the treatment sludge into the tailings slurry prior to discharge to the impoundment. Typically, the sludge to tailings ratio is less than 1:20. Here the sludge serves to fill void spaces within the tailings, in theory reducing the potential for water or air infiltration and the hydraulic conductivity of the mixture. This method of disposal could be an effective option provided that the tailings are either non-acid generating or that tailings oxidation is prevented. However, if the tailings undergo oxidation and commence acid generation, the likelihood for sludge dissolution and metal mobilization is very high. In addition, an alternative sludge disposal strategy would be required post closure as sludge continues to be generated while tailings production ceases.

When fresh tailings were mixed with treatment sludge and leached over time in the laboratory with synthetic rainwater, the long-term stability of the sludge was compromised (CANMET, 2004). Results showed that the net alkalinity only offset acid generation and metal mobility in the short term. Once oxidation was established, the available alkalinity in the sludge was quickly depleted. Under acidic conditions sludge dissolution occurs, opening void spaces and increasing infiltration and metal leaching. If under these same conditions a water cover was applied to the waste, then it is expected that limited metal leaching would occur, as oxidation would be discouraged.

Sludge as a Cover Over Tailings

The application of wet and dry covers to prevent acidic drainage is widely adopted. Wet covers provide a barrier that minimizes oxygen contact with potentially acid generating material and, except for minor oxygen dissolved in the water, precludes oxygen contact completely. Laboratory results (CANMET, 2004) suggest that sludge as a cover material was not effective to impede oxidation of tailings. Contrary to what was expected, the sludge layer did not act as a barrier to oxygen and did not significantly reduce the rate of sulphide oxidation. However, these results were obtained from laboratory trials and several limitations were encountered. Some of the issues related to the application of a sludge cover on tailings are cracking and preferential channeling. Sludge needs to be disposed in a manner in which the particles will not segregate and consequently remain saturated. Maintaining water in the sludge pore space will prevent sludge cracking and minimize exposure of tailings to oxygen. The application of a water or vegetative cover could be beneficial in keeping the sludge saturated by limiting cracking and channeling. Figure 2 presents some examples of sludge disposed of over tailings.

Figure 2: Field example of sludge layered over tailings. Inset shows a core of a sludge over tailings disposal scenario.

Mian and Yanful (2004) investigated the effect of wind-driven resuspension of sludge placed over tailings in a pond at the Heath Steele site in New Brunswick. They concluded that wind resuspension of fine sludge particles caused the total suspended solids (TSS) in the discharge to exceed the Canadian effluent limits during periods of high winds. Peacey et al. (2002) studied the same site and found that, in the long-term, sludge formation and resuspension should not be an environmental problem with this disposal option.

Sludge Disposal with Waste Rock

Disposing sludge with waste rock has several of the same potential benefits as disposal with tailings, including utilization of excess alkalinity to offset acid generation and filling of void spaces. This practice of disposing treatment sludge in waste rock piles is being adopted at some sites. NB Coal's Fire Road mine (Minto, New Brunswick) started looking at the option of codisposal of sludge with waste rock in 1993 after it was determined that there was 160-770 years of sludge storage capacity within the waste rock.

Coleman et al. (1997) conducted an investigation into the placement of sludge on acid generating waste rock. While their results showed that sludge was not effective as a capping material as originally hoped, this method was found to be a low-cost final disposal option as the sludge filled pore spaces and voids within the waste rock pile. The mine water chemistry has been monitored since 1993 and there appears to be no adverse identifiable chemical effects (Coleman and Butler, 2004).

Disposal in Mine Workings

Disposal of treatment sludge into underground mine workings has several benefits that make it an attractive sludge management option. The deposition of sludge into underground mines reduces the footprint required for disposal sites (landfills and impoundments), eliminates the potential for surface water pollution, reduces the potential for subsidence, and improves the aesthetics of the local area. Also, in acidic mine workings, the disposal of sludge underground could have the additional benefit of reducing the acidity of the mine water (Gray et al., 1997).

This practice involves pumping or trucking sludge to boreholes, which are drilled into underground inactive mines. Some the factors that need to be considered in this disposal option include:

- site availability and access
- mine capacity, void space, configuration
- sludge properties (e.g. viscosity)

Meiers et al. (1995) looked at the technical feasibility of placing fixated scrubber sludge into underground coal mines. The sludge was injected through boreholes at a rate of 215 to 500 m^3/day. Short-term results indicated no discernable chemical effects on the mine water or groundwater quality. Gray et al. (1997) identified several sites in the United States using the practice of underground mine disposal for other wastes such as coal ash and kiln dust.

Since 1987, Mettiki Coal has been injecting alkaline metal hydroxide sludge from its mine drainage treatment facility along with thickener underflow from its coal preparation plant into inactive portions of its underground mine in Garrett County, Maryland under an Underground Injection Control (UIC) permit (Ashby, 2001). Based on available data, it was felt that alkaline solids addition would assist Mettiki in maintaining an alkaline environment in its underground mine pool at closure and minimize acid generation. From 1996 to 2000 the pH of the mine water increased from 5.98 to 6.1.

Aubé et al. (2003) observed a similar trend. A laboratory study simulating the disposal of HDS and ferrous sludge into underground coal mine workings containing high strength acidic drainage was completed. The pH of the mine water increased from pH~3 to ~6.7 with increasing amounts of sludge added.

In all cases where sludge was added, the concentrations of both Al and Fe decreased in the mine water. Results showed that some metal concentrations (Cd, Ni, and Zn) increased prior to decreasing at higher sludge addition rates. These metals are typically mobile at neutral or acid pH. The results also showed that there is a greater increase in dissolved metal concentration when the ferrous sludge was added to the acidic mine water.

When sludge is in equilibrium with the surrounding mine water, little or no dissolution of the iron sludge will occur. Any addition of either OH^- ions or Fe^{+3} ions would result in precipitation. These results suggest that sludge returned to the underground workings would actually reduce the lime required to treat the acidic mine water.

This method is very attractive from an economic and environmental standpoint. However, like most disposal options presented this is clearly site specific. Sludge with high iron content can most probably be disposed of this way economically. Disposal of sludge with high Cd, Zn, or Ni content in this manner may or may not be economic or environmentally acceptable depending on contact means (solids/AMD (S/L) ratio), alkalinity of sludge, and acidity of the acidic drainage (Aubé, 2004; Aubé et al., 2005).

Disposal in Pit Lakes

Disposal in an abandoned open pit is typically one of the most economical solutions for sludge storage, if a pit is within a reasonable pumping distance from the treatment plant. Many companies frequently take advantage of open pits available on site as an appropriate short or long-term sludge disposal option. McNee et al. (2003) conducted a three-year research program studying two pit lakes at the Equity Silver Mine near Houston, British Columbia. Neutralization sludge was added to the Main Zone pit at a rate of ~5 L/s. The discharge of sludge into the Main Zone pit had a pronounced effect on its physical limnology. Their research found that the addition of sludge to the pit lake introduced oxygen into the lake through entrainment. Specifically, the input of dense oxygen-rich slurries and their rapid settling were found to cause lake mixing and produced oxygenated bottom waters. In addition, they found sludge disposal in the pit lake resulted in a plume of metal-rich particulate matter at depth (70-120 m). This did not, however, result in an increase in the dissolved metal content or total suspended solids levels at discharge. The pit lake experienced increased production as observed by the reduced light transmission and increase plankton biomass in the surface waters. It was postulated that the increased production was due to the delivery of phosphate into the lake with the sludge. Overall, the dynamics of the lake changed considerably and whole-lake mixing occurred with the introduction of the sludge (McNee, 2004). Longer-term studies are required on sludge disposal in pit lakes. However, studies to date suggest that sludge disposal does not seem to negatively impact dissolved metal and TSS concentrations in the discharge waters.

Sludge in Backfill

The use of paste backfill is a common practice in the mining industry. Paste backfill integrates tailings, sludge and slag along with other wastes into backfill material to reduce the amount of waste to dispose on the mine surface. Paste backfill is defined as an engineered mixture of fine solid particles (with or without a binder) and water, containing between 72% and 85% solids by weight. Unlike slurry, particles in a paste mixture will not settle out of the mixture if allowed to remain stationary. It can be placed in stopes with or without binder addition depending on the strength requirements for the backfill. Improved pumping technology, environmental concerns, and the need for a low cost/high strength fill in mines, are driving mine operators to consider paste backfill as a tailings management and mine backfill alternative. Incorporating sludge into paste serves to both stabilize the sludge and allow for codisposal of wastes underground. The URSTM (Université du Québec en Abitib-Témiscamingue) and CANMET (Benzaazoua et al., 2005) are investigating the option of incorporating sludge in paste backfill (Fiset, et al. 2005). The objective of their study is to develop and to evaluate the performance of a novel cemented paste backfill technique consisting of incorporating various treatment sludges within the conventional paste mixture. They found that while the performance of the Portland cement based binders appeared to be negatively impacted by sludge addition, slag based cement seemed to benefit from sludge addition.

Landfill

Landfills are a common option used for disposal of hazardous waste. A landfill is defined as a disposal facility or part of a facility where hazardous waste in bulk or containerized form is placed in or on land, typically in excavated trenches, cells, or engineered depressions in the ground. The aim is to avoid any hydraulic connection between the wastes and the surrounding environment, particularly groundwater. Disposal by landfilling involves placement of wastes in a secure containment system that consists of double liners, a leak-detection system, a leachate-collection system, and a final cover (US Army Corps. of Engineers, 1994).

The EPA defines two types of landfills; sanitary, and secure or hazardous. Sanitary landfills are disposal sites for non-hazardous solid wastes spread in layers, compacted to the smallest practical volume, and covered by material applied at the end of each operating day. Secure chemical landfills are disposal sites for hazardous waste, selected and designed to minimize the chance of release of hazardous substances into the environment. Sludge is disposed in both secure and sanitary landfills.

Landfilling is becoming less of a viable option, as environmental problems and restrictive legislation are making landfills a buried liability (Pickell and Wunderlich, 1995). One of the specific issues regarding the practice of landfilling treatment sludge is solid-liquid separation. Due to the low solids content of the treatment sludge it requires significant dewatering and drying before it can be transported. There may be additional public concern with the transportation of sludge off the mine site to a landfill facility. Depending on the sludge, stabilization may be an added requirement.

