# TREATMENT AND MONITORING OF PIT LAKES[1]

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Abstract: After closure of an open pit mining operation, a pit lake is often naturally formed. In mines where there is a potential for forming acid mine drainage or where metals are mobilised in neutral drainage, the water contained in a pit lake may require treatment before discharge. Many options exist for treating this water, including pump and treat, repeated batch treatment, and continuous treatment with overflow. The different treatment methods are presented and discussed in this paper. The examples focus particularly on batch lime treatment methods with actual examples from the field. Monitoring a pit lake is very important as layered conditions often occur due to density gradients, either caused by temperature (thermocline) or chemistry (chemocline). This layering must be taken into consideration when designing the treatment system as an attempt to treat the entire lake may be impeded by stratification. The implications related to stratified systems are discussed. The paper focuses on the steps required for successful and economic treatment of a contaminated pit lake. These steps include pit lake profiling, laboratory testing, and proper design of the treatment system for the site specific requirements. This is followed by detailed monitoring and release of water in compliance with local regulations. These fool-proof steps can be applied to any pit lake requiring heavy metal removal and will ensure successful treatment on the first attempt.

Key words: Treating heavy metals, open pit, lime neutralisation, acid rock (mine) drainage (ARD – AMD).

## INTRODUCTION

Many gold or heavy metal mines operate by open pit. When these mines are closed, the pit will often naturally fill with water, particularly in areas with a significant positive water balance. These are called “pit lakes”. In some cases, the quality of water naturally flowing to the open pit is satisfactory and meets local regulations for discharge to the environment. More often, the water accumulated in the pit does not meet local regulations for heavy metal concentrations and/or for pH. In these cases, some type of water treatment is required to ensure that the released water is not toxic to aquatic life. The metals often present in mine drainage are aluminum (Al), cadmium (Cd), copper (Cu), cobalt (Co), iron (Fe), lead (Pb), nickel (Ni), and zinc (Zn). All of these metals can be treated using hydroxide precipitation. Generally speaking, the most economical means of hydroxide treatment is using lime. This is the focus of the present paper: the options available for lime treatment of a pit lake with discussion on efficiencies of these options.

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## PIT LAKE TREATMENT OPTIONS

Biological and passive treatment has been attempted often without significant success in most cases. Lu (2004) describes how the use of sewage sludge failed to provide sufficient sulphate-reducing biological activity to treat the pit lake. Another example is Island Copper Mine, where a large open pit was partially filled with seawater and capped with freshwater to be used as a semi-passive treatment system. Nutrients are added on the surface of the pit lake to stimulate plankton growth which adsorb dissolved metals from the surface layer and sink to the bottom. The plankton also serve as a carbon source in the bottom layer of the pit to enhance anoxia and the production of dissolved sulphides which precipitate with dissolved metals in the acid drainage injected near the bottom of the pit. The system is still operating and meets treatment requirements at Island Copper Mine (Poling et al., 2003). Note that this system is not without costs due to the need for regular addition of nutrients.

One option is to pump the pit lake water to a treatment plant prior to discharge. This is sometimes the most efficient and economical option, particularly if there are other sources that require treatment on the site. In this situation, the pit lake is essentially used as large raw water pond for holding contaminated effluents from waste rock piles, site runoff, seepages, and tailings ponds. Another possibility is the capture and control of all contaminated waters before they reach the pit lake. This means that any runoff or seepage containing heavy metals is collected and treated prior to being fed to the pit. For this option, the pit lake water itself must meet compliance before it is allowed to overflow by gravity to the environment. Batch treatment of the pit lake may therefore be required before using this option. Pre-treatment of contaminated waters is one way of controlling the water quality in the pit lake following this batch treatment. It is also possible to use the pit lake as a settling pond for treatment of contaminated water from other sources (Aubé and Arseneault, 2003).

