CHAPTER 7

Drainage Treatment

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PREDICTION
•
PREVENTION
•
MANAGEMENT

The International Network for Acid Prevention

Global Acid Rock Drainage Guide

GARDGUIDE BY INAP

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7.0 MINE WATER TREATMENT

7.1 Introduction

This chapter on mine water treatment is intended to provide the user with a broad overview of different mine water treatment technologies and approaches and presents a road map to support decision making. The review includes constituents that are common to many types of mining (base metals, precious metals, coal, etc.) and many types of mining-influenced water (MIW; pit, tailings, process, etc.). This chapter also includes case summaries and links to other resources that may support a review of mine water treatment options.

This section of the GARD Guide should be considered after the options presented in Chapter 6 - Prevention and Mitigation – have been reviewed and assessed. The hierarchy of controls that lead to water treatment is presented schematically in Figure 7-1. Water treatment should be the last option evaluated to manage mine water discharges. As the Australian Guidelines state: “It makes good business sense, in addition to being leading practice, to avoid and minimize the production of acid mine drainage (AMD), and to treat AMD only as a last resort if other approaches have failed.” (Australian Commonwealth 2016).

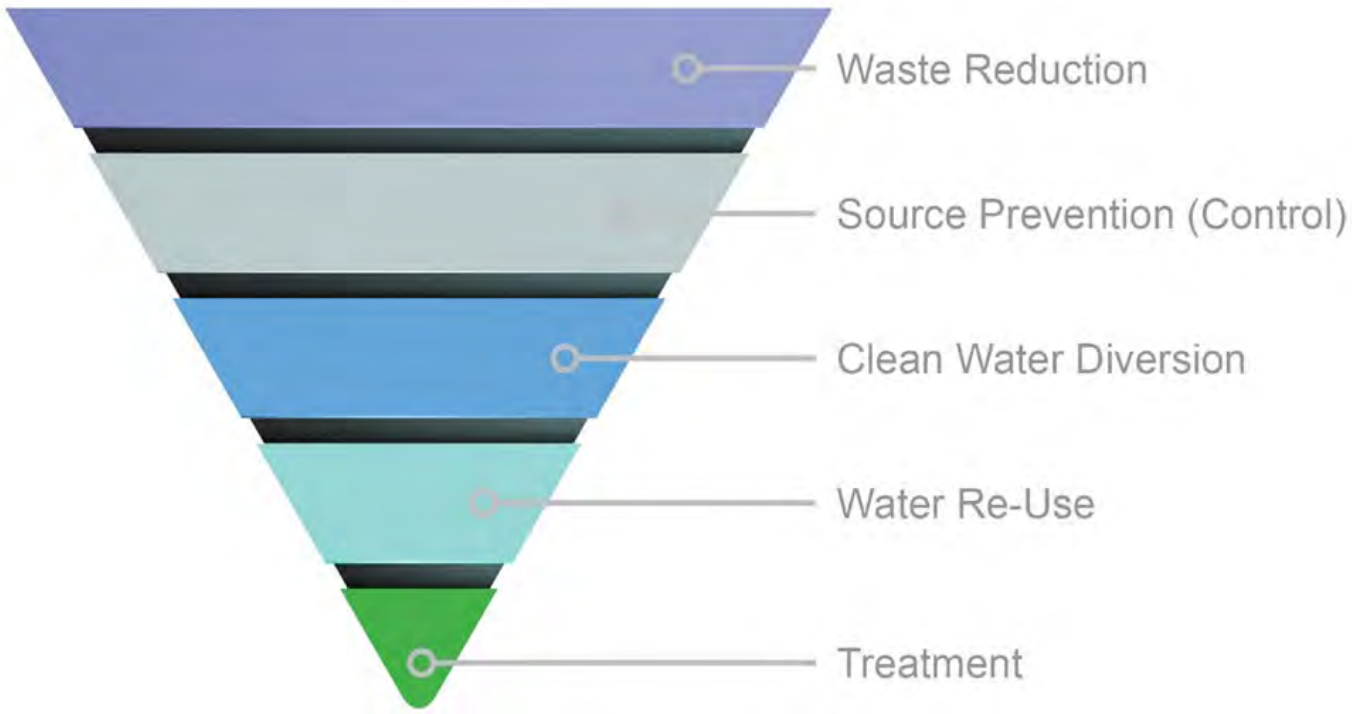

Figure 7-1: Hierarchy of Treatment Controls

Treatment may be the final option, but it is not a singular option. There are many viable treatment technologies that may be useful given site-specific details and, before embarking on an exercise to evaluate treatment options, the following key site aspects should be known:

- The constituent(s), constituent loads, and volumes to be treated
- Source(s) of water to be treated (e.g., surface water, groundwater, water from MRSs, tailings, etc.)
- The expected duration of treatment required

- Site-specific hydrologic regime and climate
- Area available for treatment infrastructure (plants, ponds, etc.)
- Treatment goals (such as regulatory requirements for closure and post closure limits)

Site characterization, including aspects related to the bullets presented above, is an important step in assessing mine water treatment and can be used to support a risk-based evaluation for treatments. Sustainability of mining includes consideration of litigation, management, and control of mining impacts on the environment. In many cases, the mining impacts on water resources are long term and persist in the post-closure phase. Mine drainage treatment may be a component of overall mine water management to support a mining operation over the mine's entire life and enhances post-closure and sustainable use of the mine property long after the ore deposit is depleted. The following sub-chapters provide the framework for selection of the mine water treatment approach once the site-specific aspects are known.

7.2 Risk-Based Approach

As with evolving industry practices across many disciplines, the selection of treatment technologies should follow a risk-based approach. An assessment of risk should be conducted early in the design of the operation and cover five main areas:

- **Nature of MIW to be treated**: variability in flow rates, including seasonal variability, concentrations of regulated constituents, variation in loading, and background water quality. Mine water can be influenced by total composition and non-regulated constituents as well, such as calcium, magnesium, chloride, and total dissolved solids (TDS).
- **Systems**: mechanical failure, power failure, plugging of infrastructure and treatment components, failure of delivery systems, armouring of reactants, failure of reagent delivery systems, failure of process control components, inadequate design volume of holding ponds, scaling of plant components, shutdown due to labour disruption, etc.
- **Regulatory or stakeholder requirements**: failure to meet compliance (total or dissolved metals, pH, etc.), failure to meet community or NGO expectations, effluent toxicity test failure, change in permit requirements, inability to meet receiving environment water quality, etc.
- **By-product management:** low sludge density, lack of appropriate on-site disposal, off-site transportation and disposal issues, poor sludge stability (chemical mobilization, physical instability), sludge pond access risks (human/fauna), dusting (airborne contamination), etc.
- **Physical site conditions:** the site setting (high elevation, seasonal precipitation, cold climates) along with the risk of natural disasters to the treatment system (e.g., earthquakes, excessive precipitation, etc.). The potential for change within the site, including site expansion, new catchments, larger footprints, climate change, etc.

7.3 Setting Objectives for Treatment

As outlined in the preceding section, mine water treatment forms part of the toolbox available for managing mine water, mitigating mining impacts and, in some cases, converting mine-impacted water into a resource for beneficial use.

Water is a precious resource and many regions where mining occurs are already water-scarce. Indications from climate change projections are that both increases in water surplus or water scarcity are possible for mine sites. With increased risks in water security, mine water quality management has become increasingly important.

Mining uses water but may also generate large volumes of mine-impacted wastewater. Therefore, most mining operations already focus considerable attention on the reduction of water use, re-use of mining-influenced water, and on water and waste management approaches to lessen the occurrence of deleterious drainage and reduce the impacts and volume of water affected by mining. In conjunction with these measures, several considerations need to be included to assess whether water treatment is required, and what the objectives of the treatment should be.

Each mine site is unique and the range of mine water qualities, volumes to be treated, environmental objectives and regulatory conditions to be considered is too vast to capture in detail. Furthermore, the objectives outlined below are broad and should serve to inform users of the GARD Guide of the considerations that should be included in planning, implementing, and assessing mine water treatment options. As indicated in Section 7.1, the objective of this chapter is to provide a high-level road map aimed at mine water and environmental practitioners rather than water treatment specialists. As such, this chapter is framed to allow readers to understand the basic principles and considerations of mine water treatment.

The key goals of mine water treatment typically are the following:

- **Protection of human health and the environment**. Where mine water has the potential to impact downstream or adjacent water users, mine water treatment objectives will include considerations for the protection of human health and the environment. This is more prevalent in situations where people may come in contact with the impacted mine water through indirect (fishing and wildlife) or direct (water consumption) use of mine drainage.
- **Protection of the receiving environment**. Mine drainage may act as the transport medium for a range of pollutants, which may impact on-site and off-site water resources. The objective of mine water treatment would be to remove constituents of concern or to reduce their concentrations sufficiently to prevent or mitigate effects on the receiving environment.
- **Stakeholder acceptability**. While the former two considerations and the economics of the mine water treatment typically drive selection of the technology, stakeholder input and acceptance should be obtained (see Chapter 10 of the GARD Guide). Mine water treatment is often a long-term and expensive undertaking, and the expectations of stakeholders should form part of the decision-making process for selecting an approach or technology for each mine water stream to be treated.
- **Generation of recoverable by-products**. Useful and potentially saleable products may be recovered from mine drainage. It is unlikely that by-products recovery would be a sole driver to the installation of a water treatment facility. However, when commodity prices are high, the recovery of saleable products will improve the financial viability of mine drainage treatment projects. Conversely, generation of by-products that require further management, are produced in high volumes, or have the potential for adverse effects, may lessen the feasibility of some treatment options.
- **Producing water that can be repurposed for beneficial use**. Most mining operations aim to reduce water use and storage of excess water. Typically, a mine site has a range of activities that have different volumetric demands and water quality requirements for different water uses. Mine drainage treatment, in this case, is

aimed at modifying the water quality such that the treated effluent can be used for a different purpose on site, for instance in processing, conveyance of materials, and other operational applications (e.g., dust suppression, mine cooling, and irrigation).

- **Achievement of license conditions and/or regulatory acceptance**. In line with the environmental or end-use requirements, regulatory requirements may stipulate a mine water discharge quality or associated discharge contaminant loads. Treatment objectives need to consider both current and known near-future regulatory conditions that may be imposed on the mine water to be discharged.

Setting multiple objectives for treatment, and prioritizing those objectives, will support the selection of appropriate treatment technologies. There are many technologies which may apply to a given effluent, as illustrated in Figure 7-2, but the key objective(s) may help identify the right technology.

7.4 Water Collection and Treatment Approach

Selecting a treatment technology requires an integrated approach that brings together:

- Treatment objectives (Section 7.3)
- Source identification and characterization
- Water collection and management

7.4.1 Source Identification and Characterization

There are several main types of drainage that may require treatment before discharge from a site: acid rock drainage (ARD), neutral drainage (ND), and saline drainage (SD). Each type of drainage, while distinct in its composition and chemistry, can typically be treated using similar, if not identical, treatment technologies. Chapter 2 provides more detail on the compositional characteristics of these mine waters. Certain mine waters, for example from coal operations, may contain specific constituents that are challenging to treat, such as selenium.

Potential drainage sources include mine rock dumps, tailings impoundments, haulage roadways, milling areas, contaminated surface, and underground mine workings. Characterization of the mine drainage in terms of flow and key properties of ARD, ND, or SD should include careful consideration of temporal and seasonal changes. Flow data are especially important because this information is required to properly size any treatment system. Particular emphasis should be placed on extreme precipitation and snowmelt events to ensure that the collection ponds and related piping and ditches are adequately sized and maintained.

The key properties of mine drainage relate to acidity and alkalinity, sulfate content, salinity, metal content, microbiological quality, and the presence of specific compounds associated with particular mining operations, such as cyanide, ammonia, nitrate, arsenic, selenium, molybdenum, and radionuclides. Coal mine drainage (CMD) typically contains iron, aluminum, and manganese in significant concentrations. Other metals are usually only present in trace concentrations in CMD and, as mentioned in Chapter 2, these are usually removed in the process of meeting the typical CMD water quality objectives for manganese. There are also a number of properties of the mine-drainage constituents (e.g., hardness, sulfate, and silica) that may not currently be of regulatory or environmental concern in all jurisdictions, but that could affect the selection of the preferred water treatment technology. A summary of the applicability of broad treatment categories to constituents typical of MIW is presented in Figure 7-2.

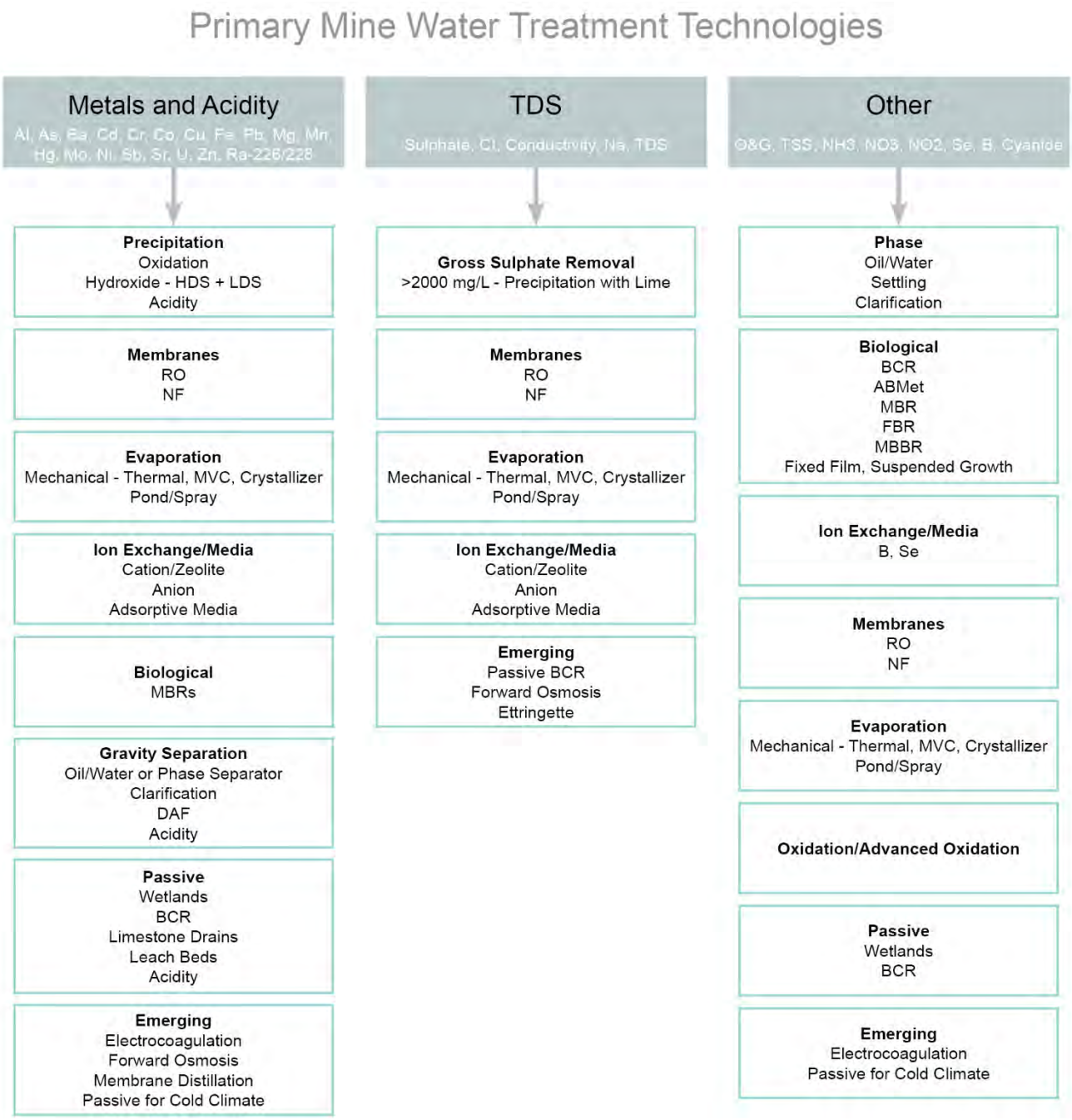

Figure 7-2: Principal Mine Water Treatment Technologies

The characterization of MIW and assessment of loadings and constituents for treatment are addressed in Chapter 4 and Chapter 5, respectively. The identification of constituents and prediction of concentrations and flow rates are key to the appropriate selection of technologies, as there may be site-specific constraints or opportunities to consider.

7.4.2 Water Collection and Management

Water treatment first and foremost relies on the identification of which waters require treatment and the effective collection and/or storage of those waters (Figure 7-3).