Reprocessing of Sludges

Many sludges have potential economic value as they contain high concentrations of recoverable metals such as Zn and Cu. For instance, Cu ore normally contains less than 1% Cu, where Cu precipitate sludges from the printed wire board industry average 10% to 15% Cu (IPC, 2000). Acidic drainage treatment sludge can contain upwards of 22% Zn (Aubé and Zinck, 1999). Wastewater treatment sludges from electroplating operations, predominantly from the metal finishing and printed wire board industries, represent one of the largest sources in the United States of untapped metal-bearing secondary material amenable to metals recovery (Abrams, 2000).

Metal recovery from sludges has been discussed for decades. The cost of sludge reprocessing is often considered to be prohibitive and the process problematic. As a result, technologies for metal recovery from sludges are rarely adopted. However, with increasing environmental pressures and mining costs the option for metal recovery from treatments sludges becomes more attractive especially when coupled with the revenue from the recovered metals. With this in mind, we may see a move towards technologies that recover metals from mine wastes such as sludge.

There are two principal approaches used for metal recovery: hydrometallurgical and pyrometallurgical. Many of the hydrometallurgical approaches involve leaching of the sludge followed by solvent extraction or ion exchange, while the pyrometallurgical processes tend to involve metal recovery using smelting.

Hydrometallurgical recycling methods use wet chemistry to extract usable metals from sludges. While these methods have been in use for many years, they are currently receiving more attention due to their ability to extract and reuse metals from sludges. Zinck (2005) discusses options for metal recovery using hydrometallurgical processes in more detail.

Recovering metals present in treatment sludge through smelting is an attractive sludge management option. Depending on distance to the nearest smelter, transportation costs, quantities generated, and contaminants present, the mining industry may be able to use some of these options as alternatives to current disposal methods. Unlike hydrometallurgical options, metal recovery using pyrometallurgy requires sludge drying (via rotary dryer to less than 20% moisture). In addition, certain impurities in the sludge can have a negative impact on smelter performance. However, process upsets may be offset by advantages such as additional metal revenue and minimal costs (including liability) associated with surface sludge disposal. Examples of sites utilizing smelting practices to recover metals from sludge are given in Zinck (2005).

In the majority of these metal recovery processes, the heavy metals are recovered for revenue and environmental reasons. Typically, a sludge still remains but it is free of many of the metals of concern and is thus easier to effectively dispose of or reuse.

Stabilization/Solidification

Solidification/stabilization technology as applied to wastes uses physical and chemical processes to produce chemically stable solids with improved contaminant containment and handling characteristics. There are six main types of stabilization methods: sorption, lime-based, cement-based, thermoplastic techniques, polymeric and encapsulation.

Several studies have been conducted to investigate stabilization/solidification (S/S) techniques for metal hydroxide sludges (Tseng, 1998; Chang et al., 1999; Conner and Hoeffner, 1998). Treatment sludge typically consists of metal hydroxides, gypsum, unreacted lime and calcite. The solubility of metal hydroxides is pH dependent; each metal has its own metal precipitation domain. The majority of metals are soluble at pH below 6, and some anionic complexes (As, Cr) exist in the range of 10-12. The S/S process is an interesting technology for sludge treatment because it can convert the waste into an inert material independent of the metal solubility of each metal. Also, it is possible to control some physical and chemical parameters such as permeability, compressive strength and metal mobility by proper selection of chemical additive types and ratios. The strength development could be improved by increasing the curing temperatures, lowering the water to cement ratio, or using early strength Portland cement or $CaCl_2$ additives. Various waste solidification methods have been developed using Portland cement (Cohen and Petry, 1997; Fisher et al., 1990; Taub 1986; Bowlin and Seyman, 1989), fly ash (Gabr et al., 1995), fluidized-bed-combustion ash (Knoll and Behr-Andres, 1998), silicate (Bowlin and Seyman, 1989; Reimers et al., 1989) and phosphate (Rao et al., 2000).

Sludge characteristics have a great influence on the compressive strength of a solidified sample (Tseng, 1998). Concentrations of Zn, Cu, Pb and Cd may cause a large variation in setting time and significant reduction in physical strength (Tseng, 1998). Also, organic materials tend to interfere in the hydration of cement.

Limitations of the Portland cement-sludge mixture are related to the effect of the sludge on the setting and stability of the silicates and aluminates that form when Portland cement hydrates (Culliane and Jones, 1989). Also, transportation, operational and cement costs are important limiting factors. The availability of cements and of the pozzolanic material near the mining site is very important for economic reasons. Mixture designs must be optimized for each site because of sludge characteristic variation from site to site.

A recent CANMET study (Fiset et al., 2003) revealed that Portland cement could be used as a binder to chemically and physically stabilize treatment sludge. Other binding systems such as combinations of Portland cement and fly ash, Portland cement and slag, lime and fly ash and a phosphate binder were also evaluated. For two different stabilized sludges, compressive strength values typically ranging between 0.3 MPa and 3.0 MPa were obtained using 5 to 20% of binder. Fiset et al. (2003) estimated the cost to stabilize acidic drainage sludge with Portland cement and fly ash to be in the range of $5/tonne.

Vitrification is another method used to stabilize wastes. Vitrification, or molten glass processes, is solidification methods that employ heat up to 1,200°C to melt and convert waste materials into glass or other glass and crystalline products. Material, such as heavy metals and radionuclides, are incorporated into the glass structure, which is generally a relatively strong, durable material that is resistant to leaching. In addition to solids, waste materials can be liquids, or wet or dry sludges. Borosilicate and soda lime are the principal glass formers and provide the basic matrix of the vitrified product. Vitrification produces a very durable material but because of its very high cost (~$300/t) it is only recommended for extremely hazardous sludges.

Additional high temperature stabilization/recycling technologies are discussed by Zinck (2005) including thermal bonding and sludge slagging.

Sludge Reuse Options

For the most part, the components that make up sludge, such as gypsum, calcite and ferrihydrite are minerals that are utilized as raw material in the manufacturing of construction materials or other products. It is often the heavy metal components that discourage the reuse of acidic drainage sludge. Further work in the area of sludge reuse is needed. Some studies have looked at the utilization of sludge in construction materials and water treatment; however the adoption of these technologies is limited.

Building Materials

The inorganic components in sludge can be used for the production of building materials (Levlin, 1998). In this option, the environmentally hazardous contaminants are bound as mineral to the material and utilization of sludge reduces mining of raw material for production of building material. The high Al content of sludge produced from treatment of acidic drainage at some coal and gold mines may be useful for production of aluminous cement (Lubarski et al., 1996).

Pulverized sludge ash and dewatered sludge/clay slurries have been used successfully in lightweight concrete applications without influencing the product's bulk properties (Tay and Show, 1991). Sludge based concrete has been deemed suitable for load-bearing walls, pavements, and sewers (Lisk, 1989). The sludge proportion and firing temperature are key items to the compressive strength of the material.

Many of the constituents in sludge are the same as that used in cement manufacturing. Calcite, gypsum, silica, Al, Fe and Mn are common raw materials for cement. Simonyi et al. (1977) found that acidic drainage sludge could be added to cement in amounts less than 5% with little or no net effect on compressive strength. Other studies (Hwa et al., 2004) have suggested that sludge can replace up to as much as 30% Portland cement in blended cement. As with most reuse options, the sludge requires drying before it can be utilized. The practice of utilizing treatment sludge in cement manufacturing has been adopted in some specific sites in the United States (EPA, 2000).

Agricultural Land Applications

For low metal content sludges, such as sludges from coal mining operations, it was found that the excess alkalinity present in the sludge can be utilized to raise soil pH. In an attempt to limit the use of landfills, the Minnesota Pollution Control Agency (MPCA) (1999) examined the land application of coal ash as a fertilizer. The blend of agricultural lime and coal ash were found to contain useful nutrients such as S and B. In order to prevent build up of constituents of concern the MPCA place limits for As, Cd, Cu, Pb, Hg, Ni, Se, and Zn on the permit. While this option has very limited application due to public health and other social concerns, it demonstrates that the non-toxic sludge components can be beneficial to other industries.

Metal Adsorbent in Industrial Wastewater Treatment

The iron (ferrihydrite) component of sludge is highly adsorbent. Several researchers (Edwards and Benjamin, 1989) have conducted studies on ferrihydrite ($Fe(OH)_3$) and found it to be highly effective for metal removal. Both sludge dosage and pH affect metal removal using sludge from lime treatment plants. Shultz and Xie (2002) found that metal recovery was most effective at pH 7.8. Increasing the sludge dosage increases the metal removal. Copper was found to be the easiest metal to remove. Zinc was also readily removed at pH 7.8. Extreme pH conditions, greater than pH 11, are necessary to remove Cd (Edwards and Benjamin, 1989) and Mn.

Similarly, treatment sludge has also been used to remove carcinogenic dyes/colors from wastewater. Netpradit et al. (2003) found that dye adsorption was greatest at pH 8-9, close to the zero point charge (pH_{zpc}) and the maximum adsorbent capacity of the sludge was determined to be 48-62 mg dye per gram sludge.

Carbon Dioxide Sequestration

The same mechanism that generates CO_2 in the production of lime can be utilized to sequester carbon dioxide. CO_2 gas can react with treatment sludges and Fe-rich metallurgical residues to produce solid Ca, Mg and Fe carbonates while stabilizing the sludge/residue and its impurities. There is evidence that these reactions occur naturally in sludge/residue ponds, but the method requires development and optimization. An estimated 60,000 t CO_2 annually could be sequestered in Canada (not including steel mill sludges) enhancing the stability and compactness of sludges and residues.

Other Uses

Spray-dried sludge can be utilized as a rock dust substitute for explosion control (Simonyi et al., 1977). In addition, sludge 'gravel' can be produced by drying, pulverizing, pelletizing, and sintering to produce a lightweight, high strength aggregate (Hwa et al., 2004).