Another option is to batch treat the pit lake water in-situ as needed. Both this option and the option of pre-treatment of contaminated waters have the advantage that the stored water can be of high quality – an advantage for local fauna (particularly birds) that may attempt to use the water body as if it were a natural lake. This also reduces liabilities related to the storage of contaminated water. The focus of this paper is on the in-situ treatment of a pit lake. This can either be the only control system or if there is a continuous source of contaminated water, it can be followed by continuous treatment of these waters prior to being fed into the pit lake.

Note that the principles of treatment discussed here are described for pit lakes but can also be applied to any large water body that requires treatment. Treating a tailings pond or contaminated natural lake can be accomplished using the same methods described here. The biggest difference between treatment of a pit lake and that of a tailings is that a pit lake is typically much deeper. This depth can result in layering of the pit lake while a shallow water body is often fully-mixed. The depth of a pit lake can also be useful for long-term storage of sludges produced by lime treatment of heavy metals.

### Lime Treatment Theory

A water body contaminated with any of the following metals can normally be treated by lime precipitation: Al, Cd, Cu, Co, Fe, Mn, Ni, Pb, and Zn. Other potential contaminants such As, Mo, and Se are metalloids that require a different type of treatment that is not discussed in detail here (see Aubé, 2004). Heavy metal treatment is typically completed by lime addition to attain a desired pH where the metals form hydroxide precipitates. The preferred pH depends on the metal of concern as well as the chemistry of the water. Metals such as Al and Cu can be treated at slightly alkaline pH, while Ni and Cd require pH values of 10 or higher. More discussion on general lime treatment of metals can be found in Aubé (2004).

The basic treatment method is simply a matter of precipitating the metals by controlling the pH in the entire pit lake and allowing the time for the newly formed metal hydroxides to settle. The setpoint pH may vary from site-to-site even if the same metals are involved. This is determined using bench tests, as discussed in the following sections.

## PREPARATION AND PLANNING FOR PIT TREATMENT

Before designing a treatment system for a pit lake, it is necessary to know what the chemical and physical requirements will be for successful treatment. The first step is therefore to define the physico-chemistry of the pit lake. Due to the large depth of a pit lake, taking samples from the surface is not sufficient as layering is common. As shown in Figure 1, stratification is caused by density gradients that are formed either due to temperature (thermocline) or due to chemistry (chemocline).

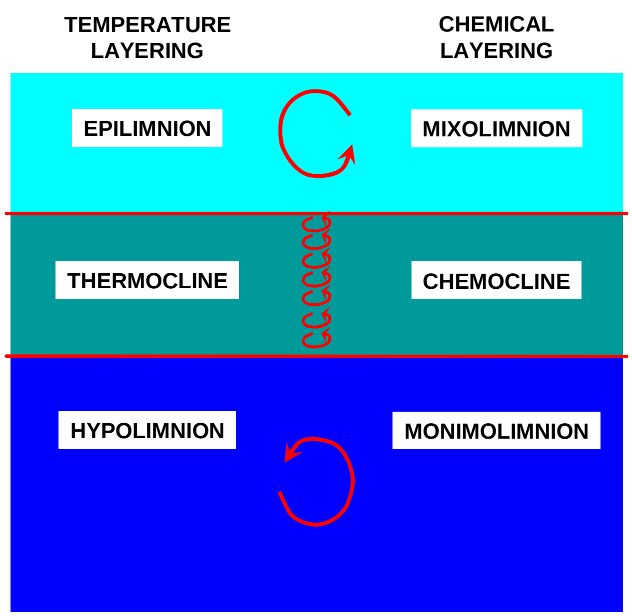


Figure 1: Stratification in a Pit Lake

The thermocline often occurs during the summer months for a pit lake in a temperate climate. This is caused by the increasing temperature of the surface waters, and the difference in density of water depending on temperature. In most temperate climates, a thermocline is seasonal and a pit lake “turnover” can occur twice per year, in the spring and fall. This occurs as the highest density for water is at a temperature of 4ºC. In Canada, for example, when the air temperature decreases in the fall, the lake surface layer (epilimnion) eventually reaches 4ºC. Depending on the temperature of the water below the thermocline (hypolimnion), the surface layer becomes either more dense or has the same density as the hypolimnion. A little wind action can then be sufficient to cause currents to mix the layers and make the entire volume homogeneous.