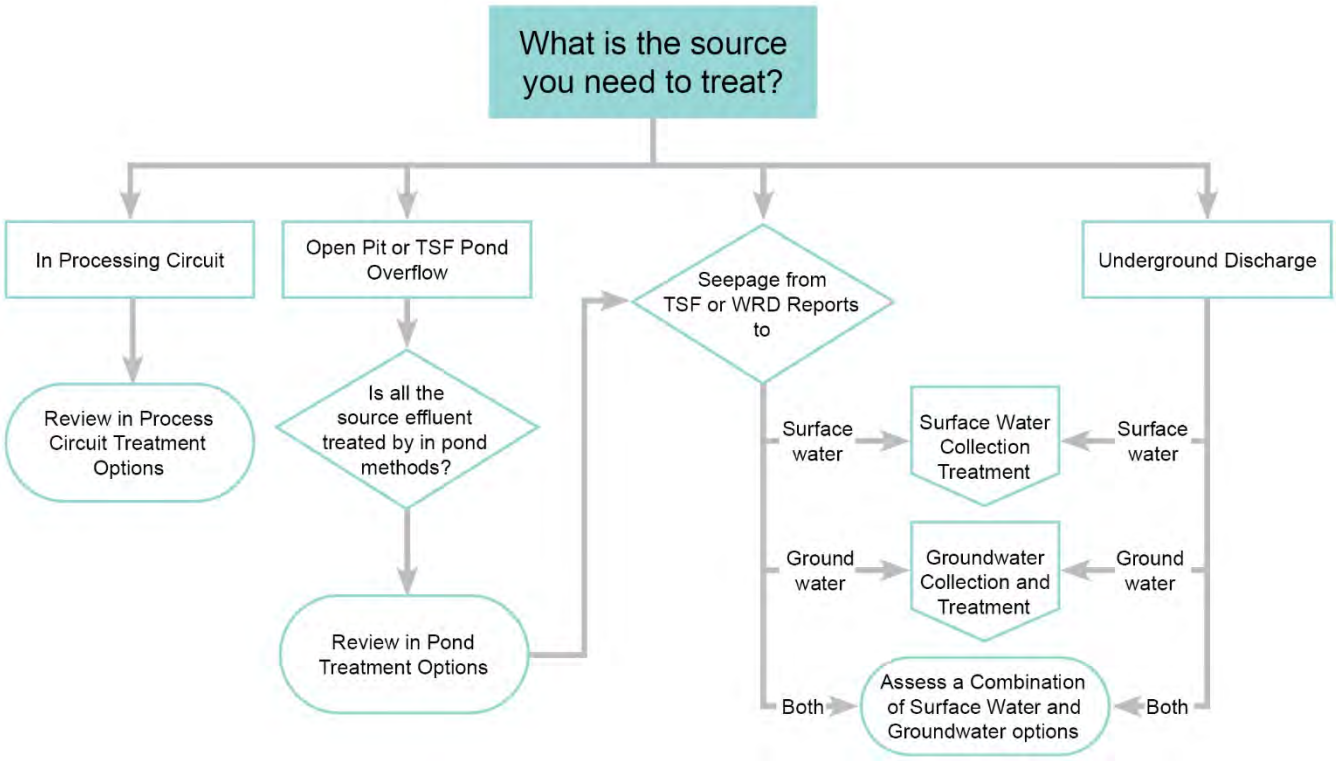

Figure 7-3: Source Identification and Pathways for Treatment

Once the location(s) for treatment and the key source(s) to be treated have been identified, the options for the collection and conveyance of water can be developed. Some treatment technologies are flexible and can accept variable inflow rates, while some technologies perform better with constant flow rates. Either way, water management plays an integral part in treatment technology selection. Options for water collection and conveyance for treatment include:

- **Ponds**: these can be existing ponds on site (open pit or TSFs) or constructed ponds designed to manage water. Ponds generally provide flow equalization (or storage for process use), but could also include pre-treatment (pH adjustment, settling, etc.) prior to another treatment technology.
- **Channels/ditches**: open channels can be used to convey water around a site by gravity, but some passive treatment technologies (Section 7.8) can be used in-channel.
- **Pipelines**: generally used to convey water mechanically around a site.
- **Groundwater**: groundwater is generally challenging to manage, and in-situ treatment system may be required or an interceptor system may be required to recover groundwater and transfer to a ex situ water treatment plant.

The water management system components and infrastructure pose engineering and operational challenges because of the variable flow rates and the corrosive or scaling nature of many types of mine drainage. The considerations in the development of a mine drainage collection and conveyance system include the following:

- Properties of mine drainage, including corrosiveness, scale/precipitate forming potential, solids deposition, organic fouling, and plugging
- Variable mine drainage flows and qualities dictated by climatic and seasonal changes and by the different stages of the life of the mine (the sizing of collection ponds and ditches is particularly critical where snow or precipitation events can combine to overtop and cause failure of these facilities)
- The size of the collection ponds and ditches may be defined by the regulatory requirements (i.e., to meet a 24-hour, 100-year precipitation event)
- The effect of climate change on water management and conveyance design criteria (for both water quality and infrastructure requirements)
- Site and route selection based on consideration of topography, geotechnical conditions, and climate
- Selection of appropriate materials of construction
- Engineering features, including pretreatment before conveyance, pumping installation, and piping systems
- Operational and maintenance aspects related to access, regular cleaning, and monitoring
- Potential for wildlife interaction

Mine drainage diversion, collection, and conveyance systems are critical components of any treatment project. An appropriate basis of design must be developed and integrated into the overall treatment project. Surge ponds may be a valuable feature in the case of highly variable mine drainage flows and pollutant loads as this will afford some protection against surcharging the treatment system. It is typically not economically feasible to build very large raw water retention ponds nor is it economical to build small ponds and very large treatment plants. Optimum sizing should consider the tradeoff between plant size, real estate availability, flow variability, and pond sizing to identify the preferred cost/efficiency ratio. Examples exist of failed projects because of the neglect of the design, operation and maintenance of the mine drainage collection infrastructure. For example, Figure 7-4 shows the early stages of a polishing wetland (left) and after it was overwhelmed (right) and rendered ineffective by breakthrough of highly acidic and metal-rich seepage (Australian Commonwealth 2016).

Figure 7-4: Example of Wetland Maintenance Issues

7.5 General Constraints for Technology Selection

The array of mine water qualities encountered, and the range of treatment objectives means that there is not a one-size-fits-all solution when selecting the appropriate mine water treatment technology. A selection of common constraints is included in the following sub-sections. This overview is not exhaustive but is based on common aspects provided by a range of mine site, corporate, consulting, and academic professionals from the fields of mine waste, mine water management, and water treatment. More information on constraints is provided in the US Environmental Protection Agency (EPA) Reference Guide to Treatment Technologies for Mining-Influenced Water (EPA 2014), which addresses the following: the amount of available land surface and its topography; water treatment system longevity and maintenance needs; flow rates to be treated; site accessibility and remoteness; availability of power sources and the objectives of the treatment.

Additional factors that influence treatment selection are provided in Section 7.6.

7.5.1 Applicability of Active versus Passive Treatment Systems

While passive treatment is attractive due to the perceived lower level of effort required compared to active treatment, the majority of mine water requiring treatment is handled through active water treatment plants. While active treatment involves regular reagent and labour inputs for continued operation, passive treatment ideally only requires occasional maintenance and monitoring.

For passive water treatment schemes, the flow rates and acidity or metal load required to be treated are often the most important constraints, especially under acidic conditions. The flow rate is the primary driver for sizing active or passive treatment systems. Consistent flow rates are preferred in passive systems.

Passive systems, in general, can only handle relatively small flows (usually less than 50 L/s) unless a significant area is available for passive treatment to be successful. For acidic MIW, the acidity load is often the deciding factor. Under most conditions, passive treatment can effectively treat lower acidity loads. Passive systems are well suited to treating MIW with moderate acidity (generally with acidity less than 800 mg $CaCO_3$ /L) and relatively low acidity loads (generally less than 100–150 kg $CaCO_3$ per day) (Australian Commonwealth 2016).

As a guide, the realm of passive AMD treatment can be illustrated by considering flows and loads (Australia Commonwealth 2016). Figure 7-5 shows a general range of acidity load for selection of passive or active treatment in a graphical format.

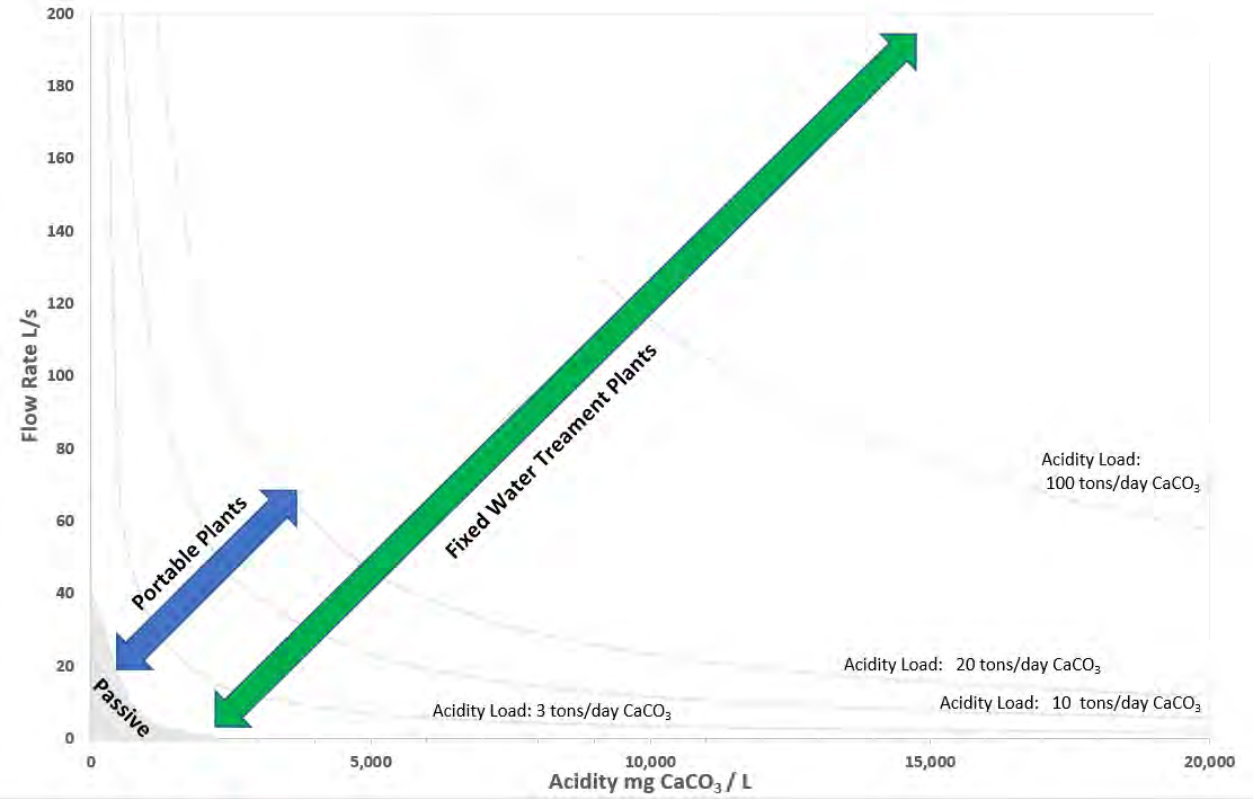

Figure 7-5: Acidity Versus Flowrate and Impact on Treatment Type (After Taylor et al. 2005)

Taylor et al. (2005) also provide the following broad guidance to decide on the applicability of active or passive treatment shown in Table 7-1 based on general ranges for acidity, flow and pH.

Table 7-1: General Guidelines for Selection Active versus Passive Treatment (after Taylor et al. 2005)

Treatment System	Average Acidity Range (mg $CaCO_3$/L)	Average Acidity Load (kg $CaCO_3$/day)	Av. Flow Rate (L/s)	Typical pH Range	Max pH Attainable
Passive	1–800	1–150	< 50	> 2	7.5–8.0
Active	1–10,000	1–50,000	No Defined Limit	No Defined Limit	14

Under neutral to slightly acidic conditions, much higher flows can be treated through passive treatment, especially where sufficient real estate is available and where the concentrations of iron, which is often the largest problematic dissolved constituent, can be decreased through aeration.

Most passive treatment systems currently in operation are used for post-closure, neutral, or low acidity load MIW sources. Where passive treatment systems are used for operating mine sites, they are most commonly associated with facilities that generate low flow rates of generally neutral water.

7.5.2 Temperature

Mine water treatment and its efficacy are impacted by temperature and its variation at a mine site. This is particularly important for passive systems, and other treatment technologies where microbial activity is relied upon to sustain reaction rates to treat an array of contaminants, such as nitrate, sulfate, and metals. This temperature variability affects solubility limits of the aqueous and solid species involved, as well as the solubility of interacting gases, such as oxygen in aeration processes, increased oxygen solubility at lower temperatures, or the rates at which degradation of, for example, cyanide may occur.

Temperature effects on the volumes of MIW requiring treatment are also important, especially in colder climates where flow rates may be impacted by freeze/thaw conditions. The EPA Reference Guide (EPA 2014) represents a useful summary document regarding limitations to treatment due to low temperatures. This includes observed limitations in the use of biological chemical reactors, fluidised bed reactors, reverse osmosis, zero valent iron, ion exchange, and biological reduction methods.

Another consideration for temperature is on the effluent side where discharge is to surface water. Surface water discharge permits often contain a requirement that discharge water temperature is close (+/-5°C) to the receiving water temperature. In colder climates particularly, the temperature of treated effluent may need to be considered compared to the ambient receiving environment temperatures.

7.5.3 Area/Real Estate Available for Treatment

The area available on a mine site or the downstream area between the source and discharge point can be a significant constraint to water treatment selection, especially for passive systems. Many active systems can be accommodated within a relatively small footprint. Conversely, in passive systems, aspects such as retention times, flow rate alignment with reaction kinetics, and the frequent need for multiple stages of treatment mean that a large area is frequently required. Additionally, the real estate may need to be amended to change the slopes such that the flow rates can be aligned with the required contact, reaction, and retention periods. Slopes that are too steep may result in flows that are too fast, whereas if the slopes and gradients are too gentle, metal precipitates can accumulate (in acidic conditions, this may lead to armouring or coating of limestone particles and precipitation may take place to decrease the porosity by filling the pore space). This can act to reduce the efficacy of the treatment/neutralisation and adversely affect the nature of flows in the passive system. Sufficient real estate is also needed to allow settlement of sediment or reaction products from the treatment.

Where active treatment is needed with limited real estate, modular systems have been used at several mine sites. Examples are in situ portable plants that are smaller and have lower capacity, but also have lower capital costs. Modular systems are often used for acid neutralisation through pH amendment. Typically lime (calcium hydroxide [$Ca(OH)_2$]) dosing can be applied for emergency or short-term pH neutralisation. Several options are available that use slightly different approaches to treat low flow or static sources (e.g., ponds or pits) through chemical amendment.

Another consideration in the selection of a mine water treatment alternative is disposal or storage of the treatment products. Technologies that generate significant treatment products, such as sludge, or technologies that generate large volumes of treated water or treatment brines, may also require significant real estate at the mine site or treatment area.

7.5.4 Constituents, Speciation, and Antagonistic Effects

Mine water treatment is not a one-size-fits-all solution. Because much of the focus is on acidic MIW, neutralisation and aeration/oxidation form a key part of many treatment arrays, but they are not appropriate for treatment of many other parameters of interest. Conversely, treating parameters such as selenium (a common contaminant in MIW) requires a chemically reducing environment. Under sufficiently reducing redox conditions (i.e. low E_h) for treatment of selenium, anions such as nitrate and sulfate will be preferentially reduced as these reactions are energetically favoured. Thus, although the reduction of selenate to selenite (or elemental selenium in selected cases) is the objective, high concentrations of sulfate and nitrate (or where atmospheric or dissolved oxygen is available) will act antagonistically and inhibit the efficacy of the selenium treatment.

7.5.5 Regulatory requirements

Targets for treated water quality will be site-specific and depend on a number of factors, including issues relating to the protection of the environmental values of receiving waters, the nature of the constituents of concern, and the regulatory environment. In many jurisdictions, direct discharge of treated water is only allowed if the discharging water has similar properties to the water in the receiving environment. As such, water treatment selection is typically constrained by the technology/range of technologies that can meet the general water quality criteria as well as the local catchment/state/provincial regulations. Even where the MIW is treated to remove the majority of the dissolved content (for example, through technologies such as reverse osmosis or ion exchange/ultrafiltration), there may be a further need to amend the treated water so that it does not cause environmental disruption from dilution or oxygen availability changes in the downstream environment. This is often represented as a regulatory requirement for effluent to be non-toxic or maintain a certain range of general constituents (e.g., the effluent does not change alkalinity, or DO by more than 10% from background).