Reclamation

Once sufficiently dewatered, natural colonization of vegetation on alkaline ARD treatment sludge is very slow making it prone to erosion and dusting. These sludges pose many of the same reclamation constraints encountered with fine-grained tailings, such as small particle size, compaction, lack of nutrients, high metal content and, in some cases, salinity. However, the two biggest reclamation challenges are alkaline pH and lack of nutrient availability (Tisch et al., 2004). While acidic tailings can be limed to improve or optimize pH and metal availability, purposely decreasing the pH of treatment sludge is not an option due to the high risk of metal leaching. In addition, metal toxicity can occur, as both Al and Zn are toxic to roots at relatively low concentrations (Hogan and Rauser, 1979; Rauser and Winterhalder, 1985).

While the high pH is effective for limiting the availability of metals for uptake by plants, it can also severely limit the availability of plant nutrients, especially P. As discussed earlier, lime treatment sludges are composed primarily of calcite, gypsum and a large amorphous ferrihydrite-like phase. While this ferrihydrite phase is an effective scavenger of metal species such as Al, Cu, Fe, Mg, Na, Ni and Zn (Zinck and Dutrizac, 1998; Zinck et al., 1997), it is also an important sorbent in soil (Guzman et al., 1994). Inorganic fertilizers applied to the sludge will quickly be rendered unavailable to plants both through precipitation with Ca and adsorption to ferrihydrite. As a result, fertilization of alkaline sludges with inorganic fertilizers tends to be very ineffective and expensive. The use of acid generating fertilizers such as those containing NH_4^+ may assist in releasing P, but any associated decrease in pH is likely to also result in increased metal release (Tisch et al., 2004). The introduction of organic matter or the use of organic fertilizers (including biosolids, papermill sludge etc.) may be a more efficient method of limiting rapid phosphorus fixation.

The use of alkaline tolerant and P efficient species in reclaiming these areas will certainly assist in overcoming some or all of the hurdles associated with treatment sludge. However, the more common reclamation species, at least those that develop extensive root systems that are more efficient in terms of erosion control, tend to be only mildly alkaline tolerant. Species such as Alkali Grass (*Pucinellia distans*) have shown promise as being a key component at some sites (Tisch et al., 2004).

Conclusions

Sludge management is an ever-increasing issue as the inventory of sludge continues to grow through perpetual pump and treat. Current sludge management practices are ad hoc and frequently do not address long-term storage, and in some cases, long-term stability issues. While there is a plethora of disposal strategies available for sludges, many have not been fully investigated and monitoring data on the performance of these technologies is limited and not readily available. Further research is required into disposal options that can recover metal, densify existing sludge or safely dispose of the material in a way that it can either be easily reclaimed or disposed in mine workings. Promising options must be both technologically feasible and cost effective. In addition, sludge management options must be able to meet increasing environmental standards and pressures. With such limited data available on sludge characteristics, standardized methods, long-term laboratory and field performance, it is important to focus efforts now to address some of these gaps in the knowledge base.

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International ARD Treatment and Sludge Management Survey[1]

Janice Zinck[2] and Wesley Griffith[3]

[2] Natural Resources Canada – CANMET-MMSL, Ottawa, ON, Canada, K1A 0G1, jzinck@nrcan.gc.ca

[3] Natural Resources Canada – CANMET-MMSL, Ottawa, ON, Canada, K1A 0G1, wesgriff@nrcan.gc.ca

ABSTRACT

Acid rock drainage (ARD) treatment and sludge management are two important facets of mine site environmental control practices. Most sites employ some form of treatment to address ARD issues. The type of treatment implemented varies from site to site. Previously there was no single, comprehensive database containing treatment and sludge management information for mine sites. CANMET-MMSL (Natural Resources Canada) has just completed an extensive survey of ARD treatment and sludge management practices at over 100 operations in Canada and around the world. A detailed questionnaire was developed and used to survey mining companies, government organizations, consulting firms and others. The information collected was compiled into an interactive database. This paper will discuss the results of this survey such as: operation type and site status; ARD sources, composition and flowrate; treatment methods; reagent usage; costing, treatment issues; novel and best practices. As well the paper will elucidate on sludge management options, including sludge production rates, composition and disposal methods in addition to sludge handling challenges and opportunities. The database will provide operators and regulators with the information necessary to make informed decisions regarding ARD treatment and sludge management practices.

Additional Key Words: acid mine drainage, lime, active treatment, disposal, metal recovery, costing.

INTRODUCTION

Most sites require treatment of surface, process and mine water prior to discharge. The type of treatment implemented varies from site to site. Some sites use chemical treatment, while other sites use biological or separation technologies. Information on various treatment applications is often limited and process specifics, especially cost data are often difficult to obtain. Previously there was no single, comprehensive database containing treatment and sludge management information for mine sites. At the request of the Mine Environment Neutral Drainage (MEND) Program, CANMET-MMSL (Natural Resources Canada) conducted a survey of acidic drainage treatment and sludge management practices and developed a comprehensive database.

Data Collection Process

A detailed survey was prepared that requested information such as site background and history, acidic drainage characteristics, type of treatment and reagents used, treatment issues, sludge composition, sludge management practices and issues.

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[1] Paper presented at Securing the Future and 8th ICARD, June 23-26, 2009, Skellefteå, Sweden.

A list of contacts was developed including personnel from mining associations, companies, and federal, territorial and provincial governments. After which, introductory letters attached with a survey questionnaire were sent to the various contacts. The response from these questionnaires accounted for about 52% of the database. The remaining 48% of the data was extracted from technical papers, company press releases, website information, and government public releases. The data was compiled into an interactive database. This paper summarizes some the information contained in the database. The full report is available through MEND (Zinck and Griffith, 2009).

Site Information

Data on treatment practices and sludge management was collected on over 100 sites. Most sites are in Canada but other sites in USA, UK, Australia, Mexico, Peru, China, South Africa, New Zealand and Hungary also populate the database. Figure 1 shows the site locations.

Figure 1. Locations of treatment sites in database.

Of the over one hundred sites in the database the majority are base and precious metal sites. Figure 2 graphically displays this information. Half of the sites are in operation, while the others are orphaned, abandoned or closed sites (Figure 3).

The survey focused on the treatment of acidic drainage; however several sites reported the treatment of a variety of contaminated waters including process, surface and mine waters as well as neutral drainage. The database captured information on the composition and flowrate of these waste streams, as well as information on the effluent receiving environment.

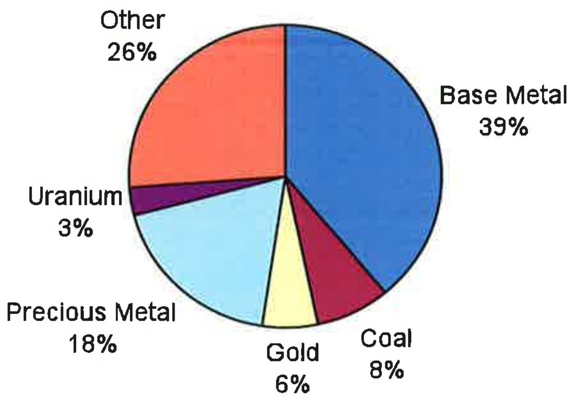

Figure 3. Mine site status

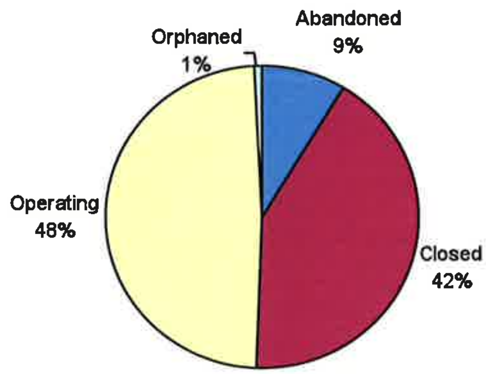

Figure 2. Type of mine operation

TREATMENT PRACTICES

The majority of sites surveyed reported that they expect to treat *in perpetuity* and as such their choice of treatment is critical for not only economic but environmental reasons. There are a variety of treatment processes that can be applied either in isolation or in combination to remove metals and neutralize acidity (MEND 5.4.2e, 2000; Aubé and Zinck, 2003).

Process Components

Figure 4 presents an array of treatment processes that were reported in the survey. Active treatment processes are most prevalent with chemical treatment processes more common than physical (membrane) and biological treatment processes combined. Roughly the same number of basic (simple) treatment processes as high density sludge (HDS) processes are in used. Many sites are moving towards HDS processes that employ mechanical agitation, flocculation, and sludge recycle to optimize treatment performance, increase sludge density and reduce reagent consumption. Other sites plan to modify their basic treatment systems to improve performance without investing in the high capital cost of a high density sludge treatment systems. For example, some sites will utilize reactors without sludge recycle to enhance mixing and precipitation; while others will add a simple sludge recycle line back to the start of their process. Treatment is generally site specific, and what works for one site may not be suited for another.

Membrane separation and biosulphide treatment are also practiced at several sites. The adoption of these relatively new technologies is increasing as regulations for lower effluent discharge criteria and demand for 'zero discharge' are on the rise.

If ferrous concentrations are significant (>100-200 mg/L), aeration is often required to oxidize the iron to a more stable ferric form. About 10% of the sites reported using aeration as an addition to their processes. Aeration is a common component in HDS systems and in this case aeration would not be considered an add-on.

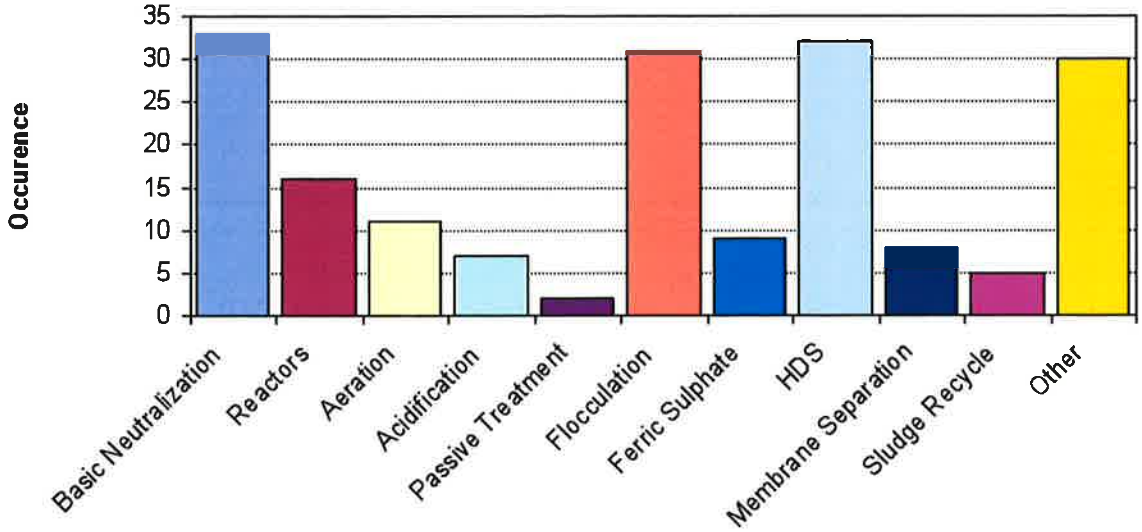

Figure 4. Range of treatment processes reported. Other includes biosulphide process, pipe reactor, pit lake treatment, Rotating Cylinder Treatment System™ RCTS technology.