The layering in a chemocline is caused by density gradients as a result of salinity or dissolved solids in the water. The deeper layer (monimolimnion) often contains high concentrations of salts. In a chemically stratified lake, the density gradients are more important than the density changes due to temperature. This stratification is therefore typically permanent and results in a meromitic lake – a lake that is deprived of oxygen in the deeper layers. Chemical layering is more common in pit lakes than in natural lakes due to the depth ratio and the frequent presence of acidic drainage (Boehrer and Schultze, 2006).

Pit lake stratification means that the water chemistry at the surface is often different from the chemistry at depth. It also means that treatment of one layer won't likely treat the others. To determine the presence of stratification, it is necessary to complete some pit lake profiling. This is accomplished by measuring the physico-chemistry of the lake with depth. The preferred method is to immerse a multi-probe with sufficient line to approach the bottom. There are many manufacturers of multi-probes with the potential to reach depths of more than 100 meters. Typical probe measurements are for depth, temperature, pH, redox potential (or Eh), dissolved oxygen concentration (DO), conductivity (or total dissolved solids - TDS), and turbidity. Profiling using a multiprobe will determine if the pit lake is stratified.

It is also necessary to take samples at different depths for chemical analysis. These can either be collected using depth samplers or immersing a tube to a specified depth and pumping up water samples. When using depth samplers, it is preferable to use a vertical-type (such as Kemmerer bottles) to ensure collection of a proper sample that is not mixed with water from other layers. Horizontal samplers such as Van Dorn bottles are more difficult to use efficiently, particularly when sampling to depths of more than 10 m. When pumping water, it is standard procedure to pump three full volumes of the intake line between samples to eliminate any risk of cross contamination from the previous sample depth. These pump lines can be attached to the profiling device in order to complete both the physico-chemical profiling and the sampling simultaneously.

If dissolved metals are required as well as total metals, it is important to complete the filtration on-site immediately following sampling. This is critical particularly if Fe is present as oxidation of ferrous iron can occur rapidly and cause the precipitation of ferric hydroxides. Ferric hydroxides will in turn cause the removal of other metals in solution due to co-precipitation. The samples designated for metal analysis should be stabilised with acid. As samples are being collected, it is also possible to measure the pH and temperature on surface. With this option, it is critical to take the measurements rapidly, while still in the boat or raft on the pit lake. This is due to the rapid dissolution of oxygen from samples which may have been in anoxic conditions. The temperature may also change rapidly if sampling is done on a warm summer day or during winter. Either of these sample changes will result in chemical reactions which affect the sample pH, redox, DO, conductivity and even the chemical results as precipitation can also occur rapidly. It is for these reasons that a submersible multi-probe is preferred.

**Laboratory Testing**
Once the profiling is complete, a large representative sample is required for laboratory testing. A series of bench-scale tests can be applied to define the setpoint pH, lime consumption rate, sludge production rate, and need for coagulants. Depending on the results of the profiling, this sample may represent a mix of different layers in the pit lake. Another option is to treat each layer separately and define the treatment needs for each layer. In many cases, the epilimnion can represent a small fraction of the total volume of water due to depth of the pit lake. In such a case, the laboratory tests can focus more specifically on a sample collected at depth.

A typical example of laboratory tests completed for pit lake treatment purposes can be taken from Les Mines Selbaie project, as described in Aubé et al. (2007). In this project, a series of tests were conducted in 1-L beakers to control pH to different setpoints with lime addition. After 24 hours of settling, the supernatant was sampled for total Zn concentration among other elements. Figure 2 shows the results of these tests with two different y-axes, one linear and one logarithmic for a clearer understanding of the result at low concentrations. As shown, a pH setpoint of 10 easily surpassed the regulations (Zn of 0.5 mg/L) and met the treatment target of 0.3 mg/L. A pH setpoint of 10 showed a lime consumption rate near 0.09 g/L, which for a pit lake of 22 $Mm^3$ results in a total consumption rate of about 2000 tonnes of lime.