7.6 Evaluation and Selection of Drainage Treatment Technologies

The approach adopted for mine drainage treatment will be influenced by a number of considerations discussed above, as well as factors outlined below. The considerations for evaluating and selecting water treatment do not differ significantly between active and passive treatment approaches and include:

- Properties of the MIW to be treated (water quality, acidity, contaminants of concern, and flow rates or water treatment volumes). While acidity, metals/metalloids, and pH are typically the focus, removal of major ions, such as magnesium and sulfate, may also be required.
- The objectives of the water treatment (stakeholder/regulatory expectations, final water use, characteristics of the receiving environment) and discharge location.
- Whether the mine is operating, in closure, or a legacy abandoned mine and the longevity of the project or treatment duration. Include life of mine for operating mines, closure period and strategy for mines in closure, and in-perpetuity operations versus other remedies for legacy properties.
- An understanding of changes over time. This could include changes in flow volumes or composition of the MIW between operations and closure, or the effects of climate change on the system. The treatment system should be flexible within the identified life-cycle changes. Flexibility should include the understanding of and the ability to implement additional phases or capacity (e.g., the use of modular designs).
- Seasonal flows and quality changes resulting in the required turn-up and turn-down range for the treatment equipment and mechanical systems. This is especially challenging for biological systems.

- Practical mine site features which may influence the construction, operation, or maintenance of a treatment facility, including mine layout, available area, source locations, etc.
- The handling and disposal of treatment residues (location, volume, proximity, etc.), etc.
- Staffing and power requirements. Site access and availability of trained operators (including skill level, cost of labour, etc.) and operator requirements should be considered. Sustainable power is required for reliable operation at remote sites.
- Proximity/visibility of the site to the public and its effect on public perception and sustainability goals.
- Financial factors including capital investment, capital replacement costs, operations, and maintenance costs, etc.

A simplified decision tree for selection of appropriate management alternatives is presented in Figure 7-6.

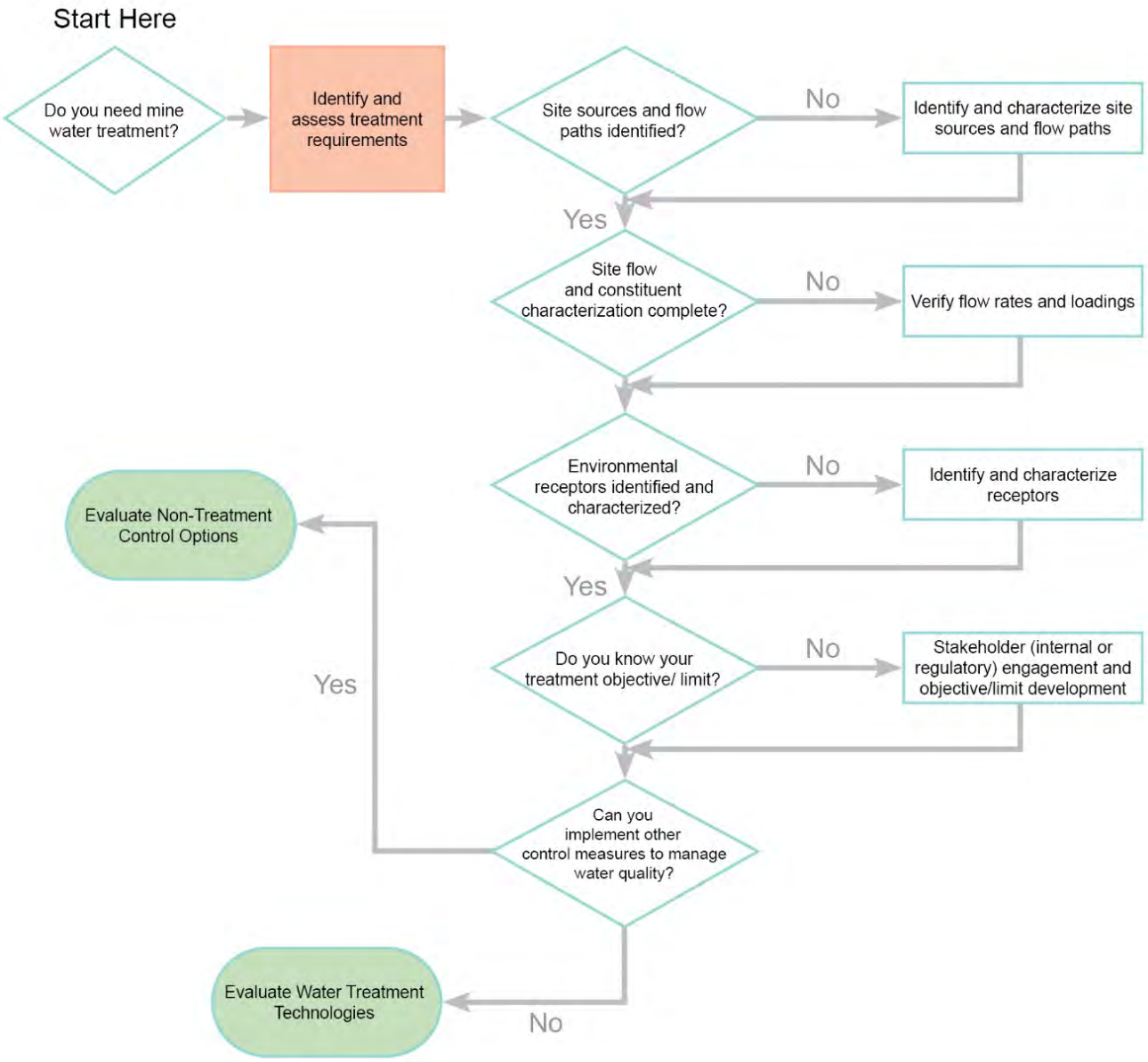

Figure 7-6: Simplified Tree for Decision Making

Very few treatment processes are stand-alone. Most mine water treatment systems include several treatment steps, chemical storage and feed systems, and residuals management systems for either brine or solids. In selection of the treatment process(es), there are multiple site-specific factors that may result in treatment of similar water quality at different sites by different treatment trains. As an example, Figure 7-7 shows the typical steps in an active treatment train as well as the technologies often used in MIW treatment in each step. This figure does not include chemical storage and feed systems or residuals management systems, but only shows the main flow path. Treatment train development for passive systems is similar, comprising influent and effluent equalization, beneficial steps, pre-treatment to remove constituents that may foul a primary treatment, one or more primary treatments, and potentially polishing treatment.

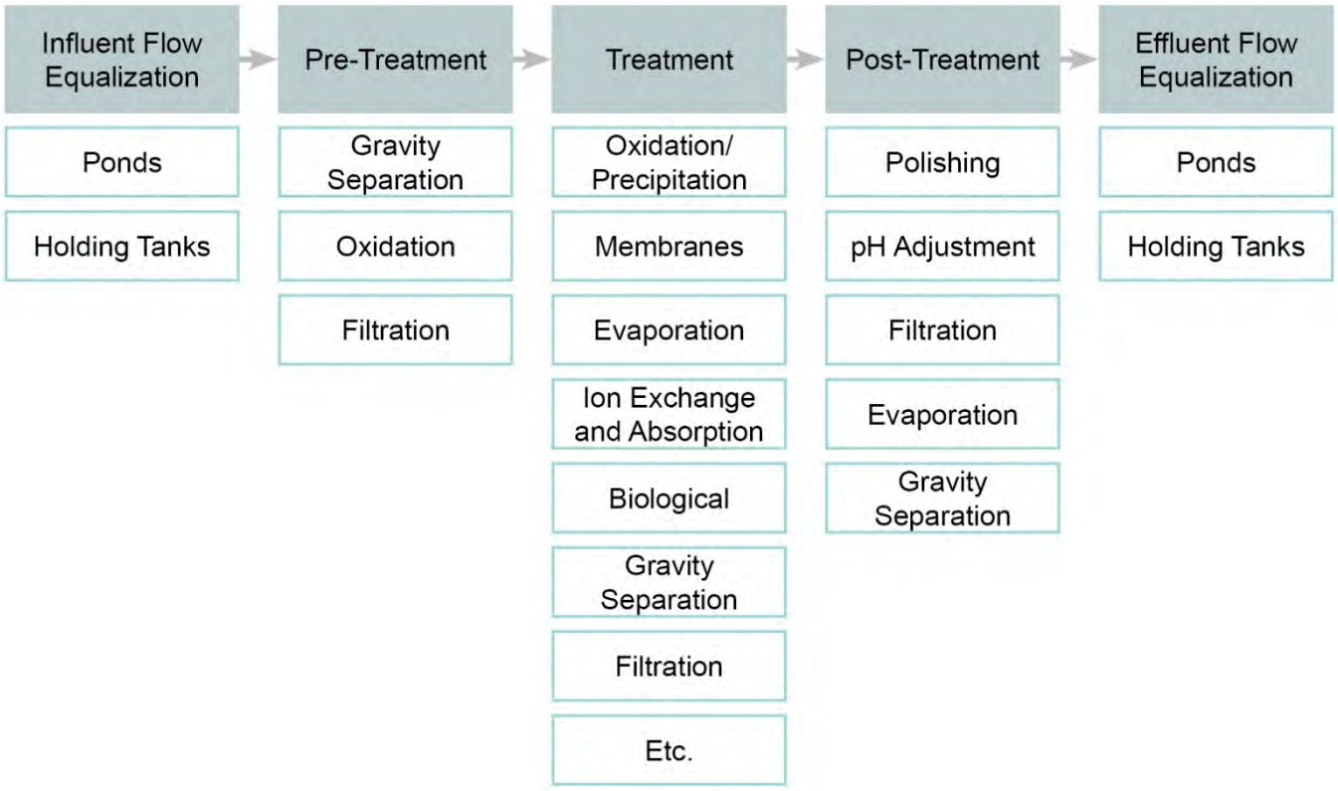

Figure 7-7: Active Treatment Train Example

A wide spectrum of MIW treatment technologies has been developed, proven, and applied to many different sites. The generic range of mine drainage treatment technologies is reflected in Figure 7-2. The summary descriptions of the different treatment technologies are divided into three sections to present active (Section 7.7), passive (Section 7.8), and in situ and in-mine (Section 7.9) treatment. The discussion in each of these three sections is framed in the context of current best practice of proven technologies, with emerging technologies specifically identified as emerging in mining applications.

Figure 7-8 presents an example decision path for acid mine drainage treatment and how to determine which sections of the following technologies presented could be applicable to specific water quality. Note this figure is intended to be an example of how to use the GARD Guide for evaluating potential treatment needs. As discussed previously in this chapter, there are many factors that affect treatment. The following sections are not dependent on earlier sections but can be used as standalone information sources for specific subject areas.

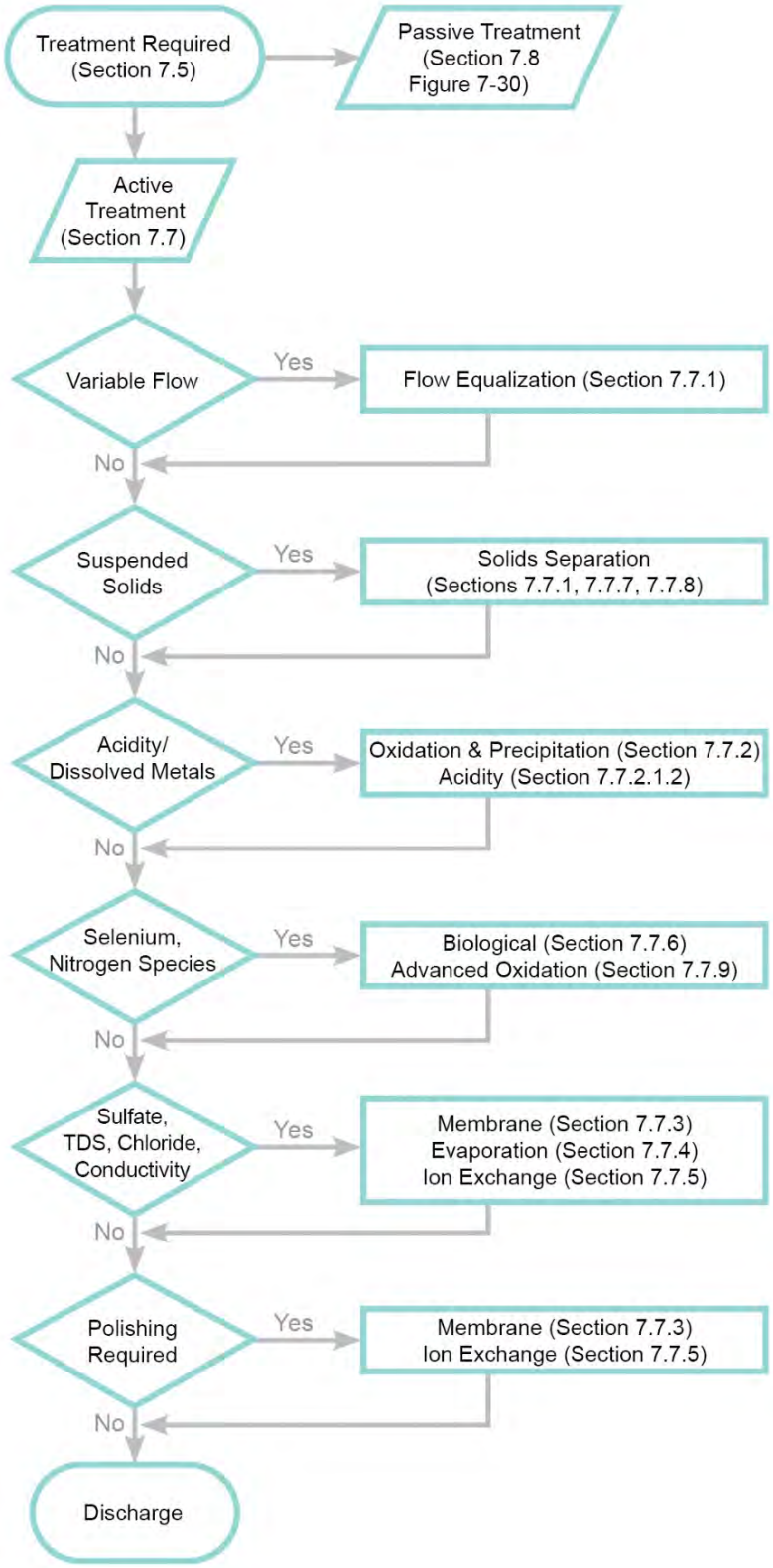

Figure 7-8: An example decision path for ARD treatment

In summary, the selection of MIW treatment is site-specific. However, based on broader industry experience (as presented in the remainder of this chapter), a general “scorecard” for the different treatment types is presented in Table 7-2 and Table 7-3. These general scorecards are intended as a broad overview of typical applications, however, as stated previously site-specific factors may result in a different perspective for some applications.

Table 7-2: Active Treatment Scorecard

Primary Contaminant Removal Technology	Constituents Typically Removed in Mining Applications	Pre-Treatment	Operational Requirements	Maintenance	Sludges	Implementation Mining/ Other	Overall
Oxidation	Iron, alkalinity	pH adjust in some cases	Low	Low	Low	Widespread	Well Developed
Precipitation /Coprecipitation	Most metals, some metalloids, SO_4^{2-}, some constituents of TDS and conductivity	Low	Low to High	Moderate to High	Moderate (caustic, sulfide) to High (lime)	Widespread	Well Developed
Membranes (RO and NF)	Most metals, some metalloids, Se, SO_4^{2-}, TDS, Conductivity, NH_4^+, NO_3^-, NO_2^-	Moderate to High	Low	Low	Moderate to High Volume Brine	Moderate/Widespread	Well Developed
Evaporation	Most metals, most metalloids, Se, SO_4^{2-}, TDS, Conductivity, NH_4^+, NO_3^-, NO_2^-	Moderate	Low	Low but specialized	Low Volume Brine	Low/Low	Well Developed
Ion Exchange and Adsorptive Media	Metals, metalloids, Se, SO_4^{2-}, TDS, Conductivity, NH_4^+, NO_3^-, NO_2^-	High	Low	Low	Low to Moderate Volume Brine	Low/Wide-spread	Well Developed
Biological	Se, NH_4^+, NO_3^-, NO_2^-	Low to Moderate	Moderate	Moderate	Low	Low/ Widespread	Well Developed
Gravity Separation	TSS, O&G, precipitated solids	NA	Moderate	Low	Low to Moderate	Widespread	Well Developed
Filtration / Solid Liquid Separation	TSS, O&G	Moderate	Moderate	Low	Low to Moderate	Widespread	Well Developed
Advanced Oxidation	Cyanide, NH_4^+, NO_3^-, NO_2, sulfides, Se	Moderate	Low	Low	Very Low	Low/Moderate	Well Developed

Table 7-3: Passive Treatment Scorecard

Primary Contaminant Removal Technology	Constituents Typically Removed in Mining Applications	Pre-Treatment	Operational Requirements	Maintenance	Sludges	Implementation Mining/ Other	Overall
Wetlands	Some metals, some metalloids, SO_4^{2-}, NH_4^+, NO_3^-	Moderate to High	Low	Low	Requires restoration/rebuild at site-specific frequency	Low to Moderate/ Moderate to High	Well Developed
Biochemical Reactors (originally known as sulfate reducing bioreactors)	Some metals, some metalloids, Se, SO_4^{2-}, NO_3^-	Low to Moderate	Low	Low	Requires restoration/rebuild at site-specific frequency	Moderate/ Moderate	Developed
RAPS (originally known as SAPS)	Some metals, some metalloids, SO_4^{2-}, NH_4^+, NO_3^-	Low to Moderate	Low	Low	Low, requires restoration/rebuild at site-specific frequency	Moderate/ Unknown	Developed
Anoxic Limestone Drains	Some metals, some metalloids, SO_4^{2-}	Low to Moderate	Low	Low	Low, requires restoration/rebuild at site-specific frequency	Moderate/ Unknown	Developed
Open Limestone Drains (also known as open limestone channels)	Some metals, some metalloids, SO_4^{2-}	Low to Moderate	Low	Low	Low, requires restoration/rebuild at site-specific frequency	Moderate/ Unknown	Developed
Limestone Leach Beds	Some metals, some metalloids, SO_4^{2-}	Low to Moderate	Low	Low	Low, requires restoration/rebuild at site-specific frequency	Low to Moderate/ Unknown	Developed
Manganese Oxidation Beds (also known as manganese removal beds)	Mn	Low to Moderate	Low	Low	Low, requires restoration/rebuild at site-specific frequency	Low to Moderate/ Unknown	Developed

7.7 Active Treatment Technologies

Active treatment refers to technologies requiring regular operator attention, maintenance, and monitoring based on external sources of energy (electrical power) and often using infrastructure (e.g., highways, rail lines, power grid). The active treatment technologies typically utilized at mine sites and considered state-of-the-practice proven technologies for primary contaminant removal include oxidation and precipitation, membranes, evaporation, ion exchange/media absorption, biological, and solid/liquid separation. There are also some emerging technologies that will be discussed in this section that show promise, are in development, are proven for treatment of other industrial wastewater sources, and/or have been installed in a few mining applications. Other equipment (pretreatment, residuals management, and chemical feed systems) required for each primary active treatment technology is also discussed in the relevant subsections below.