Reagents

Lime is the most prominent reagent used for sites that apply chemical treatment. Lime was used in one of three forms: quicklime (CaO, without slaking) – 6%; hydrated lime ($Ca(OH)_2$) – 59%; and slaked lime ($Ca(OH)_2$ slaked on site) – 35%. Slaked lime can be prepared with either a ball mill, paste or slurry slakers. In the database, slurry slakers were most frequently recorded. More information on lime slaking can be found in Zinck and Aubé (2000) and Hassibi (1999). Caustic soda ($NaOH$) is also used for hydrolysis and acidity neutralization. Caustic soda is very efficient and reacts rapidly; however it is almost ten times more expensive than lime and sludge densification is more challenging. Limestone is also used for hydrolysis and neutralization, but its application is limited as it armours easily and can only neutralize to pH ~7. Figure 5 shows the reagents used for treatment.

To treat low strength waters (low total dissolved solids (TDS)), sites will often apply a coagulant such as ferric sulphate to improve metal removal by surface adsorption and co-precipitation. The iron sulphate quickly dissolves and causes the iron to re-precipitate as ferric hydroxide/ferrihydrite. Ferric sulphate serves to agglomerate the precipitates and also to adsorb any metals remaining in solution. Larger particles are formed by combining with the ferric hydroxide and settle much faster than the smaller particles. Ferric sulphate was used by 9% of the sites (Figure 5). Barium chloride is used for radium-226 removal and accounted for a fraction of the reagent usage.

Depending on the contaminants to treat and the pH set-point, the effluent pH may require adjustment prior to discharge. Most sites sparge carbon dioxide to decrease the pH prior to discharge while a few sites use sulphuric acid or a combination of both (Figure 5).

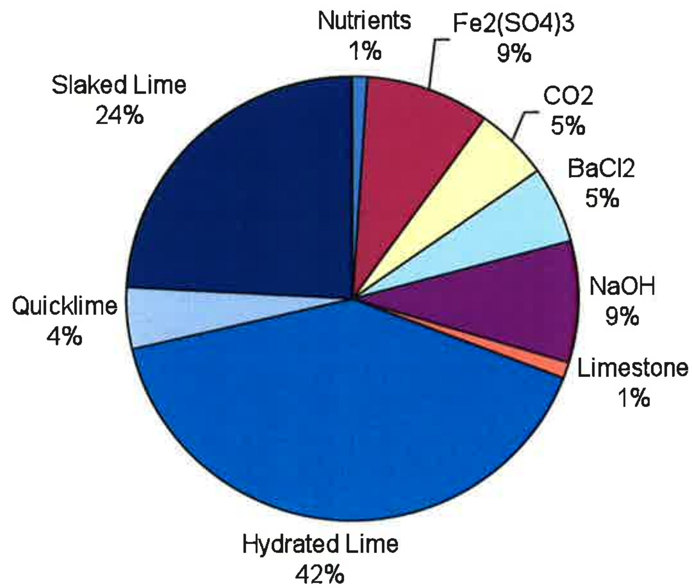

Figure 5. Type of reagents used for treatment.

Flocculation

The primary purpose of flocculation is to agglomerate the finer particles and enhance settling to obtain a clear effluent. Flocculation aids in clarification by promoting the formation of flocs which settle more rapidly. The flocculant type and concentration have a major impact on effluent quality and sludge properties and typically account for 2-5% of treatment costs (Zinck and Aubé, 2000). Flocculant was used in approximately 32% of the treatment operations (Figure 5) and a range of flocculant types were recorded (Table 1). Magnafloc 10 was the most common flocculant used. It is a non-toxic high molecular weight anionic polyacrylamide flocculant.

Table 1: Various types of flocculant used in mine water treatment.

Name	Number of sites
Amerifloc 300	1
Flomin SNF	1
GE Betz Polyfloc 1103	1
Golden West 1883A	1
Magnafloc 10	10
Magnafloc 155	1
Magnafloc 156 (E10)	3
Magnafloc 338	5
Magnafloc 1011	4
Polyclear 2748	1
Polyfloc AE 1125	1
Potassium Permanganate	1
Powerfloc 3056 SH	1
Super Floc A110	1

Solid/Liquid Separation
Solid/liquid separation is a critical step in any water treatment processes whether it is simple gravity separation or more sophisticated mechanical separation. All sites with active treatment have some type of solid/liquid (S/L) separation. The types of S/L separation used, as recorded by the survey, are shown in Figure 6. Over 50% of respondents used a conventional thickener/clarifier while six sites reported using lamella clarifiers. Settling ponds were also commonly used. For enhanced sludge dewatering, some sites reported using filter presses or centrifugation. To improve effluent quality and to reduce turbidity, sites employ polishing ponds and sand filters (Figure 6).

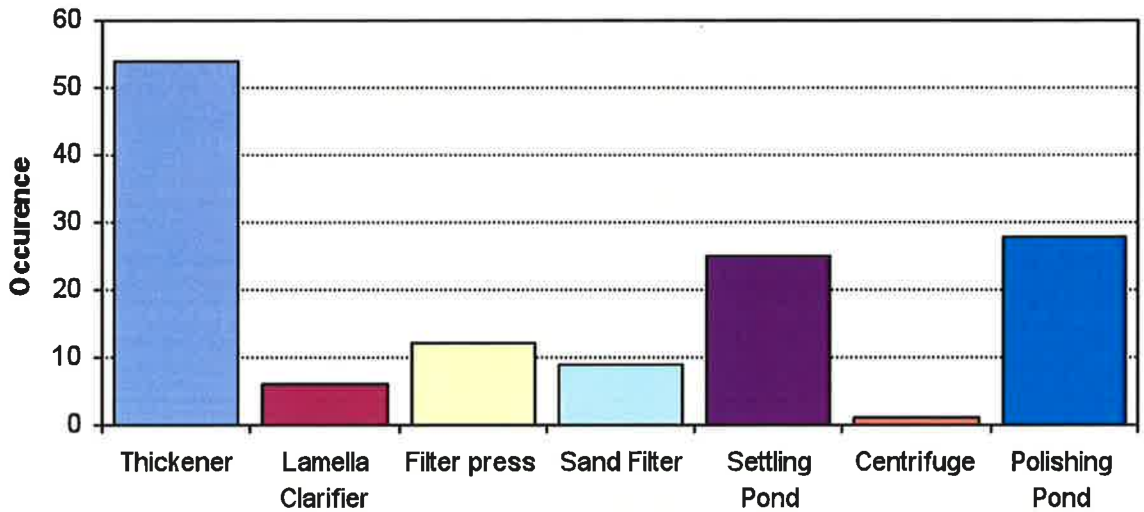

Figure 6. Solid/liquid separation methods used.

Treatment Costs
The database contains details on capital and operating treatment costs. Some sites recorded treatment costs as low as \$0.02 US/m^3 for basic treatment and \$0.06 US/m^3 for HDS treatment. Passive and semi passive treatment costs were variable while no costs per cubic metre were given for either membrane treatment or biosulphide precipitation. Sites were asked to provide a breakdown of annual operating costs (e.g. labour, reagents, power, etc.). The averaged breakdown for all sites reporting is given in Figure 7. The majority of the costs are for reagents and labour.

Treatment Issues
As part of the survey, respondents were invited to list treatment issues. Many respondents listed gypsum scaling of the process equipment and lime slurry lines as their major concern. Some noted that the application of sludge recycle/HDS treatment reduced scaling. Other issues noted were: the control of total suspended solids (TSS) in the final effluent, managing high flows, algal blooms in collection ponds, poor settling, lime handling and mixing, polymer mixing during winter months, difficulty in maintaining high density sludge, inefficient mixing, and acidity in the water due to residual thiosulfate (S_2O_3) derived from the mill processing.

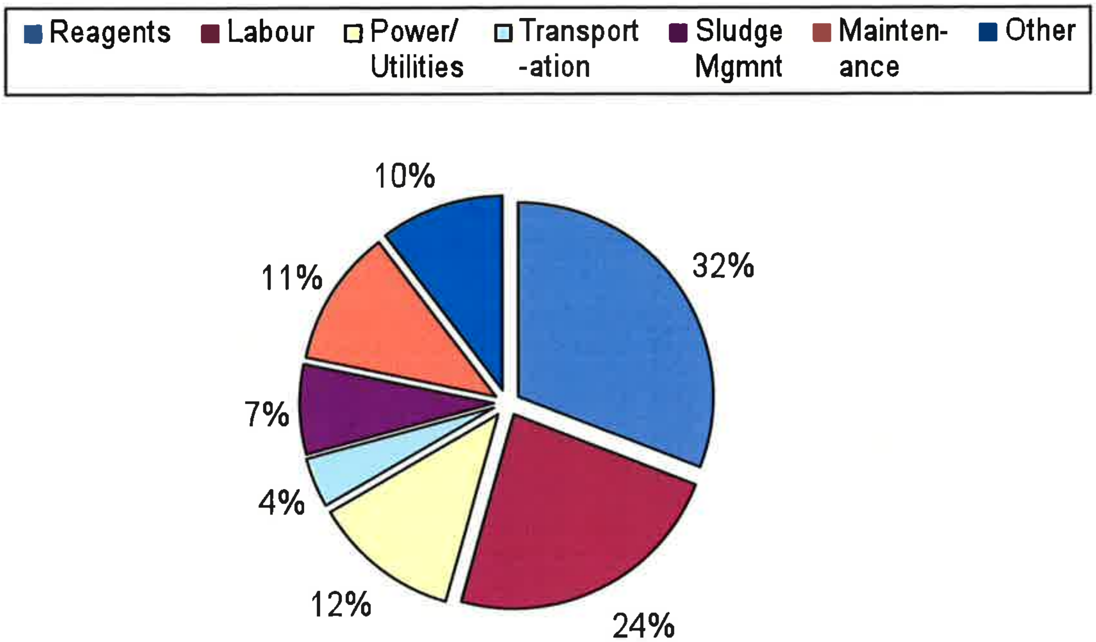

Figure 7. Annual treatment cost breakdown.