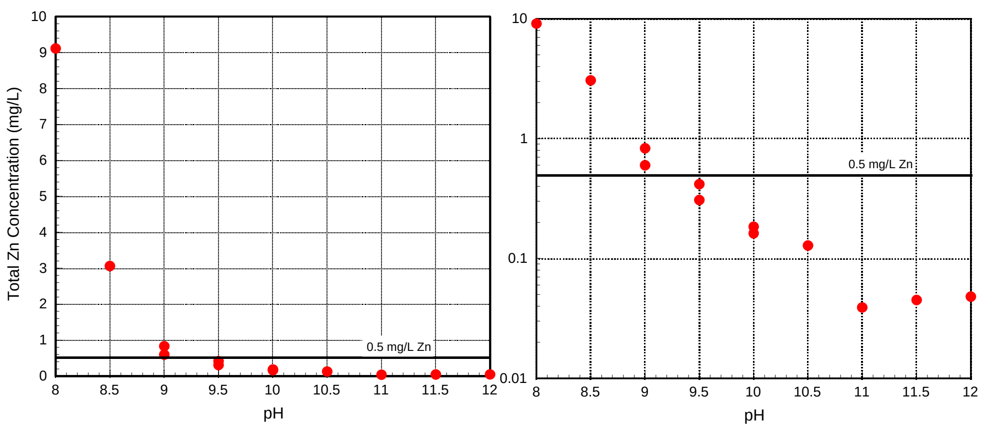

Figure 2: Zn Concentrations with pH for Selbaie Lime Addition Tests (Aubé et al. 2007)

The example above is one of many historical tests completed to determine the needs for pit lake treatment. In the Mines Selbaie example, there were also tests completed with different coagulants, but they were found to be unnecessary in this case. Experience has shown that two sites with similar concentrations of metals may have different treatment needs due to other characteristics of the water. The most important effects that are not always known are those of carbon species present in the water, whether it is present in organic or inorganic form. TIC (total inorganic carbon) can increase lime consumption and either help or hinder solid-liquid separation. TOC (total organic carbon) content can cause complexation of metals, affect precipitation, and change the settling properties of formed precipitates. There may also be bacterial or algal populations present in the pit lake that can make treatment either easier or more difficult.

The best way to define the treatment requirements is to test the actual raw water. Before designing a treatment system and going ahead with lime addition to the pit lake, it is preferable to complete this testing in order to properly define the required mass of lime and/or coagulants needed. Once this is defined, the lime addition system can be designed and the cost optimisation can be completed to ensure that treatment will be most effective.

**Pilot Testing**

Pilot testing pit lake treatment is not like a pilot plant operating continuously. It is possible to try neutralising a large column of water to determine the sludge qualities and define the expected sludge stability, but the greater issues of uncertainty in pit lake treatment are related to layering. The chemical needs are determined in the bench tests, but the physical aspects of treatment are not always as obvious.

Pilot testing of pit lake treatment can be done via limnocorrals. Limnocorrals are experimental enclosures, which are open at the top and bottom and isolate a portion of the water column from lateral mixing within the lake. These were used at the Mines Selbaie project (Aubé et al. 2007) and were instrumental in defining the effects of treatment when a pit lake is layered. The limnocorrals used in this project were 2 m in diameter and 10 m in depth. It was found that treating only at the surface resulted in the epilimnion being treated rapidly, but not the hypolimnion. The thermocline acts as a significant barrier for mixing of the entire column. It was also found that as the epilimnion depth varies, it mixes with the water below. This means that you cannot treat only the surface layer and expect it to remain in compliance with discharge regulations.

The major limnocorral finding was that by recirculating water with an imposed diagonal between the pump and discharge, the entire volume can be efficiently treated. The diagonal can be applied by drawing water from surface and injecting it at depth on the other end of the limnocorral. Alternatively, the water can be drawn at depth and injected it at surface. Imposing a diagonal forces the entire water column to be treated. The limnocorral tests also served to confirm the results from the laboratory as far as lime consumption and treatment efficiency. These tests were very useful in this project but are not necessarily required for all projects. Limnocorral tests require at least a few weeks of operation and are relatively complex systems to implement. This means that at a site where time is critical, skipping the pilot step would likely be preferred. Another issue is that much experience has been gained in recent years and the results from one site can often be applied to another.