7.7.1 Flow Equalization (Flow and TSS)

Equalization, or the capacity to store a number of hours or days of influent at the peak flow, provides a damping effect on flow and/or concentration, and is an important component of water treatment. If space and logistics allow, influent and effluent equalization are highly recommended as part of any treatment system. Equalization can be provided in ponds, tanks, or naturally occurring features such as pits or other areas of the mine. On the influent side, equalization of both flow and contaminant load provides benefits to both the design and operation of the treatment system. Ideally, influent equalization is large enough to smooth spikes in flow or concentration during high-precipitation periods and dry periods. With sufficient equalization, the hydraulic design of the treatment system is not based on a short-term maximum value. Instead it can be based on an average value for the high-flow period (such as freshet, spring runoff, or the rainy season) and then the low and average flows are not orders of magnitude different than the high flow. Effluent equalization provides a damping effect on effluent quality and a safety net in the event of an upset or other reduction in treatment efficiency that may impact effluent quality.

Flexibility to accommodate a range of flows and contaminant concentrations should always be designed into an active treatment system for mine water; however, there are several challenges when flows vary by an order of magnitude or higher that impact capital cost and the operational efficiency of the system, including:

- Piping systems are designed to maintain a target linear flow for pressure drop calculations and to ensure gravity flow and/or pumping systems operate as expected. In addition, mine water treatment systems typically have several piping routes for carrying suspended solids that must maintain a minimum linear flow to prevent settling in the pipelines.
- Pumps can be put on variable drives to accommodate large flow ranges, which increases the cost of the pumps. There is a limit to the flow range of a variable speed drive. In addition, maintenance requirements are reduced when the pump is operating at the target efficiency on the pump curve for the majority of the time rather than a short duration extreme period. Multiple pumps can also be used to minimize this problem, but this adds rotating equipment to the maintenance schedule and there are still operational and maintenance requirements to rotating equipment if they are offline most of the year and only used during high-flow periods.
- Mechanical water treatment equipment requires maintenance even if it is offline for several months per year. Oversizing equipment or having parallel trains of equipment provides significant system flexibility, but does increase the labour requirements, even when offline.
- Equalization of the effluent also provides benefits and should be considered in addition to influent equalization.

Equalization is an important part of a mine water treatment plant and, in general, is less expensive to operate than increased installation of equipment and mechanical systems.

The equalization pond can also provide gross removal of TSS or be designed for TSS removal and provide equalization. Regardless of the purpose of the pond, if TSS is present in the influent water, ideally the pond should be designed to store a number of months or years of settled solids and then consideration given to campaign-style dewatering. Consideration for sediment removal needs to be included in the pond design and operations strategy. The influent equalization/settling pond can also be designed for addition of a settling aid, if desired, and often may be the only treatment step required if TSS and particulate metals are the contaminants of concern. TSS removal is also discussed in Sections 7.7.2.3 and 7.7.7. More in-depth guidance on design and sizing of settling ponds is available in several sources (BCMOE 2015, IECA 2018, Clark 2010, EPA 2013).

7.7.2 Oxidation and Precipitation (Acidity and Metals)

For the purposes of this section, oxidation and precipitation include treatment steps where a soluble contaminant is removed from a mine water source by altering the conditions of the water to promote the formation of a solid precipitate. Advanced oxidation for removal of soluble species such as cyanide is addressed in Section 7.7.9. Acidity mitigation in mine water treatment is generally achieved by adding some form of lime and in a smaller number of cases, sodium hydroxide or caustic may be used. This is described in more detail in the hydroxide precipitation section (Section 7.7.2.1.2).

Oxidation and/or precipitation may be the most implemented treatment process for mine water. Subsets or specific types of precipitation used for mine water treatment include:

- Oxidation by aeration
- Oxidation by chemical addition (hypochlorite, peroxide, and similar chemical oxidants)
- Acidity mitigation by hydroxide addition
- Hydroxide precipitation (calcium hydroxide, sodium hydroxide, magnesium hydroxide, and other forms of lime are the most common)
- Hydroxide precipitation using lime in a high-density sludge (HDS) configuration
- Softening
- Sulfide precipitation
- Coprecipitation (iron, aluminum, barium)
- Barium precipitation of sulfate to low levels

7.7.2.1 Overview and Contaminants Removed

Precipitation techniques are effective on most metals, concentrations of sulfate higher than the gypsum solubility limit of approximately 1,600 mg/L to 2,500 mg/L (as sulfate), hardness, alkalinity, and fluoride. Acidity is addressed by the addition of a hydroxide chemical (i.e., lime) which increases the pH and also promotes the precipitation of metal hydroxides. TDS removal can also be achieved in some applications. Parameters that are not well removed by precipitation techniques include most organics (such as volatile organic compounds and dissolved BOD and TOC), ammonia, nitrate, nitrite, selenium, boron, chloride, sodium, and potassium. While sulfate is removed as calcium sulfate if lime is used for precipitation, it cannot be removed to lower than the gypsum solubility limit (in the range of 1,600 to 2,500 mg/L of sulfate) with lime precipitation. Sulfate can be precipitated to lower levels by ettringite precipitation (Section 7.7.10.1) or with barium chloride (or carbonate).

Barium sulfate is highly insoluble and addition of barium salts is extremely effective at removing sulfate to very low levels. However, barium is an expensive water treatment chemical and this rarely represents a cost-effective treatment option. TDS can also be reduced in some cases, but achieving low (typically in the range of 1,000 to 2,000 mg/L) TDS residual levels is also limited with precipitation.

Selenium is an element that can be present in many forms in MIW and its treatment is strongly impacted by its speciation. An overview of selenium chemistry is presented in the white paper addendum on the State-of-Knowledge on Selenium Treatment Technologies (Golder, 2020). The predominant forms present in mining water typically are selenate [Se(VI)] and selenite [Se(IV)], with the selenite form removed by iron coprecipitation and the selenate form not well removed by chemical precipitation techniques. For most mining waters, selenium is predominately present in the selenate form, so technologies other than precipitation must be considered. Initial evaluation of the mining water should include selenium speciation if selenium is present in the water.

7.7.2.1.1 Oxidation/Aeration

Oxidation can be a stand-alone treatment process effective for precipitation of soluble iron or for removal of excessive alkalinity (at pH levels lower than approximately 6), and removal of organics. In the presence of soluble iron, other constituents such as arsenic or radium can coprecipitate. Oxidation is also often used as part of a chemical precipitation treatment system where it improves metals removal in combination with pH adjustment. Oxidation can be accomplished by chemical addition (hypochlorite, peroxide, and similar) or aeration. Note that ozonation and more advanced techniques used for treatment of cyanide and other similar constituents are discussed in Section 7.7.9.

For treatment of MIW where dissolved ferrous [Fe(II)] iron is the primary contaminant, aeration is a viable and cost-effective treatment option. Only about 10 mg/L of oxygen can dissolve in water, so if there is more than about 50 mg/L of Fe(II), the water must be aerated to increase the available oxygen. Even at lower Fe(II) concentrations, aeration increases the level of dissolved oxygen (DO) and promotes oxidation of iron and manganese, increases chemical treatment efficiency, and can reduce chemical costs. Aeration also drives off dissolved carbon dioxide (CO_2), which may be present in MIW. Reducing dissolved CO_2 increases the pH, reduces the total alkalinity, and can reduce reagent requirements.

Aeration can be accomplished in simple systems using gravity, such as a rock-lined channel, to more complex systems that include mechanical aeration/mixing devices and require power. In-line systems that use Venturi-based jet pumps and static mixers can be a cost-effective alternative since the air and neutralizing agent can both be introduced into the same jet pump orifice, increasing operational efficiency (Ackman and Kleinmann 1984, 1991). If there is at least 20 psi (1.4×10^5 Pa) of excess systemic water pressure (e.g., the water is being pumped to the treatment site or the treatment system lies at an elevation below the mine water source), these simple in-line systems do not require additional power. Photos of a range of simple aeration systems used for treatment of coal mine drainage are shown in Figure 7-9 through Figure 7-12.

Figure 7-9: Gravity-based cascading aeration flume at a 25-degree incline (photo courtesy of Mike Kaufman, Chemstream, Inc.)

Figure 7-10: Conventional neutralization (a lime slurry and a flocculant being added near the rear of the photo and mechanical aeration of coal mine drainage (photo by Terry Ackman)

Figure 7-11: Static mixers being used to aerate coal mine drainage after in-line neutralization using jet pumps. At this site, replacing a conventional water treatment facility with an in-line system was highly cost effective (photo by Terry Ackman)

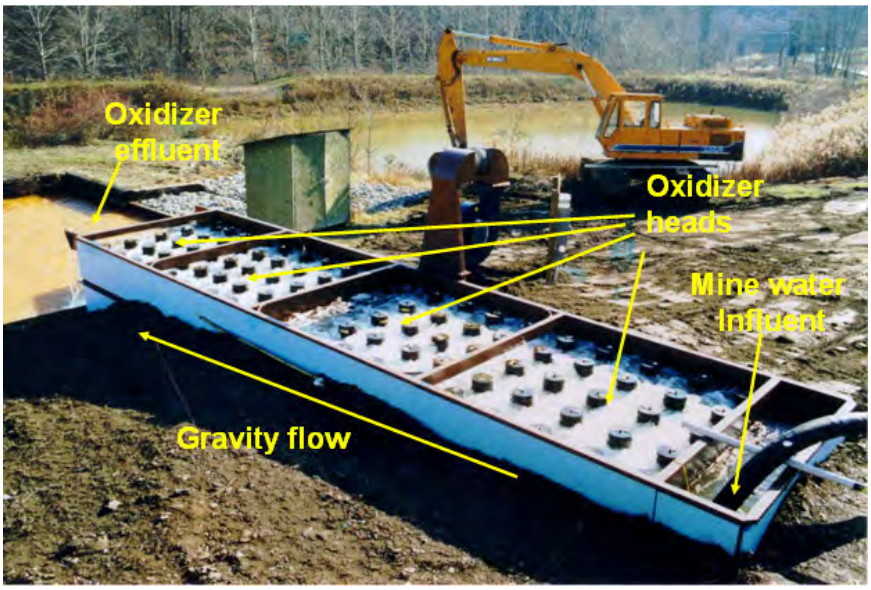

Figure 7-12: A commercial 15-horse-power (11,000 watt) aeration device (a Maelstrom Oxidizer) installed at a passive treatment site to aerate water flowing from an underground coal mine (photo by Don Budeit, Environmental Solutions Inc.)

Power requirements to operate an aeration device are low relative to other treatment equipment. For the more complex systems, equipment can include a blower, distribution system, diffusers to create fine bubbles, and mixing. Aeration systems can be installed in ponds or tanks. The blower can represent a safety hazard and proper engineering controls are required: in addition to being rotating equipment, it may need to be installed in an insulated room and hearing protection provided for work within a certain radius of the blower.

Chemical oxidation is also used for the treatment of dissolved Fe(II) by adding hydrogen peroxide, hypochlorite (sodium or calcium), or other oxidizing chemicals. Hydrogen peroxide has the advantage of not contributing TDS or additional ions to the water being treated, but treatability testing is generally required to select the best oxidant for the application. There may be additional oxidant demand from other constituents such as sulfide, manganese, other metals, organics, and similar parameters.

Oxidation may also be used to improve the treatability of target parameters by technologies other than precipitation. An example includes oxidation of arsenite [As(III)] to improve removal by reverse osmosis technologies. The oxidation techniques discussed in this section may apply as part of a treatment train where the process after oxidation is something other than solid liquid separation or chemical precipitation.

All oxidation techniques described above can also be used in combination with many of the other precipitation processes described below. The equipment and options are the same when used in combination with precipitation. Oxidation often improves metal removal and the precipitation treatment process, and should be considered in combination with precipitation.

7.7.2.1.2 Hydroxide Precipitation (Metals and Acidity)

Acidity is treated and neutralized as part of the hydroxide precipitation process where metals can also be removed if present. Metals [M] can form a number of insoluble hydroxide compounds according to the following generic chemical reaction:

Hydroxides: $M^{x+} + x\ OH^- \rightarrow M(OH)_x$

Metals removal by hydroxide precipitation typically involves alkali addition to a target pH for removal of the metal(s) of interest. The target pH is a higher pH than the pH of the influent water, promoting precipitation of the target compounds. It may also be advisable to pre-oxidize the metal (or metals) before precipitation where a metal can exist in more than one oxidation state. Pre-oxidization will assist precipitation because the more oxidized form of several metals has a lower solubility. This is, however, not true for compounds of chromium, selenium, and uranium, which are more soluble in oxidized form.

Figure 7-13 shows the change in solubility of several metal hydroxides with pH. Some metals have an amphoteric property, with decreasing solubility to a threshold pH, above which the metal solubility increases again because of the formation of a different set of soluble complexes. The figure also demonstrates that the point of minimum solubility is not the same for the typical metals of interest in mining waters. Most MIW has several metals present, and generally a target pH that provides the best removal of all metals is utilized. Most metals of concern can be effectively precipitated at a target pH in the range of 7 to 10.5, which is often experimentally determined. This is the range that is often effective for cadmium, chromium, cobalt, copper, iron, lead, manganese, nickel, silver, and zinc. If cobalt and/or manganese removal to low residual levels is required, the target pH will typically be greater than 10; however, if oxidation is included in the reaction system, then effective removal may occur at lower pH values, but low residual concentrations may not be achieved. There are also elements that are removed more effectively at lower pH values, such as aluminum. Depending on the mix of metals in the mine water source and the treatment requirements, it may be necessary to use two or three pH stages to achieve the required effluent goals. Solid-liquid separation is usually required between each pH step. Oxidation and the presence of soluble iron (either naturally in the mining water or added as ferric chloride or ferric sulfate as a treatment chemical) will both improve metals removal.

The most common alkali sources are lime and sodium hydroxide (NaOH), although magnesium hydroxide, limestone, sodium carbonate and other alkalis are used in some applications as discussed in Section 7.7.2.1. The selection of alkali source is mainly driven by cost, but there are other factors:

- Lime is one of the least expensive water treatment chemicals. At operating mine sites, the usage is usually much higher at the mill than for water treatment, so the cost is often even lower when the pricing is part of the overall mine usage.
    - Lime is supplied as either calcium hydroxide (hydrated lime) or calcium oxide (quicklime). The lime used for chemical precipitation is hydrated lime ($Ca(OH)_2$), but is often supplied as quicklime (CaO) that must be slaked on site to convert to hydrated lime. The choice of procuring hydrated lime versus quicklime is typically based on economics, with the benefit going to quicklime for usage greater than around 680 kg per day (1,500 pounds per day).
    - Lime storage and feed systems are notorious for requiring more labour and maintenance than other treatment components. Lime is sparingly soluble and is generally made up as a slurry that settles quickly. The slaker can also require higher operator attention.
    - The solids resulting from precipitation with lime typically settle and dewater better than treatment of the same water source with sodium hydroxide. The final sludge volume that must be disposed is lower than when sodium hydroxide is used even if the mass of sludge is higher with lime precipitation. The lime solids typically dewater better to a lower volume even when the mass is higher when compared to caustic precipitates.
    - Lime adds calcium, which can precipitate sulfate (to a residual concentration as low as 1,600 mg/L), alkalinity, and fluoride if removal of these constituents is required. For typical ARD with elevated levels of

metals and sulfate, the use of lime also provides TDS reduction because the lime precipitates both the metals and the sulfate.