SLUDGE MANAGEMENT

Most treatment processes will require some type of residue management whether it be iron-metal-gypsum sludge from lime treatment, residue from treating membrane concentrate, uneconomic residuals from biosulphide treatment or the substrate from passive treatment systems.

Sludge Disposal Practices

Figure 8 presents the type of sludge management practices reported. Details on these and other sludge disposal and management options are available in MEND 3.42.3 (Zinck, 2005).

The majority of the sites surveyed utilize sludge ponds for dewatering and permanent sludge disposal. Disposal in a pond can minimize potential remobilization as the sludge is isolated from the acidic waste. However, many sites prefer to have one waste disposal area and choose to dispose of their sludge with tailings. There are several methods to co-dispose sludge with tailings. One method involves mixing the sludge with tailings (~ 2-5% sludge in tailings) prior to disposal in the tailings pond. More commonly, sites will utilize the sludge as an alkaline rich cover over acidic tailings, while other sites will simply dispose of the sludge in the pond (neither mixed nor as a cover). Some sites, such as NBCoal, have had success disposing of their sludge in their waste rock dumps (Coleman and Butler, 2004).

If site availability, mine capacity and configuration are appropriate, sludge disposal in abandoned mine workings offers an excellent sludge management strategy. Benefits of this option include potential for the sludge to assist in mine water neutralization and minimization of surface reclamation. Six sites reported sludge disposal in mine workings.

Disposal in an abandoned open pit is one of the most economical solutions for sludge storage, if a pit is within a reasonable pumping distance from the treatment plant. Many companies frequently take advantage of open pits available on site as an appropriate short or long-term sludge disposal option. McNee (2004) found that disposing sludge in a pit lake could cause increased suspended solids, productivity, dissolved oxygen and entrainment in the pit lake and ultimately could result in whole-lake mixing. Six sites reported using pits for sludge disposal. Landfill disposal is necessary for some sites that do not possess sufficient area for on-site disposal. No sites noted reprocessing their sludge at this time.

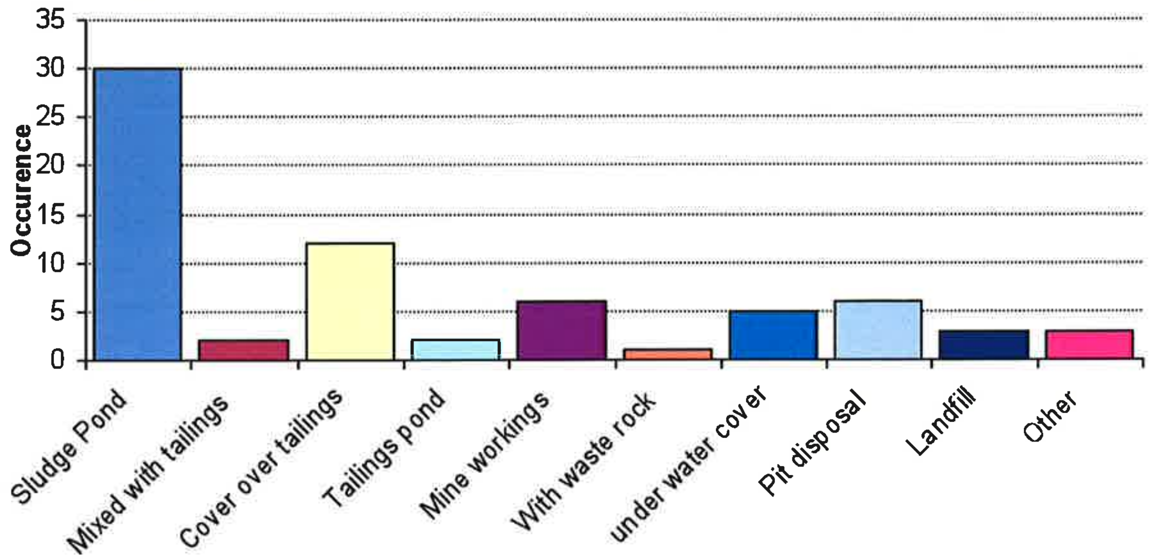

Figure 8. Sludge management practices. "Other"– includes heap leach pad, and hazardous waste disposal.

Sludge Characteristics and Production

The database includes information on the chemical composition and to a lesser extent the mineralogy of the sludge produced. Some sites indicate that leach testing had been performed on the sludge. If completed, the leach tests tended to be batch type tests (TCLP- Toxicity Characteristic Leaching Procedure, SWEP- Special Waste Extraction Procedure). Much of the data on sludge characteristics originates from earlier MEND work (Zinck et al., 1997).

The annual sludge production rate and long term storage capacity were also captured by the survey. Figure 9 presents the sludge production rate for some site in dry tonnes per year. One site not recorded on the graph produced 135,000 dry t/y. It is important to note that considering the high water content in many sludges, volumes (m^3) are frequently 20-30 times that of recorded tonnages.

Disposal Costs

The costs associated with sludge disposal are not well recorded. The survey found that only a fraction of sites examined had disposal cost data. Many disposal costs are hidden within other treatment and operation costs. The annual costs recorded in this survey ranged from ~$10k to >$100k per annum (Figure 10). However, other sites have been known to spend over $1M per annum on sludge dredging costs alone. This inconsistency in data highlights the need to better quantify the true costs associated with sludge disposal. Figure 7, presented earlier, showed that on average sludge disposal accounts for about 7% of the overall treatment cost.

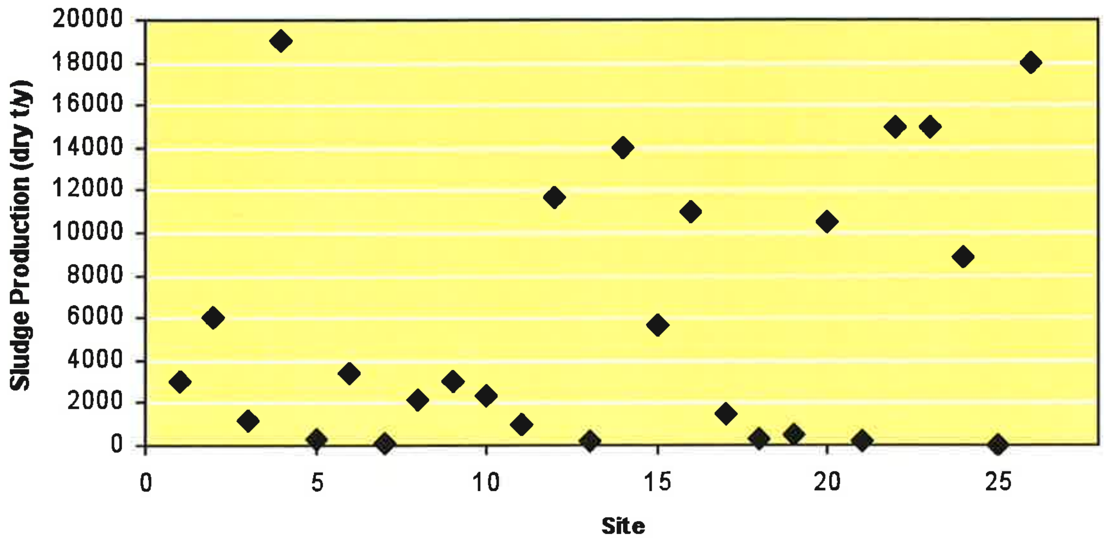

Figure 9. Sludge production rates (dry t/y) recorded through the survey.

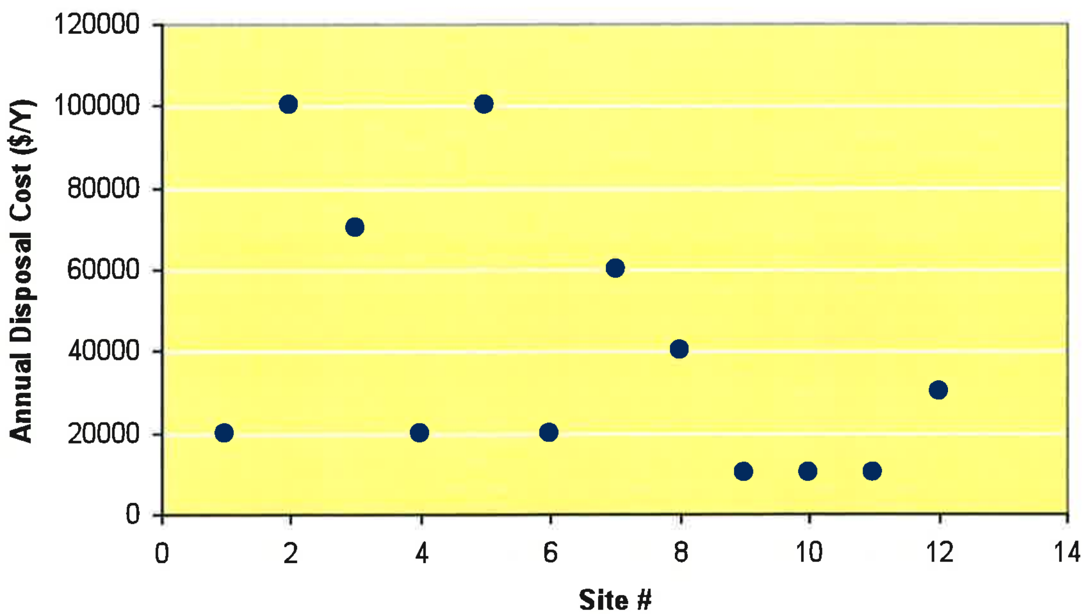

Figure 10. Sludge disposal costs ($US/y) recorded through the survey.