## LIME TREATMENT OF A PIT LAKE

Effective treatment of a pit lake is completed by adding dissolved alkalinity to the lake water which then reacts with the dissolved metals to form metal hydroxides. Whatever portion of the lime particles that does not dissolve, will end up as part of the solids or sludge at the bottom of the pit lake. The efficiency in treatment is therefore a result of the percentage of the lime added that was dissolved and used to increase the pH of the pit lake water and precipitate the metals. Even in a well-designed lime treatment system, 100% efficiency is not attainable. Part of the reason for this is that unreactive materials, often in the form of grits, are always present to some degree in industrial lime. The grit content in lime can vary from 1% to more than 10%. In Canada, the grit content will typically vary from 3 to 6% of the lime. This means that a “perfect” lime treatment system can achieve an efficiency in the order of 95%. There are numerous ways to treat a pit lake with lime, each with different efficiencies of lime usage. These include simple lime addition, lime addition with aeration, liming using off-the-shelf devices, and recirculation liming. Each of these methods is discussed in the following sections.

**Simple Lime Addition**

Simple lime addition is the method most often used for treating pit lakes. This entails adding a lime slurry or hydrated lime powder directly to the pit lake by either sparging it or pumping it to pit lake surface, as illustrated in Figure 3. Using this method, the lime is added while mostly still as a solid particle of hydrated lime [$Ca(OH)_2$]. As there is little or no mixing involved with this addition method, the lime particles tend to settle to the bottom without considerable dissolution.

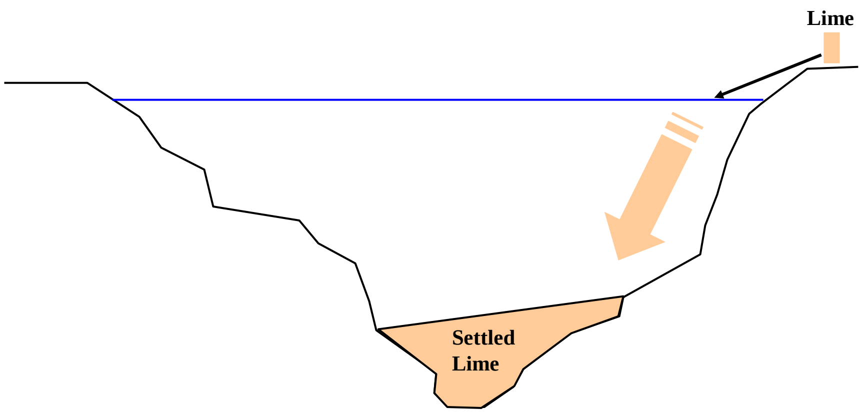


Figure 3: Conceptual Representation of Simple Lime Addition in a Pit Lake

Öhlander et al. (1997) describe the use of this method and how it was estimated that approximately 15% of the lime was effectively used to increase the pH of the pit lake water. There is another example of an un-published trial to treat a highly contaminated pit lake with an initial pH of less than 3 using this method of simple lime addition. After adding more than enough lime to treat the entire volume, the pH had barely changed. Part of the reason for this is that the very high ferric iron content of the pit lake resulted in a quick coating of the lime particles with ferric hydroxides. Whether the lime particles are coated or not, they will mostly settle to the bottom of the pit lake as there is no significant mixing to enhance dissolution. When added as a slurry, the slurry itself will settle and have a high surrounding pH around the particles which also reduces the dissolution efficiency. As the goal is to add dissolved alkalinity (or actual hydroxide ions ($OH^-$) to the water), this method will not meet the objective in an efficient manner.