  - Lime is generally less of a safety concern than sodium hydroxide because of the low solubility of lime.

- Sodium hydroxide is supplied as a 50% liquid or pelletized solid and relative to lime is much more expensive. The liquid can be used “as is”, but the solid requires makedown to a solution.

  - Handling of sodium hydroxide requires less equipment and operator labour, particularly if the 50% solution is procured. Only a storage tank and feed are required, although 50% sodium hydroxide freezes at approximately 13°C, so heating and insulation of the storage tank may be required.

  - Usage in pond or pit treatment may also be an advantage because the liquid chemical is denser than water.

  - For small usage requirements, sodium hydroxide can be preferred to lime because of the ease of use, with the feed coming directly from a tote or drum so that storage is not even required.

  - Sodium is added to solution rather than calcium so that sulfate, alkalinity, and fluoride will not precipitate, which reduces precipitate mass and scaling potential of the water. This may result in less of a reduction in TDS.

  - The liquid sodium hydroxide is also caustic and, therefore, requires specialized handling procedures and protocols.

Using a combination of alkali sources, such as limestone and lime or lime and sodium hydroxide, has also been proven effective.

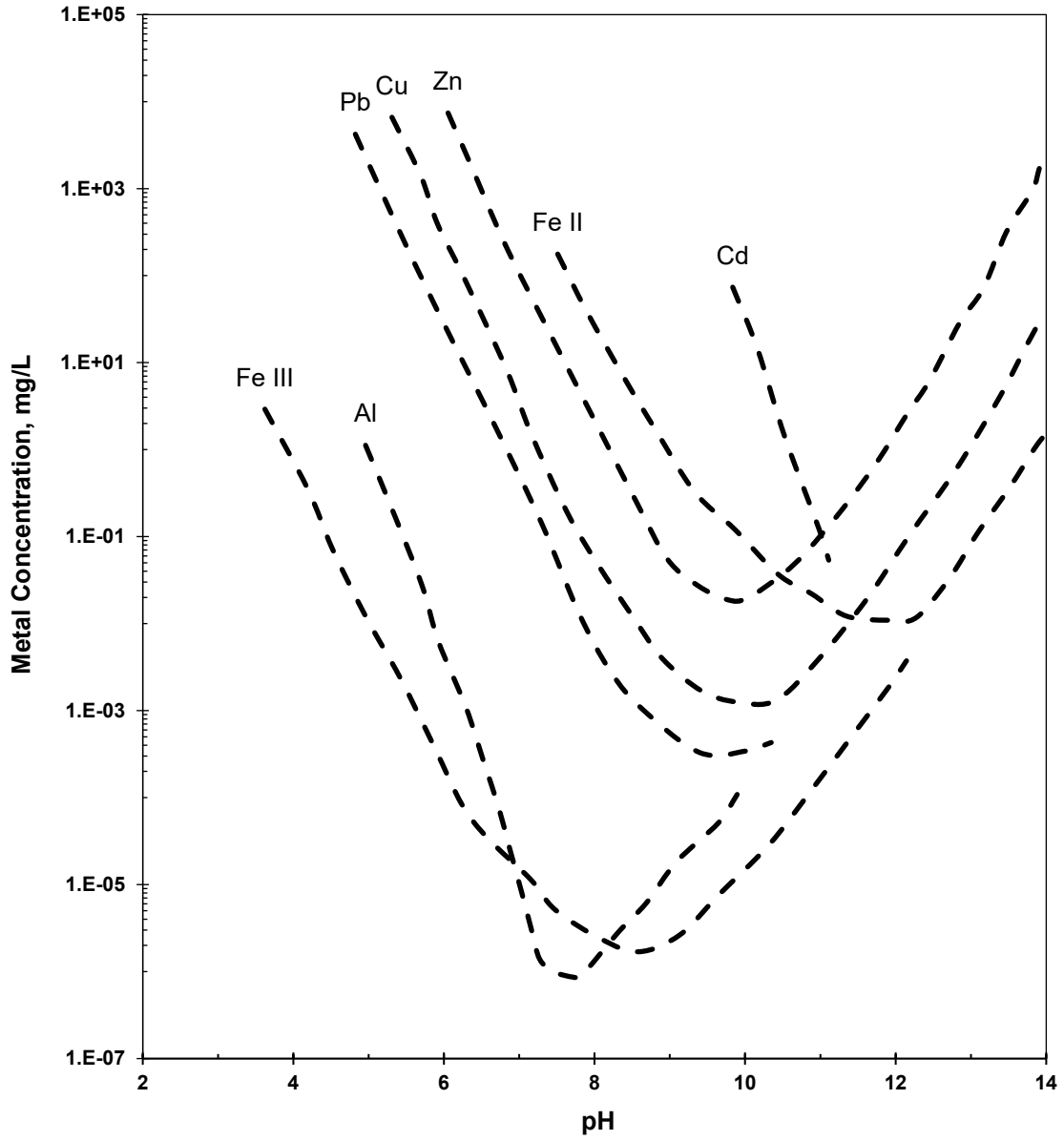

Figure 7-13: Examples of metal hydroxide solubility with pH (after SENES, 1994)

7.7.2.1.3 Lime High-Density Sludge

Lime HDS is a common configuration used for lime treatment of ARD and other MIW, providing improved contaminant removal and reduction in the volume of sludge requiring disposal. The HDS process utilizes familiar equipment and is similar to conventional lime treatment or low-density sludge (LDS), but it adds the lime to the system in an additional reaction tank called an alkalization or densification tank. Recycled sludge and lime are mixed in the alkalization tank, and the contents of this tank flow to a well-mixed reaction tank where influent water is also introduced. The reaction tanks may also include aeration or other oxidant addition and other treatment chemicals, such as iron addition if sufficient iron is not present in the influent mine water. The solids underflow in the clarifier has a higher solids content, or percent solids, than in a conventional LDS configuration. A portion of the clarifier underflow is recycled as shown in Figure 7-14, and a portion is sent to sludge management. If the clarifier underflow is further dewatered, the final dewatered filter cake has a lower volume and higher percent

solids than conventional LDS sludge that has been dewatered. Figure 7-14 is a flow schematic of an HDS process.

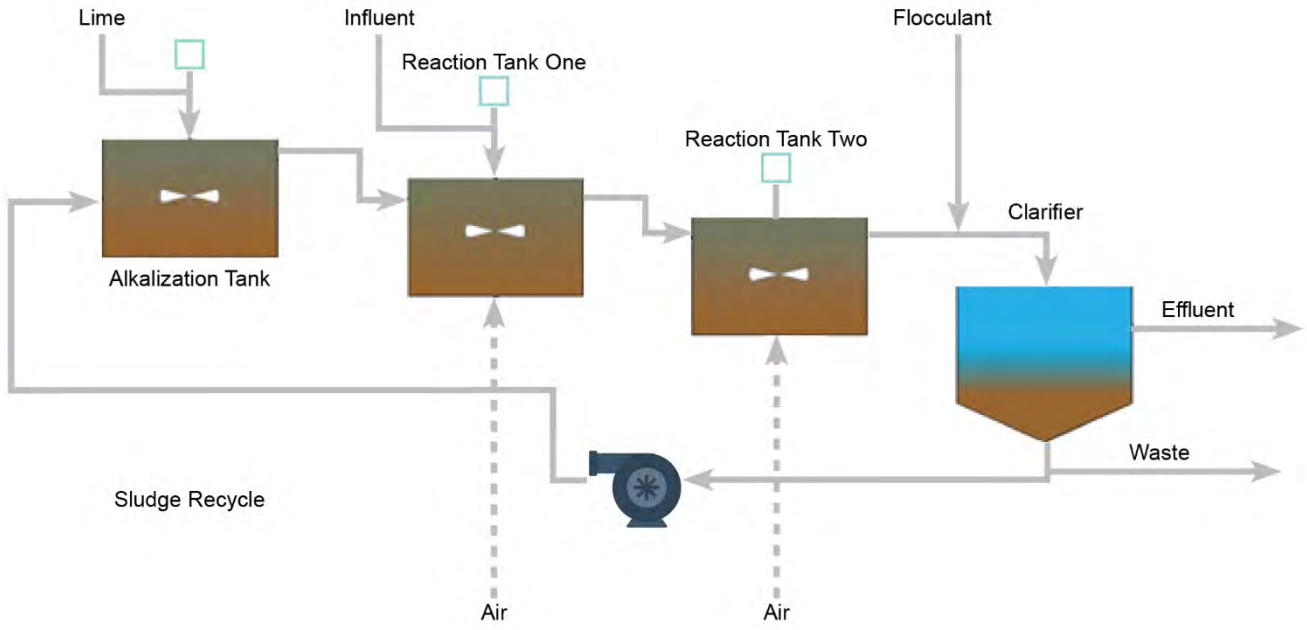

Figure 7-14: Schematic of Lime HDS Process

Note that this is a simplified diagram and does not show the chemical feed systems and sludge management, which are similar to those of an LDS system. Aubé (2019) provides information on the MacLeod Mine Water HDS treatment plant managed by the Ontario Ministry of Energy, Northern Development and Mines. In addition to design information, this presentation addresses several often-overlooked issues, such as mixing, type of pump for various duties in the plant, and includes several equipment photos.

One of the limitations of the HDS process is that the solid–liquid separation step is a conventional clarifier and there is typically no option to consider other solid–liquid separation processes with this technology. A larger clarifier is required relative to LDS treatment due to the high rate of recycled solids. Additional tankage and pumps are also required for the sludge recycle step. The lime dose and volumetric sludge generation rate are generally lower than for the conventional LDS process, and the treated effluent quality may be better (i.e., lower concentrations of residual dissolved metals).

The densified sludge in the clarifier underflow is often in the range of 10% to 30% solids (or higher) depending on the specific mine water and treatment plant. Conventional LDS clarifier underflow is typically 5% solids or lower. Dewatering the underflow provides an additional benefit, with the HDS process often producing dewatered sludge with solids as high as 35% to 50% compared to an LDS sludge, which is often closer to 20% solids. The actual solids content of the underflow and from the filter press is highly dependent on the ratios of iron, aluminum, and manganese sludge, as well as the calcium sulfate contribution. The result is that HDS produces a lower sludge volume that requires disposal and consumes less lime. Operation of the HDS system may necessitate a higher level of operator skill than other precipitation technologies and there is more equipment, so the labour requirements may be higher, although the sludge dewatering requirements are reduced.

HDS is one of the most-implemented active mine water treatment processes using precipitation, and so there is ample information available in the literature on constructed cost, process flowsheets, water quality, flow rates, and other information. For example, the State of Colorado operates three lime HDS plants as follows:

- The Argo Tunnel Water Treatment Plant began operating in 1998, treating ARD with a chemical precipitation system based on sodium hydroxide addition. The plant was converted to a lime-based operation in 2004 and later converted to lime HDS. See the case study in Section 7.14 for additional information and a Fact Sheet (CDPHE 2015).
- The North Clear Creek Water Treatment Plant treats contaminated water from historic mine workings and tunnels, and began operation in 2017. Information regarding the plant flowsheet, capacity, and constructed cost is provided on the Grand Opening Fact Sheet (CDPHE 2017).
- The Summitville Mine Water Treatment Plant began operations in 2011 as a new lime HDS system. The HDS system was a completely new build, replacing an existing conventional lime-based treatment plant that had been in operation for approximately 20 years. The treatment plant is not operated in the winter from approximately mid-November to approximately mid-March due to heavy snowfall and extreme weather. Water is collected in an impoundment during this time period and treated when the plant is operational. See the fact sheet for more information, flow diagram and photos (CDPHE 2019a).

7.7.2.1.4 Limestone

Limestone has been used for decades to raise pH and precipitate metals in MIW (Deul and Mihok 1967, Mihok 1970). It has the lowest material cost and is the safest and easiest to handle of the ARD treatment chemicals. It is particularly useful when the only contaminants of concern are iron and aluminum, as is often the case in CMD. Unfortunately, its successful application is limited due to its low solubility and tendency to develop an external coating, or armour, of iron (hydr)oxides (e.g., $Fe(OH)_3$) when added to ARD. Limestone, when simply placed into mine water, should be very fine grained (a high particle surface area / volume ratio), and with good mixing. The goal is for the limestone to dissolve before it becomes armoured. When pH is low and the metal concentrations are also relatively low, finely-ground limestone may be positioned into drainage directly (limestone sand application) or limestone gravel may be ground into powder by water-powered rotating drums (limestone drum stations) and metered into the drainage. Sand-sized limestone has also been placed in a large cylindrical tank and mixed with the ARD which is introduced into the bottom of the tank; these are called diversion wells (Faulkner and Skousen 1995, Arnold 1991). Diversion wells use the power of the drainage to fluidize (form a suspension) the limestone. The limestone particles rub against each other vigorously, which allows dissolution without armouring. Limestone has also been used to treat MIW in anaerobic (e.g., anoxic limestone drains) and aerobic environments (e.g., open limestone channels). These are covered in more detail later in this chapter, as part of passive treatment (Section 7.8).

A novel integrated limestone/lime neutralization process was developed at the South African Council for Scientific and Industrial Research (CSIR) (Geldenhuys et al. 2003), as shown in Figure 7-15. The integrated limestone/lime process incorporates the following three process steps:

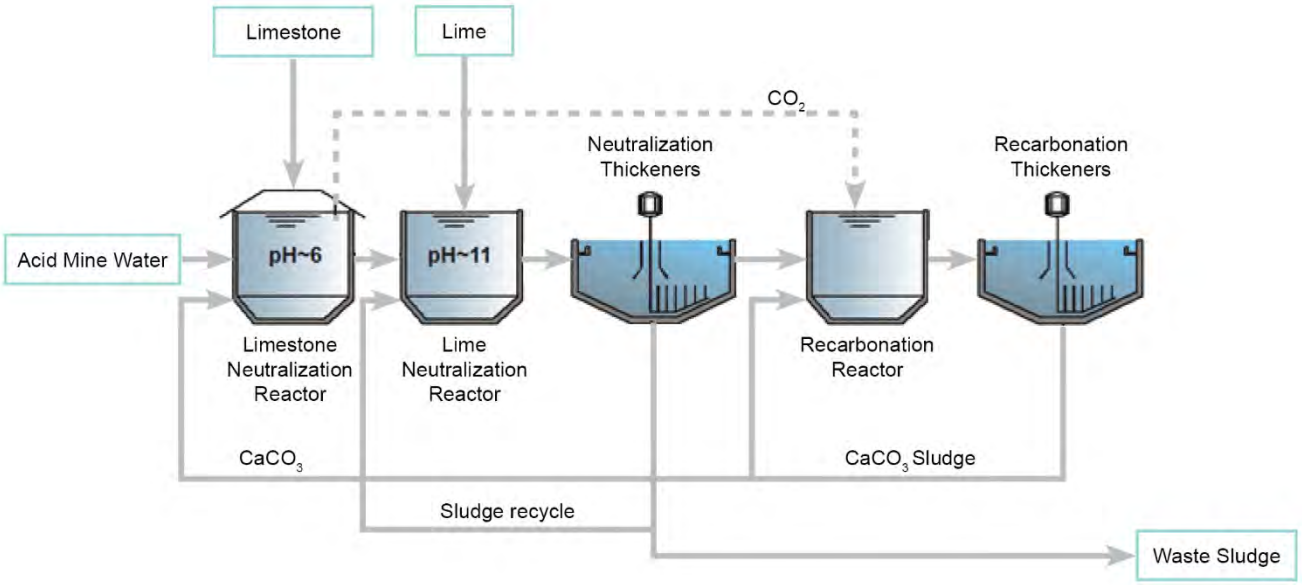

Figure 7-15: Integrated Limestone/Lime Neutralization Process

The integrated limestone/lime process incorporates the following three process steps:

- Pre-neutralization using relatively inexpensive limestone
- Lime neutralization to a pH target, which is dictated by the treatment targets such as specific metals removal (this step is also designed to precipitate gypsum)
- Re-carbonation and pH adjustment using the CO_2 generated in the first process step

The benefits of the integrated limestone/lime process relate to the efficient use of relatively inexpensive alkali materials and reuse of alkali sludge produced in the process. Many process streams within mineral processing facilities are highly alkaline (e.g., waters from flotation plants). Therefore, excess process waters from the flotation plant could be mixed with ARD for neutralization.