Sludge Management Issues

Several issues associated with disposal and management of the treatment sludge were highlighted during the survey. Sludge desiccation, dusting, and the inability to drive machinery on the sludge for dust control were noted. Some sites noted 'running out of room' to dispose the sludge and difficulty in dredging sludge ponds. High disposal costs and the stability of the sludge were also noted as issues.

CONCLUSIONS

The database contains valuable information on various aspects related to mine water treatment and the management of the resultant sludge. The database will serve as a clearinghouse for relevant treatment information and provide information on best practices and novel strategies. The data can be used to draw useful correlations between treatment parameter with the intent to improve treatment performance in terms of economic and environmental performance. While the data contained in the database has been summarized for this paper, additional details can be found in MEND report 3.43.1 (Zinck and Griffith, 2009). The database will be continually updated with new site data. The electronic version of the database will be managed by Natural Resources Canada.

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Evaluation of Sludge Management Options

Janice Zinck[1] and Wesley Griffith[1]

[1]CANMET Mining and Mineral Sciences Laboratories, Natural Resources Canada, Ottawa, ON, jzinck@nrcan.gc.ca

Abstract
With many sites opting to pump and treat in perpetuity the question remains what is the most effective way to manage the sludge? A recent survey of treatment options has documented that there are a variety of practices being used to manage the sludge produced from the treatment of acidic drainage and process effluent. The selection of the most appropriate option is clearly site specific and depends on an array of factors including composition, climate, topography, other waste streams, and economics. However, some options outperform others in terms of long term stability of the precipitated/ adsorbed metals, metal recovery potential, economics, etc. Using data collected from long-term sludge disposal studies, detailed sludge characterization and plant/management information this paper will discuss the performance of various sludge management strategies and their applicability under different conditions. Options to be discussed include pond disposal, codisposal with other waste, disposal in underground workings, re-processing opportunities and sludge as an oxygen barrier or metal sorbent.

Key Words: lime treatment, codisposal, reprocessing, metal recovery, acidic drainage, effluent

Introduction
Most if not all sites will be required to treat mine effluent or acidic drainage at some point during the mining life cycle. Regardless of the treatment option applied (chemical, biological or physical) the result is a metal-laden residue or sludge that requires further management. The options available to manage the residue are directly dependant on several factors which include the mass of sludge produced, whether the mine is operating or closed, dewatering ability of the sludge, sludge density (moisture content), sludge volume, chemical and physical stability, sludge composition, disposal location availability and economics (Zinck 2005). The ability of sludge to dewater may limit the options available. Sludge that can dewater without mechanical assistance will not only reduce the area required for disposal, but also can be more readily reprocessed. The ability of sludge to dewater depends on its particle size, morphology and surface charge. As a particle deviates from a spherical shape, the surface area per unit volume increases, resulting in reduced settleability and decreased dewatering rate. These characteristics are linked directly to the water treatment process that generates the sludge and to the raw water chemistry (Zinck 2005).

Several options are available for sludge management ranging from simple pond disposal, to placement in underground workings to recovery of sludge components by reprocessing (Figure 1). This paper describes several of these options and where possible provides performance data.

Resource Recovery
Sludges provide potential sources for recoverable metals and many sludges contain high concentrations of metals such as zinc and copper, which offer economic opportunity for recovery. For instance, copper ore normally contains less than 1% copper, where copper precipitate sludges from the printed wire board industry average 10% to 15% copper (IPC 2000), copper in treatment sludge is typically an order of magnitude lower (Zinck *et al.* 1997). Acidic drainage treatment sludge can contain upwards of 22% zinc (Aubé and Zinck 1999). Abrams (2000) states that one of the largest sources of untapped metal-bearing secondary material amenable to metals recovery in the US is treatment sludge from electroplating operations.

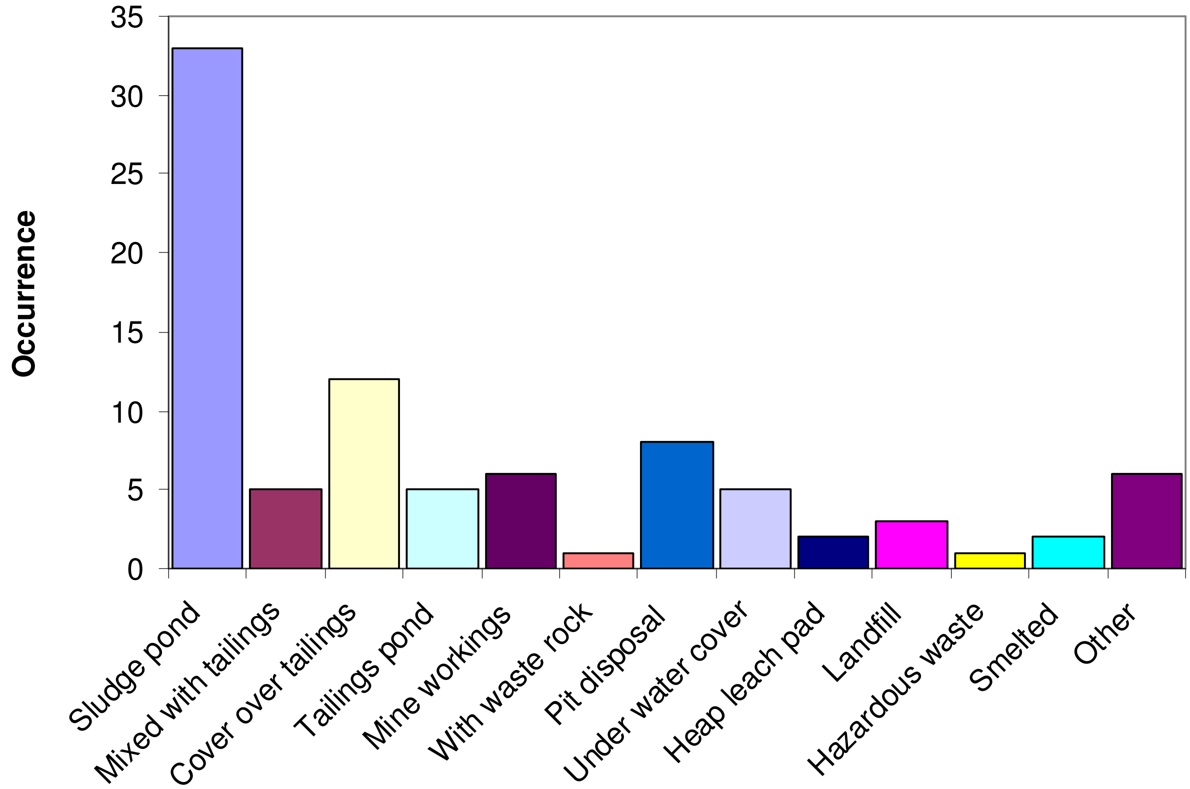

Figure 1: Sludge management options recorded (Zinck and Griffith 2012).

Two principal approaches are used for metal recovery: hydrometallurgical and pyrometallurgical processing. Many of the hydrometallurgical approaches involve leaching of the sludge followed by solvent extraction or ion exchange, while the pyrometallurgical processes tend to involve metal recovery using smelting.

The extraction of zinc from a zinc-bearing treatment sludge can be achieved with alkaline solutions. In a recent study, Fiset *et al*. 2009 proved that sodium hydroxide was a more effective lixiviant than ammonia to recover zinc from hydroxide sludge. The zinc was mobilized as the NaOH attacked the ferrihydrite phase, as evidenced by the dissolution of small amounts of iron. Despite its strong complexing affinity for zinc, ammonia gave relatively low zinc extractions when applied in dilute solutions. The efficiency of NaOH increased considerably with increasing concentration, with 2M NaOH found to be the optimum concentration. A preliminary batch counter-current circuit showed that up to 80% of Zn could be extracted in three stages with high selectivity. The precipitation of ZnS from the pregnant leach solution was found to be technically feasible and this approach would allow the recovery of Zn in a marketable form and regenerate the NaOH solution for recycling.

Recovering metals present in treatment sludge through smelting is an attractive sludge management option. Depending on distance to the nearest smelter, transportation costs, quantities generated, and contaminants present, the mining industry may be able to use some of these options as alternatives to current disposal methods. Unlike hydrometallurgical options, metal recovery using pyrometallurgy requires sludge drying (to less than 20% moisture). In addition, certain impurities in the sludge can have a negative impact on smelter performance. However, process upsets may be offset by advantages such as additional metal revenue and minimal costs (including liability) associated with surface sludge disposal.

Sludge Reuse Options

For the most part, the components that make up sludge, such as gypsum, calcite and ferrihydrite are minerals that are utilized as raw material in the manufacturing of other products. It is often the heavy metal components that discourage the reuse of acidic drainage sludge. There is significant potential to reuse all or part of the treatment sludge produced and while some studies have developed sludge reuse options, the adoption of these technologies is limited.

Building materials

Calcite, gypsum, silica, aluminum, iron and magnesium are common raw materials for cement. Simonyi *et al.* (1977) found that acidic drainage sludge could be added to cement in amounts less than 5% with little or no net effect on compressive strength. Other studies (Hwa *et al.* 2004) suggested that sludge could replace up to as much as 30% Portland cement in blended cement. As with most reuse options, the sludge requires drying before it can be utilized. Coloured concrete can be formed through the addition of iron-sludge (Silva *et al.* 2011) making for a potential attractive commercial product. The practice of utilizing treatment sludge in cement manufacturing has been adopted in some specific sites in the United States (EPA 2000). The sludge proportion and firing temperature are key to the compressive strength of the material.

Pigments

The major component of sludge is ferric (oxy) hydroxide. Depending on the type of iron precipitate, a range of distinctive ochre colours will be produced; yellow for goethite to orange-brown for ferrihydrite to red for hematite (Schwertmann and Cornell 2000). Through selective precipitation Silva *et al.* (2011) produced iron pigments for use in paints and concrete. Hedin Environmental's Iron Oxide Recovery, Inc. (IOR) specializes in the production of pigment-grade iron oxide from abandoned coal mine drainage. The IOR process removes iron from polluted mine water through precipitation as iron oxide. The patented technology (Hedin 1999) consists of interconnected ponds that are designed to promote the formation of iron oxide solids and facilitate their efficient recovery. Over time, the iron oxide is removed from the production ponds, cleaned, dewatered, and transported to the processing facility for drying, milling, and packaging. Methods are being developed that will decrease the processing costs so that iron oxide can be produced passively from mine drainage in a profitable manner (Hedin 2006).