**Liming and Aeration**

The example above where a considerable amount of lime was added to a highly acidic pit lake without any significant change was followed up by aeration. This was done using a compressor and a weighted line to supply the air to the bottom of the pit where the lime had accumulated, as shown conceptually in Figure 4. This method will re-suspend some of the lime and create some turbulence to help dissolve it. Bubbling does not provide any significant shear stress which is needed to increase the dissolution efficiency of larger particles, but by re-suspending the lime particles, the dissolution is somewhat improved. Overall, it is estimated that lime addition with aeration would have an efficiency in the area of 25 to 40%. Although this is a significant improvement over the lime addition alone, more than half the added lime is expected to settle to the bottom of the pit lake and not be available for increasing the pH of the water and precipitating the dissolved metals.

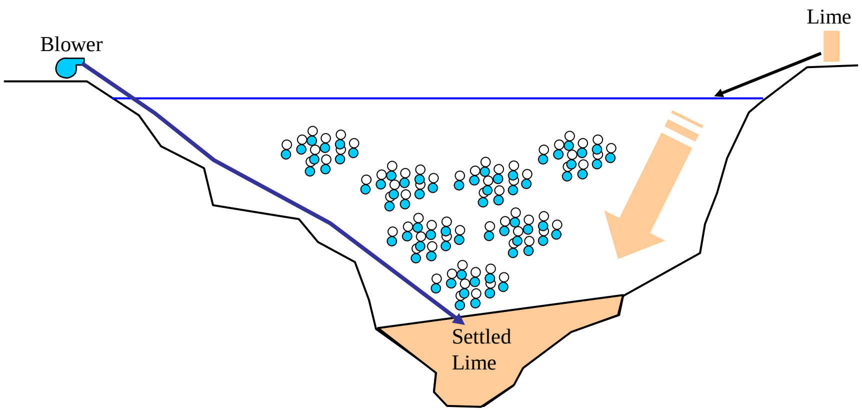


Figure 4: Conceptual Representation of Lime Addition with Aeration

**In-Situ Slaking and Treatment**

An Australian company, Earth Systems Pty Ltd, has developed a floating slaker that can be used for adding lime in a pit lake. This was used at the Gilt Edge Mine Superfund Site South Dakota, USA (Lewis et al. 2003). The authors claim that the overall liming efficiency was in the order of 71%. This system has some advantages over simple lime addition but there are also some disadvantages such as winter operation and the fact that it can only disperse the lime in its' immediate vicinity. This can be overcome by moving the unit around but it could be difficult to do while still slaking lime. This system may be suitable for smaller open pits.

**Recirculating Treatment**

In this scenario, the water is drawn at one end of the pit lake, lime is added, and the limed water is then injected at a significant distance (see Figure 5). A diagonal must be imposed both on the vertical and the horizontal. The vertically imposed diagonal does not need to reach the bottom of the lake, but it must at least enter into the lower layer of the pit lake (hypolimnion). The horizontal diagonal does not necessarily reach the farthest end of the lake, but must be sufficiently spaced to prevent short circuiting of the limed water back towards the intake of the pump. At least two thirds of the distance to the other shore is recommended.