7.7.2.1.5 Other Forms of Alkali Addition

Magnesium hydroxide and other alkalis may have advantages over lime or sodium hydroxide in some applications, but their usage is not as common as lime or sodium hydroxide for moderate and higher flow mine water treatment and should be evaluated on a case-specific basis. Boron, for instance, has been shown to coprecipitate with magnesium, and so magnesium hydroxide may provide a benefit if boron removal is required. There are also instances, typically when the annual alkali requirement is lower, in which some of the other alkali sources, such as limestone or soda ash, should be considered. Skousen et al. (2018) provide a comparative description of six alkali materials and their use in treatment. Some of these other alkali sources are discussed in the following paragraphs.

At sites where it is not possible to provide as much supervision as the use of hydrated lime requires, pebble quicklime (CaO) has often been used, in conjunction with the Aquafix water treatment system. This device is powered by the force of the stream, using a water wheel concept (Jenkins and Skousen 2001). The advantage of this approach is the amount of maintenance and manpower is much less than required for a hydrated lime treatment plant, although it is still greater than for a passive treatment system. The amount of chemical added is dictated by the movement of a water wheel, which causes a screw feeder to dispense the chemical. The hopper

and feeder can be installed in less than an hour. This system was initially used for small and/or periodic flows with high acidity because CaO reacts very quickly. Recently, water wheels have been attached to large silos for relatively high flow/ high acidity situations.

Soda ash (Na_2CO_3) is generally only used to treat MIW in remote areas with low flow and low amounts of acidity and metals. Selection of Na_2CO_3 for treating ARD is usually based on convenience rather than chemical cost. Soda ash comes as solid briquettes, and is gravity fed into water by the use of bins or barrels. The number of briquettes to be used each day is determined by the rate of flow and quality of the water being treated. One problem with the bin system is that the briquettes absorb moisture, causing them to expand and stick to the corners of the bin. This prevents the briquettes from dropping into the stream. For short-term treatment at isolated sites, some operators use a much simpler system, employing a wooden box or barrel with holes that allows water inflow and outflow. The operator simply fills the barrel with briquettes on a regular basis and places the barrel in the flowing water. However, this system offers less control on the amount of chemical used.

7.7.2.1.6 Softening

Softening is a specialized subset of precipitation to treat “hard” water and is utilized in the treatment of MIW as a pretreatment step to other processes where scaling negatively impacts a treatment process such as evaporation and reverse osmosis. In softening, precipitation is used to remove calcium, magnesium, silica, and other divalent species by addition of lime and sodium carbonate (soda ash). The equipment and processes are the same as required for other precipitation processes.

7.7.2.1.7 Sulfide Precipitation

The sulfide precipitation process uses the addition of a chemical sulfide reagent to precipitate metal sulfides. Sulfides are reducing agents and precipitation is a reducing chemical reaction. Biologically produced sulfide can also be used, but is generally not considered to be a cost-effective alternative where metals concentrations are relatively high. The generic chemical reaction of sulfide with metals is similar to that of metal hydroxides:

Sulfides: $y\ M^{x+} + x\ S^{2-} \rightarrow M_y(S)_x$

Sulfide precipitation can have advantages over hydroxide precipitation in some cases because metal sulfides generally have a lower solubility limit than metal hydroxides (and thus, lower metal concentrations can be achieved), less sludge may be generated, and metals can sometimes be recovered from the sludge, providing an economic benefit. See Section 7.11 for more information on metal recovered.

Influent water is blended with the chemical sulfide solution and thoroughly mixed to promote the formation of insoluble metal sulfide precipitates. The process is most effective in the pH range of 6.5 to 9.5, so less pH adjustment is typically required compared to lime treatment.

The chemical sulfide reagents used for precipitation include iron sulfide, sodium hydrosulfide, sodium sulfide, calcium sulfide, and organosulfide, available as a vendor product named TMT®. Sodium hydroxide may be used for pH adjustment in the sulfide precipitation system. Although higher in cost than lime, sodium hydroxide has the advantage in this case of further reducing the sludge generation by preventing the precipitation of gypsum. The decrease in sludge volume is one benefit while the formation of gypsum can also reduce the value of sludge to a smelter if metal recovery is planned.

Contaminants removed by sulfide precipitation are metals/metalloids including antimony, cadmium, chromium, copper, lead, mercury, nickel, silver, thallium, and zinc. Iron is removed by oxidation prior to sulfide treatment due to the cost associated with sulfide precipitation alone.

7.7.2.1.8 Coprecipitation

Coprecipitation is the removal of target parameters with the precipitation of other constituents in the water. The removal of arsenic from water by coprecipitation with iron is a good example. Arsenic will not precipitate without the iron. For MIW, the presence of iron or aluminum commonly improves the removal of other constituents. Barium can also be used and is highly effective for radium removal. Mining water often has naturally high concentrations of iron and/or aluminum and, if not naturally present, they may be added as a sulfate or chloride salt. Iron is often used preferentially to aluminum due to improved dewatering of iron sludge compared to an aluminum sludge. The mechanisms associated with coprecipitation include adsorption and entrapment of the target parameter in the precipitating particles (iron or aluminum hydroxide). Substitution in the crystal lattice of the precipitating particles is another potential removal mechanism. Coprecipitation results in the removal of constituents that would normally be expected to be soluble under the conditions present in the solution.

Coprecipitation can be a stand-alone process for removal of a specific contaminant, such as arsenic or radium, or can be combined with a precipitation process and iron or aluminum can be added to the hydroxide reaction tank. Removal of metals present in MIW can be enhanced by coprecipitation mechanisms due to the high naturally occurring concentrations of aluminum and/or iron, which results in high removal efficiency and potentially lower than expected residual concentrations of metals in the treated water. Coprecipitation as a stand-alone process can be cost effective for treatment of mining water with lower influent concentrations of metals. Iron and aluminum salts have associated acidity, and pH control may be required to maintain the pH near neutral conditions depending on the dose required and the alkalinity in the water.

Parameters often treated by coprecipitation include the following:

- Arsenic – coprecipitation with iron at Fe:As ratios typically in the range of 20:1 to 50:1
- Antimony – coprecipitation with iron at lower pH values (pH 4 to 5 range) for optimal removal
- Radium – coprecipitation with iron or barium (added as barium chloride)
- Molybdenum – coprecipitation with iron most effectively at lower pH values (such as 4.5)
- Other parameters – several other metals/parameters can be effectively removed by coprecipitation and this technology is not limited to these examples

Selenite has also been removed by coprecipitation in some applications. Co-precipitation of selenite with ferric sulfate is presented in the NAMC white paper as a case study (Golder 2020). The coprecipitation process is identical to hydroxide and sulfide precipitation with regard to equipment required, operation, and waste produced.

7.7.2.2 Pretreatment, Polishing, and Ancillary Equipment

For precipitation processes, pretreatment is typically not required. The ancillary and polishing equipment is similar for all types of precipitation and includes the following:

- Chemical storage and feed systems – For oxidation by aeration, no chemical feed is required, but for other forms of oxidation, precipitation, and coprecipitation, the equipment includes storage, chemical makedown, and chemical feed systems.
- Reaction and mixing – This often includes one or more tanks and mixers, but mixing could occur in-line and a pond or other similar feature could be used to provide reaction time. An aeration system may be designed to contribute to the mixing in the reaction tank.

- Solid-liquid separation – At mine sites, this has traditionally included a pond or clarifier; however, other methods of solid-liquid separation are being implemented more frequently, including membrane filtration (microfiltration, ultrafiltration), ballasted clarification, inclined plate clarification, dissolved air or induced gas flotation, centrifugation, and other similar approaches.
- Solids storage and dewatering – May include transferring a solids slurry (typically 0.5% to 5% solids unless HDS system) directly to final storage as a slurry or may involve sludge storage tank and dewatering such as filter press, belt press, or Geotubes®.
- Effluent polishing – May include final filtration, pH adjustment prior to discharge, polishing for a specific parameter, or similar.

The lead time on this type of equipment is standard (typically 12 to 16 weeks for most equipment); however, for applications that require large capacity lime slakers, clarifiers or filter presses, the lead time can be 5 to 8 months once the treatment system has been defined.

7.7.2.3 Equipment and Typical Process Flow Diagram

The treatment equipment for the precipitation process is fairly simple and consists of a reaction tank providing a target retention time and mixing. Aeration may be incorporated as part of the mixing system. For most MIW, particularly those with high concentrations of sulfate, a longer reaction time in the range of one to two hours is used to ensure that the chemical reactions are complete and post-precipitation and scaling do not occur in subsequent treatment steps. For MIW that require more than one target reaction pH, multiple reaction tanks are provided.

The lead time on this type of equipment is fairly standard (typically 12 to 16 weeks for most equipment); however, as discussed in the previous section for applications that require large clarifiers, the lead time for the clarifier mechanism can be several months.

Example flow diagrams showing typical equipment requirements for precipitation are presented for three cases. Figure 7-16 shows relatively simple aeration and settling in a pond. This type of flowsheet would be effective for TSS removal, soluble and particulate iron removal and, if there is soluble iron present, could provide arsenic or radium removal.

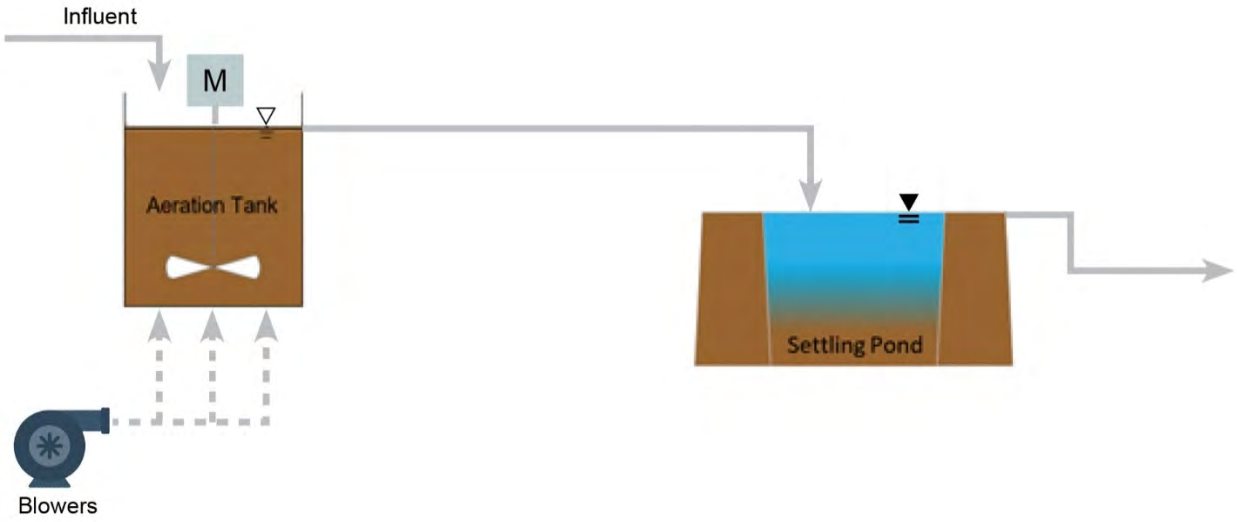

Figure 7-16: Aeration and Settling Schematic

Figure 7-17 shows a typical lime HDS treatment system effective at removing soluble metals and sulfate (down to approximately 1,600 mg/L residual sulfate). This diagram shows the ancillary equipment and is more detailed than other schematics shown in this section for demonstration purposes about the additional equipment required.

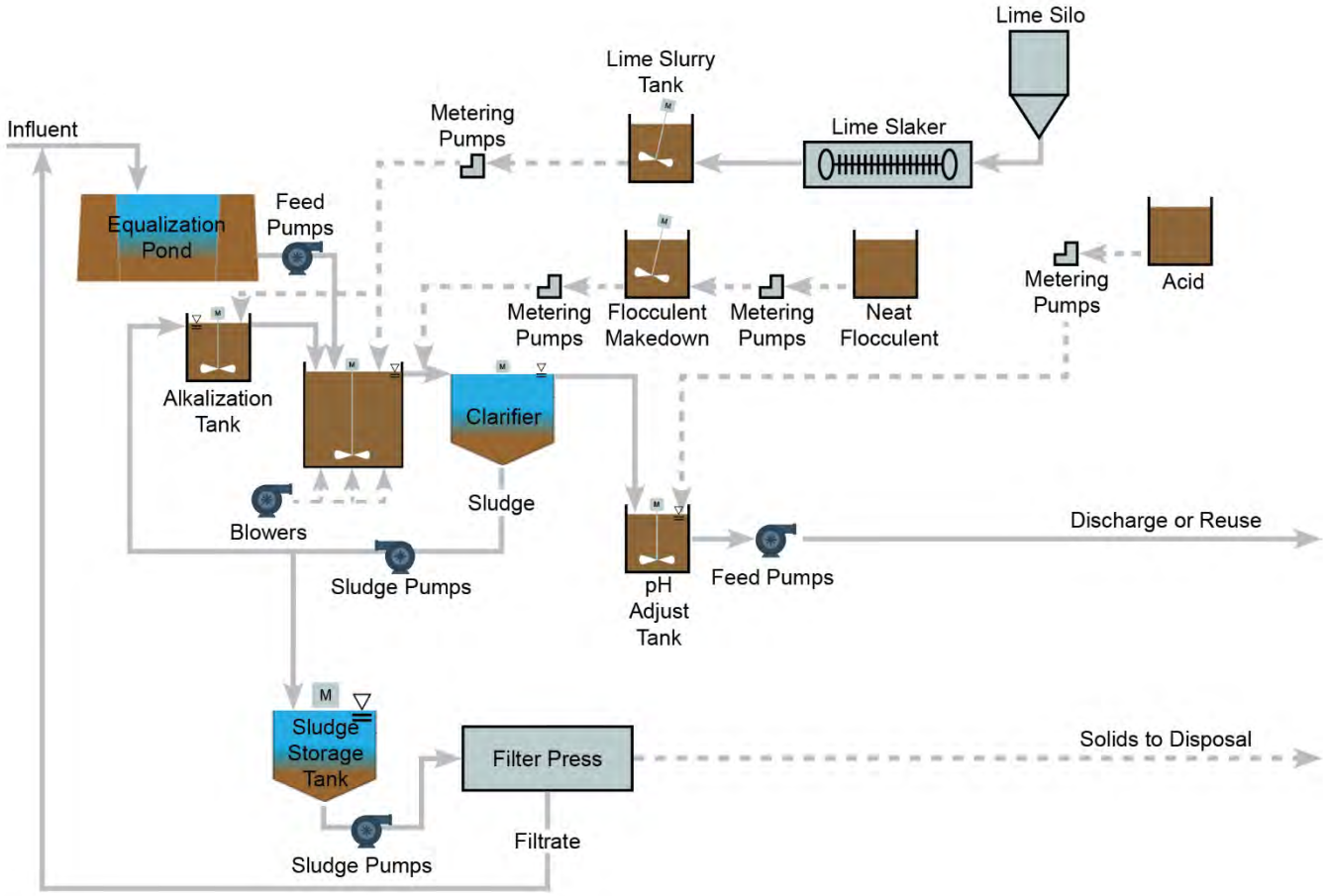

Figure 7-17: Typical lime HDS treatment system

Figure 7-18 shows a sulfide precipitation treatment process.