Metal adsorbent

The iron (ferrihydrite) component of sludge is highly adsorbent. Several researchers (Edwards and Benjamin 1989) conducted studies on ferrihydrite and found it to be highly effective for metal removal. Both sludge dosage and pH affect metal removal using sludge from lime treatment plants. Shultz and Xie (2002) found that metal recovery was most effective at pH 7.8. Increasing the sludge dosage increased the metal removal. Copper was found to be the easiest metal to remove. Zinc was also readily removed at pH 7.8 Extreme pH conditions, greater than pH 11, are necessary to remove cadmium (Edwards and Benjamin 1989) and manganese.

Sibrell *et al.* (2010) determined that drainage sludge could be beneficially used to sequester phosphorus from the environment, while at the same time decreasing the expense of sludge disposal. Similarly, treatment sludge has been used to remove carcinogenic dyes/colors from wastewater. Netpradit *et al.* (2003) found that dye adsorption was greatest at pH 8-9, close to the zero point charge (pH_{zpc}) and the maximum adsorbent capacity of the sludge was determined to be 48-62 mg dye per gram sludge. The efficiency of the adsorption capacity of sludge is highest in the slightly basic to circa-neutral pH range.

Disposal Options

If sludge reprocessing or reuse is not feasible then the sludge must be disposed. Sludge disposal involves three principle steps, namely solid-liquid separation, sludge dewatering and disposal. Several options exist if the treatment sludge produced requires final disposal. The selection of each of these options depends on various factors such as composition, stability, moisture content, operating status, and site conditions.

Pond disposal

Many sites utilize ponds as an efficient sludge management option (Figure 1). The sludge is pumped to a settling pond where solid-liquid separation, dewatering and in many cases disposal occur simultaneously. While settling and disposal in the same pond requires large surface areas, this approach is simple and requires only minimal design and construction considerations (Lovell 1973). In this discussion pond disposal refers to long-term disposal of the sludge in an impoundment.

Issues associated with pond disposal tend to be minimal. Wind suspension and dusting present problems at some sites, particularly in arid or northern regions. Due to the surface area required, land use can be a challenge for some sites. Disposal area is not a present concern at most Canadian sites, but with perpetual chemical treatment it may become an issue. Due to the thixiotropic nature of sludges (viscosity decreases as shear strength increases), pond failure could present some concerns although not to the same extent as with tailings impoundments. However, in a pond environment, either with or without a water cover, the degree of metal leaching is expected to be minimal, as the excess alkalinity available in the sludge is enough to sustain a moderate pH for decades, even centuries (Zinck *et al.* 1997).

Sludge disposal in a pond environment can be either subaerial or subaqueous. In a subaerial environment, the sludge is exposed to weathering conditions. Sludge cracking due to moisture loss at the surface is prevalent, causing an increase in surface water infiltration. Under these conditions, sludge dewatering occurs at the surface while the majority of the sludge at depth is still very moist.

A multi-year column leaching study (Zinck *et al.* 2010) was undertaken to ascertain the degree to which metals are mobilized from sludge disposed in settling ponds. For the sludges studied, the results (Figure 2) showed that metal mobility was not significant for the given leaching period. As long as the buffering capacity was available, metal mobility was minimal. However, the sludge samples showed higher zinc mobility during the leaching study, but the pH remained neutral. In general, metal and sulphate concentrations decreased with time below regulated limits.

Where sludge leaching is a concern, the application of a water cover (subaqueous) proves to be effective in reducing metal mobility. In the column leaching laboratory investigation, sludge studied was found to be more chemically stable when a water cover was applied to the pond disposal scenario. In this case, the amount of Cd, Cu, Mg and Zn mobilized was significantly lower with a water cover compared to without. The presence of a water cover over the sludge provided better distribution of the alkalinity and buffering capacity resulting in better pH control and lower metal mobility. Water covers may reduce metal mobility (e.g. zinc) by as much as 10%. Detailed mineralogy and chemical analyses conducted on the samples before and after column leaching revealed significant gypsum depletion in the sludge and a reduction in calcium and sulphate concentration in the solid phase.

The cost of pond sludge disposal depends on the production rate and the stability of the sludge. However, this method of disposal is relatively inexpensive. Unfortunately, ponds are often under-designed to meet sludge management requirements and frequently fill up prematurely. Mechanical sludge removal can cost approximately $5 to as much $30 per tonne for removal with a truck and backhoe. For example, Kidd - Metallurgical Site (Timmins, Ontario) spends upwards of $1 million per year on dredging costs (Scott 2004). Ackman (1982) evaluated sludge removal techniques in terms of storage capacity, economics, maintenance and versatility. Due to the high long-term maintenance costs of dredging, it is best if the sludge can be disposed of long-term in the pond in order to avoid frequent and costly sludge removal from the pond. If long-term pond disposal is not an option, the sludge must be removed and disposed of in a more suitable, site-specific location (e.g. in underground workings).

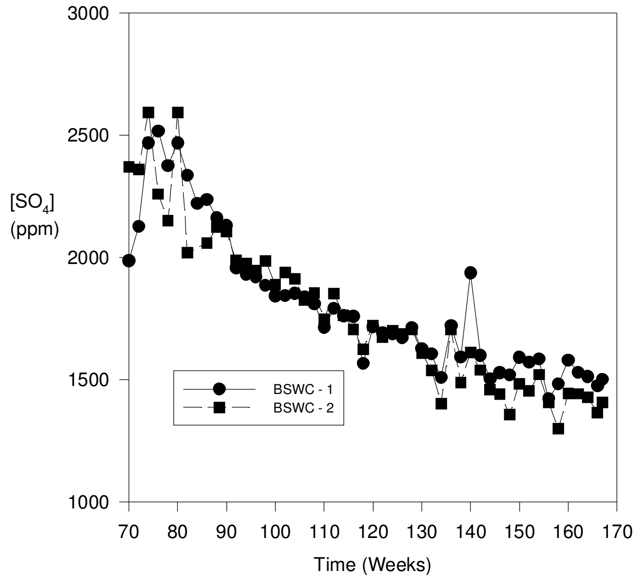

Figure 2: Brunswick fresh sludge with water cover, sulphate concentration versus time (Zinck *et al.* 2010).

Codisposal with tailings or other wastes

Disposal of sludge with other mining wastes is a common practice as it reduces the waste management resources required to dispose tailings/waste rock and sludge separately. Treatment sludge may serve as a source of alkalinity and offers the opportunity to neutralize the acidity generated by the sulphide-bearing waste. The practice of co-mixing tailings with treatment sludge for disposal involves injecting the treatment sludge into the tailings slurry prior to discharge to the impoundment. Typically, the sludge to tailings ratio is less than 1:20. Here the sludge serves to fill void spaces within the tailings, in theory reducing the potential for water or air infiltration and the hydraulic conductivity of the mixture. This method of disposal could be an effective option provided that the tailings are either non-acid generating or that tailings oxidation is prevented. However, if the tailings undergo oxidation and commence acid generation, the likelihood for sludge dissolution and metal mobilization is very high. In addition, an alternative sludge disposal strategy would be required post closure as sludge continues to be generated while tailings production ceases.

The performance of this disposal scenario seems to be very site specific particularly in relation to the waste composition. For example, in a recent study examining sludge-tailings codisposal results showed that the net alkalinity only offset acid generation and metal mobility in the short term (Zinck *et al.* 2010). Once sulphide oxidation in the tailings was established, the available alkalinity in the sludge was quickly depleted. Figure 3 shows how iron waste readily leached when fresh sludge was mixed with tailings and leached over a period of months. Under acidic conditions sludge dissolution occurs, opening void spaces and increasing infiltration and metal leaching. If under these same conditions a water cover was applied to the waste, then it is expected that limited metal leaching would occur, as oxidation would be suppressed.

Similar to mixing the sludge into the tailings, sludge can be codisposed with tailings as a cover. In this option the sludge can form a barrier to oxygen particularly if the sludge is significantly moist. Wet covers provide a barrier that minimizes oxygen ingress with potentially acid generating material and, except for minor oxygen dissolved in the water, precludes oxygen contact completely. The sludge also provides a source of alkalinity. Precipitation contacting the sludge can generate alkaline water that may percolate through the tailings. Laboratory results (Zinck *et al.* 2010) suggest that sludge as a cover material may not be effective to impede oxidation of tailings.   As shown in Figure 4 the available alkalinity could only delay the onset of acid generation for a few months. The extent of oxidation and metal leaching was evidenced by high concentrations iron and zinc leached as well as the marked pH drop from 8 to 2.5.

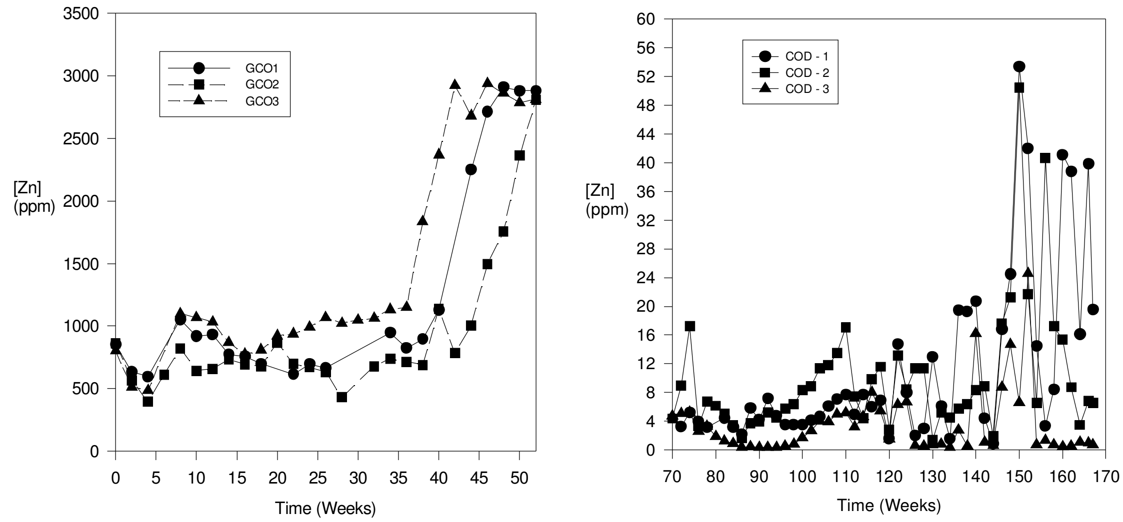

Figure 3: Zinc mobilization for two test codisposal test scenarios using different sludge and tailings samples (Zinck *et al*. 2010).