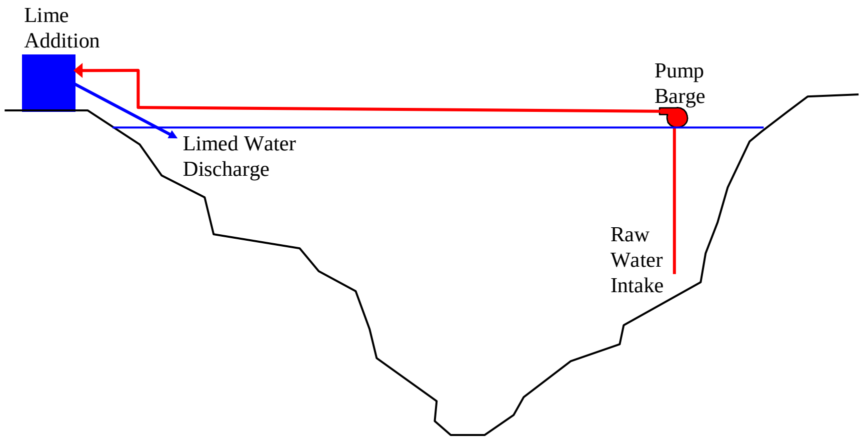


Figure 5: Conceptual Representation of Recirculating Pit Treatment

Using this type of treatment system, it is possible to have up to 95% efficiency in lime usage. This is because the lime addition on shore can be done in an agitated reactor controlled to a pH of 10.5, for example, where lime dissolution efficiency is excellent. Unfortunately, treating an entire pit lake with that pH setpoint would be time-consuming and result in other disadvantages: the power consumption for pumping and agitation, and the pH decrease in the pit lake due to carbon dioxide dissolution. The power consumption is evident – the faster the pit is treated, the less power is consumed over the course of pit treatment.

A difficulty with lime addition is that carbon dioxide dissolution can partially offset the pH increase. The issue is that as pH increases, particularly as it surpasses 8.3, the dissolution of carbon dioxide ($CO_2$) has a greater impact on pH. The dissolved carbon dioxide ($H_2CO_3$) converts to bicarbonate ($HCO_3^-$), then to carbonate ($CO_3^{2-}$). These chemical reactions release acid and decrease pH. A slow addition of lime will therefore be constantly battling against carbon dioxide dissolution and result in difficulty attaining the setpoint pH.

As previously discussed, the goal in pit lake treatment is to supply sufficient dissolved alkalinity to the pit lake water in order for the metal precipitation reactions to occur. By increasing the setpoint pH in the lime addition system in the recirculation scenario, the hydroxide ions are more rapidly supplied to the pit lake and treatment is faster. As lime dissolution efficiency decreases at pH values of more than 11, a compromise must be made on the speed of pit neutralisation versus lime efficiency. In the past, a pH setpoint of 11.5 or 11.75 has been used.

It is not necessary to recirculate the entire pit lake volume. A recirculation scenario was used for the Mines Selbaie example. Here, the target pH in the pit lake was 10.0, at which point it was expected that the Zn would be treated. At Selbaie, treatment was completed by injecting lime on the discharge end of a pump. The lime dissolution occurred in-line through the length of the floating pipe to the point where the limed water was injected at depth via downpipes supported by floating rafts (Aubé et al. 2007). Although the pH of the limed water was not regularly measured, the prescribed control was to maintain the pH between 11.5 and 12.0. This means that only a fraction of the pit lake volume is actually pumped while significant dissolved alkalinity is dispersed to the rest of the pit lake. The efficiency at Selbaie was estimated to be near 80%, but a better control on the limed water pH would have improved this. The Zn treatment efficiency exceeded expectations with final concentrations of less than 0.2 mg/L.

The disadvantage to the recirculation scenario is that it requires more infrastructure for the pumping and liming system. This incurs capital costs above those of other options. The advantage is clearly in the lime efficiency. For large open pits, this advantage becomes important and certainly worthwhile. For smaller pits, the infrastructure is not very large and the combined capital and lime costs will most likely be in the same range. If the treatment must be repeated yearly, this allows for re-use of the equipment with low lime consumption rates. For a one-time treatment, it is often possible to rent the required equipment and reduce costs.

## PIT LAKE MONITORING

Following treatment, it is important that regular monitoring be used to follow up and ensure that the metal concentrations are maintained low. The sludge produced by lime addition is typically stable when left in a neutral or alkaline environment and does not exhibit much re-dissolution. Possible increases in metal concentrations can be due to contaminated surface runoff, contaminated ground water, or oxidation of pit walls. It may be necessary to maintain the pH high on a yearly basis in order to ensure continuous compliance with local regulations. Post-treatment monitoring is done with depth using the same methods as those discussed for defining the pit lake in the preparation section.

## CONCLUSIONS

There are a number of different methods that can be applied for pit treatment, each with a different efficiency of neutralisation. The most efficient by far is that of recirculation, although the capital costs may be greater. Regardless of the method used, it is highly recommend that pit profiling and laboratory testing be completed prior to treatment, in order to properly design the pit lake treatment system.

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