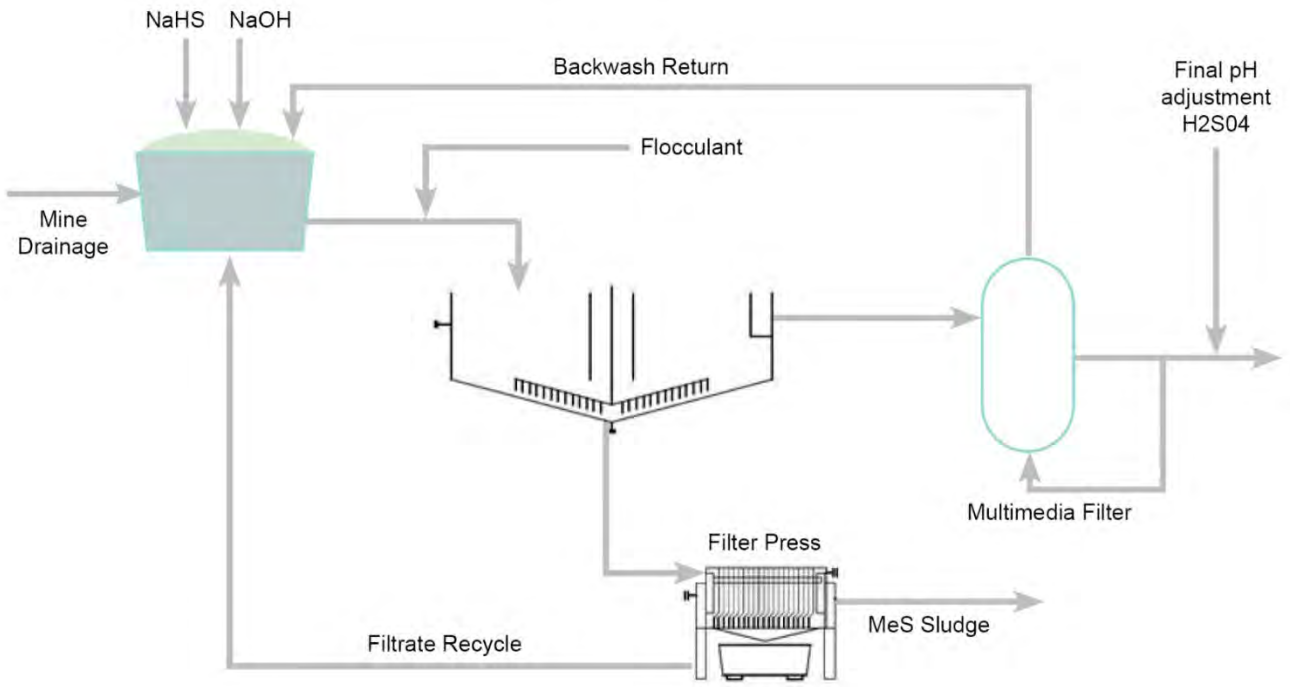

Figure 7-18: Sulfide precipitation treatment flow diagram

7.7.2.4 Operation and Maintenance Considerations

The operational and maintenance requirements for chemical precipitation treatment processes are generally higher than for other treatment processes, but this generalization is dependent on the flow rate, contaminant load, and other site factors. Aeration and iron removal are much simpler and could have fairly low labour requirements and chemical costs. The quantity of chemical required and sludge produced are major factors in the labour requirements, particularly for lime storage, slaking and feed equipment and sludge handling. These increased requirements are balanced by the overall gross quantity of contaminants removed and the overall cost compared to alternative technologies. General considerations regarding the operations of precipitation systems for typical MIW by lime HDS treatment for high metals and sulfate concentrations are as follows:

- The lime slaker and feed system, the filter press or sludge handling system, and clarifier all require regular operator attention. The systems can be automated to run unattended for one to two shifts per day but ultimately they are dependent on their robustness and the controls/alarms that influence the automation performance and reliability.
- For operating mines, the equipment used for precipitation is similar to equipment used at the mill, so the equipment is familiar to site personnel. The chemicals used are also familiar to site personnel, improving the safety of the treatment plant.
- For operating mines, maintenance personnel are available when needed and familiar with the equipment. At closed mine sites, the mechanical equipment is primarily pumps, mixers, motors, and other relatively standard mechanical equipment.
- For operating mines, there are typically areas on site for disposal of sludge, and the sludge volume is often much smaller than other residuals produced. For closed mine sites, lime sludge generally passes the Toxicity Characteristic Leaching Procedure (TCLP) and can be disposed in a non-hazardous landfill or on site if an appropriate area is available.

For treatment of MIW by oxidation for precipitation of iron and arsenic, the operation of the treatment system is much simpler whether the flow is high and handled in a pond system or low and in a small, aerated tank with associated equipment. The operational labour, sludge produced, and other factors are much different than for the lime HDS treatment system. Very little sludge will be produced with only iron hydroxide precipitating. No chemicals are required, and so the safety hazards due to chemical exposure are much lower while lifting requirements are reduced since no chemical makedown is required.

A sulfide treatment system produces much less sludge than a lime system, and so the operational and maintenance requirements are between those of a lime HDS system and the aeration system. Sulfide gas may be present and appropriate monitoring should be included.

The flexibility of precipitation systems to accommodate changes in flow and contaminant load is higher than most treatment systems as long as the hydraulic capacity of the pumps, piping, and other mechanical features is not overwhelmed. This is particularly true for pond type systems, but also for lime and lime HDS systems as long as operations personnel evaluate the operation of the clarifier and make appropriate adjustments, as required.

7.7.2.5 Process Development and Testing Required

Chemical precipitation is well defined as a treatment process for mine waters, including all the various subsets described in Section 7.7.2. Bench testing consists of jar testing which allows comparative evaluation of a number of treatment chemicals and conditions (pH, with and without oxidation) with small volumes of water (500 mL to 1 L). In addition to contaminant removal, the sludge quantity, and chemical dose can be determined. Lime HDS can also be evaluated with bench-scale testing to determine the number of sludge recycles and solids concentration. Once bench testing is complete, pilot testing can be conducted, but is not always required depending on the application and whether representative water is available and the bench-scale testing is reflective of treatment system conditions at a site level application.

7.7.3 Membranes (TDS, Sulfate, and other Dissolved Constituents)

Membrane treatment for the purposes of this section includes the membrane processes that are commercially available and proven to remove dissolved constituents from water. The membrane types included in this section are reverse osmosis (RO) and nanofiltration (NF). NF is a specialized type of membrane treatment aimed at removal of divalent and higher valence ions and does not remove monovalent ions. Other membrane processes that remove fine particulates, including microfiltration (MF) and ultrafiltration (UF), will be considered as a solid-liquid separation process (Section 7.7.8) and are not included in this section other than as a potential pretreatment step.

7.7.3.1 Overview and Contaminants Removed

RO and NF systems both utilize a series of semi-permeable membranes and a high-pressure pump to remove dissolved constituents. The clean water and extremely low levels of some ionic constituents passing through the membranes are called the permeate stream. Most dissolved constituents in the MIW are retained by the membrane in a concentrated stream called the brine. The ratio of permeate to feed water is called the recovery, so a 75% recovery indicates that 75% of the influent feed flow to the unit is permeate and the remaining 25% is the brine stream. These numbers are used for demonstration purposes, and the actual recovery achievable is dependent on a number of factors and requires complete water characterization to be determined for each case.

For RO/NF, there are two types of membranes commonly used for mine water treatment: brackish water membranes that are used for water with TDS that is generally less than 12,000 mg/L (Bates et al. 2010) and seawater membranes that are used for higher TDS up to approximately 40,000 mg/L. These membranes can concentrate up to approximately 80,000 mg/L on the brine side. There are specialty membranes that can be used

for even higher TDS water such as ultra-high-pressure membranes and extreme RO membranes, which can concentrate up to approximately 150,000 mg/L (Arrowood et al. 2016).

RO is a relatively non-selective process (removing almost all forms of anions and cations), typically providing a 95% to more than 99% removal for TDS to produce a high-quality treated effluent (permeate). Removal of dissolved constituents is termed rejection with RO and NF systems. Regulatory requirements for TDS, sulfate, chloride, sodium, and other difficult to treat, highly soluble parameters make RO one of the few treatment process choices for these applications. RO is also highly effective at removing selenium and particularly selenate, so oxidation of selenite as a pretreatment step can improve removal. RO membranes can be negatively affected by several parameters and pretreatment (discussed in Section 7.7.3.2) or chemical addition may be required. The chemical addition generally includes antiscalant which can reduce scaling of sulfate and carbonate salts. A biocide to control microbial biofouling of the membranes may also be added to the influent water.

A few contaminants are not effectively removed by RO membranes, or a specialized configuration is required to achieve high removal. Some of these constituents found in MIW include:

- Nitrate – The removal of nitrate by RO can be lower than 90% with conventional brackish water membranes, with the rejection decreasing with membrane age and cleaning cycles. Higher removal can be achieved with seawater membranes or an RO system design that includes multiple stages of permeate treatment.
- Boron – The pH of the feed water to the RO must be greater than 9.3 for removal of boron, and removal is typically not greater than 90% with a single pass using brackish water membranes. New membranes have been developed targeting boron rejection.
- Ammonia and sulfide – For ammonia and sulfide to be effectively removed by RO, they must be in an ionic form. Therefore, the pH for effective ammonia treatment must be lower (less than 7 for ammonia to be completely ionized and less than pH 8 for ammonia to be approximately 95% ionized) and for sulfide treatment must be higher (higher than approximately pH 9).

Removal to achieve low effluent concentrations can still be achieved for these parameters with appropriate treatment conditions, system design, specialty membranes, or a high-efficiency polishing process.

NF is also used in some innovative mine water treatment applications. The NF concentrates primarily divalent species (metals and sulfate) while allowing most of the monovalent ions to pass through the membrane to the NF permeate. The NF brine can be recycled, as the divalent species are concentrated, and managed by a lime precipitation process, which eliminates the brine stream. The overall reduction in TDS is not as high with NF as with RO, and if removal of sodium, chloride, or other monovalent species is required, then an NF is not the appropriate choice.

7.7.3.2 Pretreatment, Polishing, and Ancillary Equipment

RO and NF operational efficiency can be impacted by several parameters that must be pretreated or removed prior to contacting the membrane to minimize scaling and fouling. Scaling is the precipitation of salts, such as calcium sulfate, calcium carbonate, and barium sulfate, on the membrane surface. As the concentrations in the brine increase, the solubility limit of salts present may be exceeded and then precipitation can occur. Fouling of the membranes may occur when parameters such as very fine suspended solids and colloids, total organic carbon (TOC), iron, aluminum, manganese, or silica deposit on the membranes. Membrane cleaning is required to remove scale and fouling on the membranes. Cleaning is usually initiated when the permeate flow drops below a target value. Both scaling and fouling can be controlled to an extent by antiscalant chemicals. Pretreatment may also be required to reduce the influent concentrations of these parameters or may include reducing the pH to minimize the scaling potential of the water. Scaling and fouling both increase the required cleaning frequency of

the membranes, can reduce the recovery (permeate volume), reduce the rejection (contaminant removal), and increase the required operating pressure. The complexity of pretreatment requirements must be weighed against these decreases in RO efficiency to determine the most cost-effective operational and pretreatment strategy. Common scaling and fouling parameters often found in MIW are shown in Table 7-4. Oxidants are another category of parameters that should be removed prior to the membrane system as membrane damage can occur.

Table 7-4: Overview of Common Scaling and Fouling Parameters

Scaling	Fouling
Calcium carbonate, calcium sulfate, calcium fluoride	Iron
Magnesium	Aluminum
Barium sulfate	Manganese
Carbonate (only an issue if calcium is present in sufficient quantity)	TOC
Sulfate (only an issue if calcium, barium, or strontium is elevated)	Silt Density Index (less than 3 target for RO, pretreatment required if greater than 3)
Fluoride, strontium, nitrate	TSS
	Oil and Grease
	Polymer

Pretreatment to remove these constituents may be required for cost-effective RO and NF treatment of MIW. For ARD and other MIW with high metals and sulfate loads, pretreatment may be lime or lime HDS treatment for gross metals and sulfate removal. In cases where the pH of the ARD is sufficiently low that the iron, aluminum and manganese will remain soluble and the TDS of the water can be effectively treated by RO/NF, the membrane step comes first. Evaluation of NF and RO for treatment of acidic mine water is presented in many articles (e.g., Ambiado et al. 2017, Mullett et al. 2014).

The metals and sulfate are concentrated generally from 2 to 5 times (50 to 80% recovery) and then the brine requires further management. The brine stream is typically 20% to 50% of the influent flow to the RO system and is managed by evaporation, onsite disposal, solidification or further treatment. There are also instances where the brine can be reused; however, that is dependent on the brine quality. Some RO applications are achieving higher recovery and lower residual brine. Lime HDS treatment is another option for the brine since in mining applications the brine often contains divalent anions (sulfate) and cations (metals) that are amenable to lime precipitation. Depending on the discharge limits for TDS and sulfate, a portion and sometimes all the lime-treated brine can be recombined with the permeate so that there is no or little brine to manage further.

Concerns regarding the efficiency of lime treatment on the RO brine stream due to the presence of the RO antiscalants have been evaluated in research projects. One study found that oxidation with ozone deactivates antiscalants at neutral pH. Increased pH was also found to deactivate the antiscalants (Lawler et al. 2010). A combination of ozone and increased pH was determined to promote precipitation and subsequent solid-liquid separation over non-ozonated brine (Greenlee et al. 2011). Jain et al. (2019) determined that time was also a factor in the impact of antiscalants on brine precipitation efficiency. McCool et al. evaluated chemically-enhanced

seeded precipitation (CESP) of RO brine and found that the residual antiscalant was removed by adsorption. Lime was used for precipitation and gypsum was used as the seed material (McCool et al. 2012, 2013).

A unique application of RO and chemical precipitation has been operational for approximately 10 years in South Africa for treatment of water from coal mining (Hammond and Drummond 2018a). Water from local coal mines is treated at four plants, including the eMalahleni Water Reclamation Plant (EWRP) Phase 1 and Phase 2, the Optimum Water Reclamation Plant (OWRP), and the Middelburg Water Reclamation Plant (MWRP). These four plants utilize three stages of treatment that include precipitation, ultrafiltration, and RO. Stages 2 and 3 treat the brine from the preceding stage so the only brine that is ultimately managed in a brine pond is from Stage 3. The water recovery obtained is between 97 and 99% and the treated water is used as a source of drinking water. The EWRP has been operational at a capacity of 25 million liters (ML)/day since 2008, the OWRP operational at a capacity of 15 ML/day since 2011, and the MWRP has been operational at 25 ML/day since 2015. Information regarding operations and costs is available through several sources (Hammond and Drummond 2018a, Hammond and Drummond 2018b, Australian Commonwealth 2016, Merta 2019a, https://mineclosure.gtk.fi/emalahleni-water-treatment-plant/).

Other typical RO pretreatment steps may include filtration (conventional filtration, microfiltration, or ultrafiltration) to reduce suspended solids and the Silt Density Index (SDI), softening ion exchange, absorptive or specialty media (TOC, iron, and manganese removal), and similar pretreatment steps to remove scaling and fouling parameters.

Polishing treatment for a RO or NF system may include an ion exchange or absorptive media to remove constituents such as boron or nitrate that still require additional removal. The polishing treatment step should be highly efficient on permeate since the TDS of the permeate should be very low. In some cases, the polishing treatment may be addition of alkalinity and hardness to increase the TDS of the final effluent. Water with low conductivity can be corrosive and may not pass a whole effluent toxicity (WET) test. The final TDS target may be achieved by blending with a higher-TDS source or targeted addition of a salt such as calcium chloride. Polishing of the pH may also be required to achieve a target discharge range.

Other ancillary equipment that may be required for an RO system usually includes a clean-in-place (CIP) system, typically provided by the RO supplier. Cleaning chemicals for membrane systems often include a high-pH cleaner and a low-pH cleaner (citric acid), chemical feed and storage systems (acid for influent pH adjustment, antiscalant, biocide), and brine management equipment. Brine management is key to the successful implementation of an RO system. The volume of the brine stream is typically in the range of 20% to 40% of the influent stream for mining applications, which equates to 60% to 80% overall water recovery. Multi-stage high pressure and extreme or ultrahigh pressure units are also available that can reduce the volume of brine, in some cases to 5% of the influent stream. These high recoveries may require extensive and multistep pretreatment processes to remove many of the constituents commonly found in MIW.

The RO brine stream will need to be managed by treatment, blending, or disposal. Treatment can include mechanical or solar evaporation to further reduce the volume followed by stabilization of the brine through solidification or other means prior to disposal. Chemical precipitation may also be used to treat brine and remove sulfate and metals. In cases where the TDS load is predominately sulfate, a RO system can be used to concentrate sulfate in the brine stream. Lime treatment of the brine reduces the sulfate and allows blending of all, or a portion of, the treated brine with the permeate prior to discharge, thus minimizing or eliminating the brine.

The treated brine may be reused, blended with permeate up to a sulfate or TDS limit, recirculated back to the RO system, or disposed. When selenium is one of the target parameters of concern, the brine can be treated further for selenium removal. Blending may include discharge of treated brine with permeate for final discharge. The

blended TDS or sulfate concentration often limits the amount of brine that can be discharged with permeate. Other options for blending and management of brine include blending and co-disposal with paste tailings or blending for reuse within the mill. Disposal of brine includes solidification and disposal in an on-site or off-site lined disposal facility, deep well disposal, or other brine disposal options that may be available locally.

7.7.3.3 Equipment and Typical Process Flow Diagram

A typical RO system will be skid mounted and include the membranes, high pressure feed pump, a pretreatment cartridge filter, and separate membrane cleaning skid. Figure 7-19 shows a skid-mounted RO system with the blue high-pressure pump on the right side of the skid feeding the membrane bank on the left side of the skid. The front center tank is the CIP tank. For treatment of ARD or similar high-TDS MIW that may have high metal content, low pH, and high sulfate content, there may be pretreatment by lime precipitation or brine management by precipitation. For lower-TDS MIW, there is often prefiltration and then the RO system. Filtration to remove TSS may also be required and is often provided by a UF or MF.