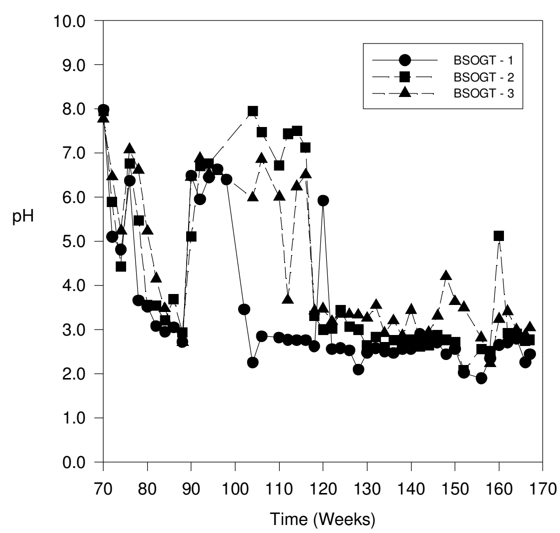

Figure 4: pH measured during the leaching period for the sludge cover over tailings disposal scenario (Zinck *et al.* 2010).

Sludge permeability plays a particularly important role in this type of disposal as the less permeable the material the less likely water and oxygen would contact the tailings, causing oxidation. The challenge is maintaining the integrity of the sludge barrier. Cracks that commonly occur in the sludge through desiccation provide for preferential channels for the leachant to travel through the sludge directly contacting the tailings.

Issues related to the application of a sludge cover on tailings such as cracking and preferential channelling can allow oxygen to reach the tailings. As well, wind suspension of fine sludge particles can cause total suspended solids (TSS) in the discharge to exceed the effluent limits during periods of high winds (Mian and Yanful 2004). Maintaining water in the sludge pore space could prevent sludge cracking and minimize exposure of tailings to oxygen. In addition, the application of a water or vegetative cover could be beneficial in keeping the sludge saturated by limiting cracking and channelling.

Another codisposal option involves disposing sludge with waste rock. This option has several of the same potential benefits as disposal with tailings, including utilization of excess alkalinity to offset acid generation and filling of void spaces. This practice of disposing treatment sludge in waste rock piles is being adopted at some sites. NB Coal's Fire Road mine (Minto, New Brunswick) started looking at the option of codisposal of sludge with waste rock in 1993 after it was determined that there was 160-770 years of sludge storage capacity within the waste rock. Coleman *et al*. (1997) conducted an investigation into the placement of sludge on acid generating waste rock. While their results showed that sludge was not effective as a capping material as originally hoped, this method was found to be a low-cost final disposal option as the sludge filled pore spaces and voids within the waste rock pile. The mine water chemistry has been monitored since 1993 and there appear to be no adverse identifiable chemical effects (Coleman and Butler 2004).

Disposal in mine workings

If site availability, mine capacity and configuration are appropriate sludge disposal in mine workings offers an excellent sludge management strategy. Benefits of this option include potential for the sludge to assist in mine water neutralization and minimization of surface reclamation. The deposition of sludge into underground mines reduces the footprint required for disposal sites (landfills and impoundments), eliminates the potential for surface water pollution, reduces the potential for subsidence, and improves the aesthetics of the local area. Also, in acidic mine workings, the disposal of sludge underground could have the additional benefit of reducing the acidity of the mine water (Gray *et al*. 1997). This practice involves pumping or trucking sludge to boreholes, which are drilled into underground inactive mines. Some of the factors that need to be considered in this disposal option include: site availability and access mine capacity, void space, configuration sludge properties (e.g. viscosity). A survey of sludge management practices found that roughly 6% of the sites reported disposing of sludge in underground mine workings. Some of the sites disposing in mine workings include Britannia Mine, Chisel Lake, Rambler Mine, Waite Amulet and Victoria Junction (Zinck and Griffith 2012).

The limited data available on the performance suggests positive results during the monitoring period. For example Mettiki Coal has been injecting alkaline metal hydroxide sludge from its mine drainage treatment facility along with thickener underflow from its coal preparation plant into inactive portions of its underground mine in Garrett County, Maryland under an Underground Injection Control (UIC) permit (Ashby 2001). Based on available data, it was felt that alkaline solids addition would assist Mettiki in maintaining an alkaline environment in its underground mine pool at closure and minimize acid generation. From 1996 to 2000 the pH of the mine water increased from 5.98 to 6.1.

Aubé *et al.* (2003) observed a similar trend. A laboratory study simulating the disposal of HDS and ferrous sludge into underground coal mine workings containing high strength acidic drainage was completed. The pH of the mine water increased from pH~3 to ~6.7 with increasing amounts of sludge added. In all cases where sludge was added, the concentrations of both Al and Fe decreased in the mine water. Results showed that some metal concentrations (Cd, Ni, and Zn) increased prior to decreasing at higher sludge addition rates. These metals are typically mobile at neutral or acid pH. The results also showed that there is a greater increase in dissolved metal concentration when the ferrous sludge was added to the acidic mine water.

When sludge is in equilibrium with the surrounding mine water, little or no dissolution of the iron sludge will occur. Any addition of either hydroxide ions or ferric ions would result in precipitation. These results suggest that sludge returned to the underground workings would actually reduce the lime required to treat the acidic mine water.

This method is very attractive from an economic and environmental standpoint. However, like most disposal options presented this is clearly site specific. Sludge with high iron content can most probably be disposed of this way economically. Disposal of sludge with high Cd, Zn, or Ni content in this manner may or may not be economic or environmentally acceptable depending on contact means (solids/AMD (S/L) ratio), alkalinity of sludge, and acidity of the acidic drainage (Aubé 2004; Aubé *et al*. 2005).

Disposal in pit lakes

Sludge disposal in open pits is an effective and commonly economical option for sludge storage and long term disposal. There are several advantages and disadvantages accompanying sludge disposal in pit lakes. In general, the stability of the sludge and at its interface with its aqueous environment is a main prerequisite for successful long term storage below a water cover. Risks such as long term change of conditions inside and around the pit lake, as groundwater contamination or as toxication of aquatic life have to be evaluated carefully (Schultze et al. 2011).

McNee *et al*. (2003) conducted a three-year research program studying two pit lakes at the Equity Silver Mine near Houston, British Columbia. Neutralization sludge was added to the Main Zone pit at a rate of ~5 L/s. The discharge of sludge into the Main Zone pit had a pronounced effect on its physical limnology. Their research found that the addition of sludge to the pit lake introduced oxygen into the lake through entrainment. Specifically, the input of dense oxygen-rich slurries and their rapid settling were found to cause lake mixing and produced oxygenated bottom waters. In addition, they found sludge disposal in the pit lake resulted in a plume of metal-rich particulate matter at depth (70-120 m). This did not, however, result in an increase in the dissolved metal content or total suspended solids levels at discharge. The pit lake experienced increased production as observed by the reduced light transmission and increase plankton biomass in the surface waters. It was postulated that the increased production was due to the delivery of phosphate into the lake with the sludge. Overall, the dynamics of the lake changed considerably and whole-lake mixing occurred with the introduction of the sludge (McNee 2004).

Schultze *et al.* (2011) provided several examples of sludge disposal in pit lakes. In these examples the addition of sludge increased the pH of the pit lake water. In addition, evaluations of potential sludge disposal in pit lakes or mine voids were completed at Gilt Edge Mine Superfund Site. In general early case studies suggest that sludge disposal does not seem to negatively impact dissolved metal and TSS concentrations in the discharge waters.

Sludge in backfill

Backfill integrates tailings, sludge and slag along with other wastes into backfill material to reduce the amount of waste to dispose on the mine surface. Paste backfill is defined as an engineered mixture of fine solid particles (with or without a binder) and water, containing between 72% and 85% solids by weight. Unlike a slurry, particles in a paste mixture will not settle out of the mixture if allowed to remain stationary. It can be placed in stopes, with or without binder addition depending on the strength requirements for the backfill. Improved pumping technology, environmental concerns, and the need for a low cost/high strength fill in mines are driving mine operators to consider paste backfill as a tailings management and mine backfill alternative. Incorporating sludge into paste serves to both stabilize the sludge and allow for codisposal of wastes underground. The URSTM (Université du Québec en Abitibi-Témiscamingue) and CANMET (Benzaazoua *et al.* 2006) investigated the option of incorporating sludge in paste backfill (Fiset *et al.* 2005). Results showed the addition of 0.15% wt and 0.3% wt of treatment sludge in cemented paste backfill does not significantly reduce the strength of the paste. Moreover, leaching tests performed on the samples indicated that contaminants were immobile.

Landfill
Landfill disposal is necessary for some sites that do not possess sufficient area for on-site disposal or require specialized disposal for sludge declared hazardous by regulatory leachate tests. Landfills are a common option used for disposal of hazardous waste. Landfilling is becoming less of a viable option, as environmental problems and restrictive legislation are making landfills a buried liability (Pickell and Wunderlich, 1995). One of the specific issues regarding the practice of landfilling treatment sludge is solid-liquid separation. Due to the low solids content of the treatment sludge it requires significant dewatering and drying before it can be transported. There may be additional public concern with the transportation of sludge off the mine site to a landfill facility. Depending on the sludge, stabilization may be an added requirement.

Conclusions
Many options exist to effectively manage acidic drainage treatment sludge. Prior to completing a sludge management plan it is imperative that data on the sludge chemical and physical characteristics be obtained. The sludge should be first considered a resource and reprocessing or metal recovery opportunities should be evaluated prior to disposal scenarios. A full column leaching evaluation should be completed if sludge is to be codisposed with potentially acid generating wastes.

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