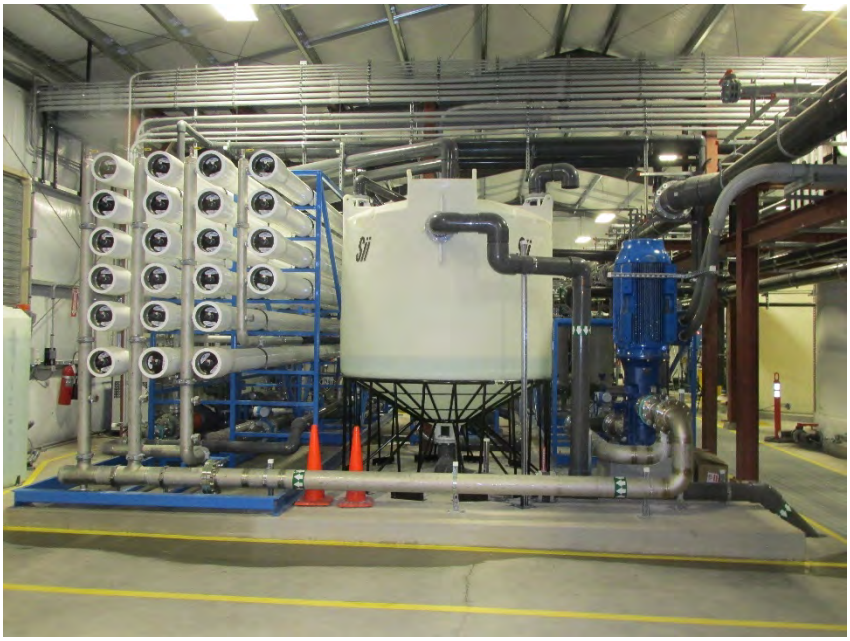

Figure 7-19: 114 m^3/h (500 gallons per minute) 3-Stage RO system (photo courtesy of Wigen Water)

Figure 7-20 shows a schematic of prefiltration by ultrafiltration, antiscalant addition, pH adjustment (to 5.5 to 6), and then RO with the brine being treated by lime HDS. If selenium were present in the water, the brine treatment would also include selenium biotreatment. The brine treatment by lime addition reduces the concentrations of sulfate and metals through precipitation. The residual sulfate concentration is typically in the range of 1,600 to 2,000 mg/L and above many surface water discharge limits. All or a portion of the treated brine can be recombined with the permeate. The proportion that can be recombined is dictated by the sulfate effluent limit and the RO recovery. One factor that may impact treatment and should be evaluated is the influence of antiscalant present in the RO brine on the lime treatment process. The antiscalant is added to prevent scaling of calcium sulfate while the lime HDS system is intended to precipitate calcium sulfate. The effects of antiscalant on further precipitation of brine have been studied, as discussed in Section 7.7.3.2.

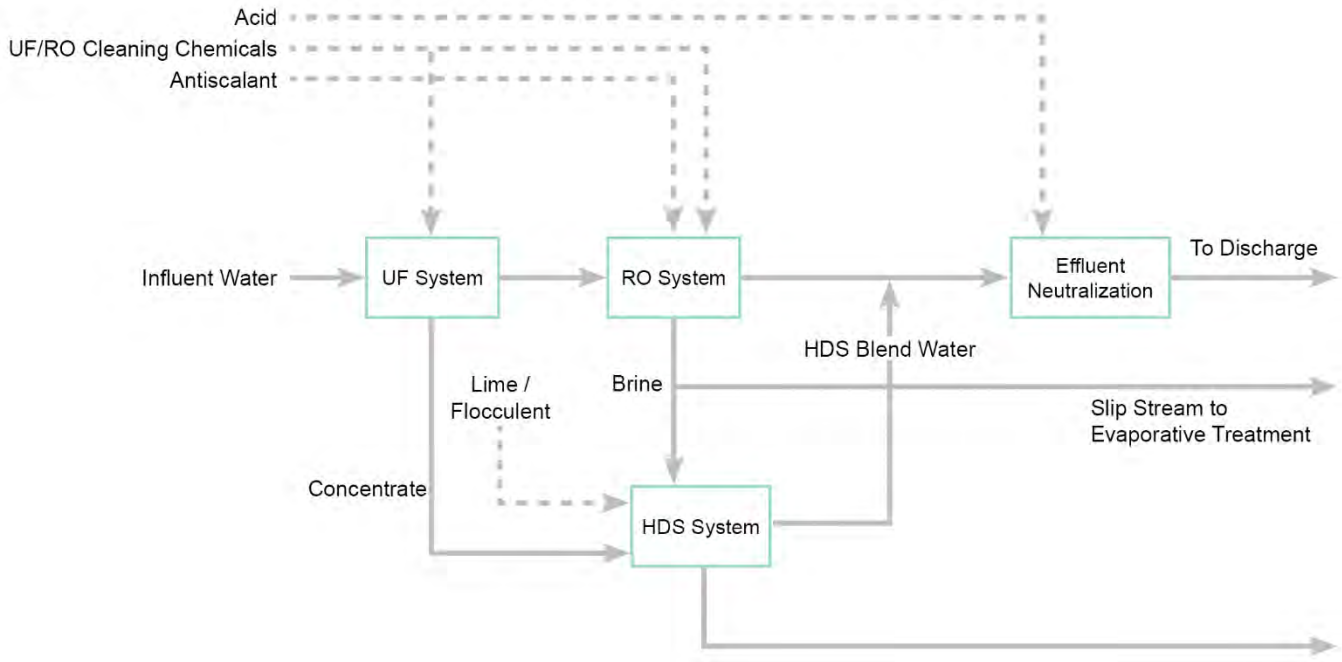

Figure 7-20: Example flow diagram of RO with lime HDS brine treatment

There are many variations of this type of system, including one where the brine is recirculated back to the tailings or influent pond. This type of system can be used to control volume in impoundments and move large quantities of water off site. However, continual recycling of the treated brine back into tailings or other storage ponds results in scale-up of constituents, particularly monovalent ions that do not precipitate, over time, and may not be a long-term sustainable approach without some type of blowdown.

RO and NF equipment are generally available with lead times from a few weeks to 12 to 16 weeks depending on the size of the system.

7.7.3.4 Operation and Maintenance Considerations

Operation and maintenance requirements for RO and NF systems are low relative to other treatment equipment. This observation does not include the operation of a lime HDS system, if required for further brine treatment. The chemicals used for cleaning are low volume on an annual basis, not used daily, and do not require operator interface other than to initiate the cleaning cycle at the control panel. Other features or operational requirements of a RO system include:

- Low daily labour requirements with system checks once or twice per day. The system can operate unattended for much of the day. Cleaning cycles are initiated by the operator, but the cleaning cycle is automated so no lifting or exposure to the cleaning chemicals is required.
- The RO membranes are operated at high pressure so care must be taken to maintain equipment properly, inspect for leaks, or other indications of potential operational issues.
- RO systems can be shut down for short periods of time; however, they should not be considered on/off type systems. If the systems are not operated for more than a few days, appropriate backflushing, cleaning and care of the membranes are required.
- The turnup/turndown of the system with regard to flow changes is limited and typically about 25% from the design conditions. Increases in contaminant concentrations may result in a decrease in recovery and an

associated increase in the brine volume. If additional flexibility is required to manage spring runoff or other seasonal changes in flow, including multiple treatment trains can provide the required flexibility.

- The residual from an RO system is a liquid brine stream which is generally in the range of 20% to 40% of the influent flow for mining water.
- Membranes must be replaced on an infrequent basis. For treatment of relatively clean water, the goal is typically five years of operational life with the replacement frequency impacted by the cleaning frequency. For mining applications, this frequency may be more often than five years; however, conventional RO membrane costs have stabilized or been reduced in the past few years.

Detail on operating costs, labour requirements and lessons learned for the Kennecott Bingham Canyon Water Treatment Plant is provided in the Mining Waste Treatment Technology Selection page of the Interstate Technology Regulatory Council (ITRC 2010a) site. This RO system treats contaminated groundwater for removal of sulfate and TDS. The regulatory limit for both is 250 mg/L.

7.7.3.5 Process Development and Testing Requirements

Testing recommended for design of an RO or NF system depends on the objectives to be achieved with the testing. If system design is the primary objective, then little treatability testing may be required. If the water is well-characterized, with data available for the parameters shown in Table 7-5 to define representative water quality, models developed by membrane manufacturers may be sufficient for system design.

Table 7-5: Influent water quality parameters required for RO evaluation

Parameters for RO evaluation (In addition to parameters of concern)	
Silt Density Index	Iron
pH	Magnesium
TDS and Conductivity	Manganese
TSS	Nitrate
Alkalinity	Potassium
Ammonia	Silica
Barium	Sodium
Calcium	Strontium
Chloride	Sulfate
Fluoride	TOC

Some of the reasons bench- and/or pilot-scale testing may be conducted are as follows:

- Proof of concept to evaluate contaminant rejection. Models developed by membrane manufacturers have traditionally focused on parameters of concern for drinking water and more traditional applications for RO. Therefore, many of the contaminants common in mining and in complex water matrices may not be well represented by modeling. This may change as more RO systems are utilized in mining applications.

- Production of permeate for additional characterization and testing (e.g., reuse purposes, WET testing, blending).
- Production of brine for additional testing (lime treatment, solidification, or similar).
- Evaluation of pretreatment on RO recovery and membrane cleaning requirements.
- Demonstration of concept and technology to regulatory agencies.
- Collection of additional design details to refine cost estimates.

Testing could include limited bench-scale testing that requires from 20 to 200 liters or an on-site pilot that operates for several weeks to several months at a much greater cost. It should be noted, however, that a short-term pilot test of a few weeks may not provide information on required cleaning frequency and membrane life, and it could take several months of operation to evaluate these parameters.

7.7.4 Evaporation (Mechanical and Pond/Enhanced)

Evaporative processes reduce the volume of water or brine that requires final disposal by evaporating the water and leaving a concentrated brine, slurry or dry residue. Volume reduction in excess of 90% is often the goal in implementing an evaporative technology, and with some equipment and/or applications dryness can be achieved. Evaporation can be implemented mechanically and using passive or enhanced solar evaporation. Mechanical evaporation, as used in this section, relies on equipment with a high capital cost and high energy input to achieve a large volume reduction in a relatively small footprint. Solar evaporation relies on the sun and may be as simple as a pond designed to maximize evaporation. This category also includes spray evaporation techniques used in conjunction with ponds to enhance the solar evaporation rate. Solar evaporation and mechanical evaporation where the vaporized water is released to the atmosphere rather than condensed are zero liquid discharge treatment processes. Mechanical evaporation can also produce a very high-quality treated water for discharge or reuse by vaporizing the brine and then condensing pure water. The waste by-product (or “bottoms”) from evaporative treatment is a concentrated brine or slurry, which may in turn be processed to a dry residue. Evaporation systems can serve as the primary treatment system for contaminated water or for management of secondary waste streams from other water treatment processes, such as brine streams.

7.7.4.1 Overview and Contaminants Removed

Evaporation is broadly applicable to removal of non-volatile contaminants in wastewater, including TDS and the most common dissolved constituents of TDS (sulfate and chloride) in mining process water. Evaporative technologies are highly flexible with regard to water chemistry and are often used for brine management, including brine from RO systems rather than for treatment of the raw influent water. In general, the energy required to evaporate a gallon of water is the same whether the water contains 1,000 mg/L TDS or 35,000 mg/L TDS. As the brine becomes more concentrated, the boiling point increases (boiling point rise), which is the reason why the energy input increases; at a certain point, the increase is discernible.

The energy required to evaporate water is much higher than the pumping energy of an RO system, which is why evaporation is often used for management of RO brine. There are very few parameters for which evaporative systems are not effective. Contaminants that may be of concern and should be monitored and characterized for thorough evaluation of the technology include:

- Chloride – Increased chloride causes corrosion concerns that may require use of a higher grade of stainless steel for construction of the evaporator system. Corrosion is also a concern with other mechanical equipment, including pumps, piping, valves, and spray systems. Therefore, chloride levels must be

measured and considered in equipment selection and design. Chloride concentrations can impact both solar and mechanical systems with corrosion problems.

- Silica – For mechanical evaporation equipment, silica can concentrate and foul heat transfer surfaces. System design and antiscalants can be used to mitigate the impacts of silica in mechanical evaporation; however, the presence of elevated concentrations of silica may limit the final volume reduction achievable or require pretreatment.
- Scaling parameters – For both mechanical evaporation and enhanced spray evaporation, scaling and fouling constituents (calcium sulfate, calcium carbonate, iron, and similar) can precipitate during operations as concentration is achieved and scale piping, pumps, nozzles, and heat transfer surfaces.
- Organics – In mechanical evaporation systems, organics may carry over with the water vapor and require pretreatment, offgas treatment for vapor discharge, or polishing treatment for condensed water vapor. Consideration should be given to whether organic volatilization from pond systems is a concern as well. Volatile organics are not a common problem in mining process water.
- Ammonia – At higher pH values, ammonia can volatilize. To prevent ammonia in the offgas, pH adjustment of influent water may be required. If ammonia does volatilize, offgas treatment may be required for vapor discharge or polishing treatment for condensed water vapor.
- Mercury – Mercury can volatilize and may require offgas treatment or polishing treatment of condensed water vapor.

Use of certain equipment configurations, antiscalants, and pH adjustment steps also can reduce the impacts of scaling and fouling due to water chemistry. Most scaling and fouling issues increase maintenance and cleaning requirements, but are typically reversible.

For solar evaporation, the natural evaporation rate is enhanced by the addition of spray systems, which increase the surface area available for evaporation by forming tiny droplets of water. The spray system can be as simple as an irrigation type sprayer laid out in a grid over the pond, but the more common type of evaporative sprayer for mining applications is based on snow-making technology. The spray equipment produces droplets by one of two mechanisms:

- Water fracturing, which produces fine droplets when the water is forced through a high-speed fan and propelled into the air over an evaporation pond.
- Water atomizing, where the air is compressed by a fan through a tapered barrel and propels the water droplets into the air. The water droplets are formed by nozzles so this type of spray system should not be used in scaling water or if TSS is present in the water.

Solar evaporative ponds with and without enhanced spray systems are dependent on weather conditions, and the rate of evaporation may vary from year to year. Typically, the systems are designed for an average or worst-case year from a number of years of record. The degree of conservatism in the design should include several factors, such as the storage capacity, alternative treatment, or alternative management options.

The treated water produced from mechanical evaporation represents a high-purity water source that can be used on site or discharged. No treated water is produced from solar evaporation and mechanical evaporation without condensation equipment. For all types of evaporation, the final residue from treatment is a highly concentrated brine that is formed due to evaporation of the water from the system and concentration of the retained dissolved constituents. The concentrated brine will be near or exceed the saturation point and solids may precipitate and

crystallize out of solution as the brine cools, resulting in a concentrated brine slurry. For mechanical evaporator systems, the concentrate will be at near-boiling temperatures and crystals will form as the concentrate cools. Further treatment in a spray dryer, crystallizer, or drying bed can produce a final waste form that is dry. Solidification or disposal are other options for concentrate disposal.

7.7.4.2 Pretreatment, Polishing, and Ancillary Equipment

Pretreatment may be required if any of the following are present in the water source to be evaporated:

- Oil and grease – Evaporative systems can handle some levels of oil and grease and if they are present, the mine water should be evaluated on a case-by-case basis to determine if pretreatment is required. For mechanical evaporation, oil and grease may foul heat transfer surfaces in some evaporation equipment. For both solar and mechanical evaporation, oil and grease may accumulate in pipelines, pumps, or other mechanical equipment, and for solar systems, the oil and grease may cause a sheen on the surface of the evaporation pond.
- TSS – Evaporative systems can handle some levels of TSS. For mechanical evaporators, there are various design configurations that are better able to handle influent TSS. For instance, the heat exchanger used for a system expecting TSS would be a shell and tube type rather than a plate and frame. For enhanced solar evaporative systems, the presence of TSS in the influent water is typically not an issue, but the type of spray system should be evaluated to determine whether TSS can block the sprayer equipment.
- Calcium, magnesium, and silica – Softening pretreatment may be desired to improve operational efficiency, reduce final brine volume, and reduce cleaning cycles for mechanical evaporation. Iron can also cause fouling problems on mechanical equipment and surfaces.

Polishing the treated water is limited to mechanical evaporation systems with condensation since the other systems are zero discharge. Polishing treatment could be required for any parameter that could carry over, such as volatile organics, ammonia, or mercury. In addition, some adjustment of the mineral content (TDS) of the condensate stream may be required for surface water discharge. Condensate is corrosive due to the very low ionic strength of the water. It is unlikely that condensate from an evaporator would pass a WET test. The evaporative system should be designed to recover heat from the condensate if surface water discharge is planned as most permit requirements have temperature limits. For the concentrate, additional treatment may be required to further reduce volume for final disposal. Spray evaporation or crystallizer equipment may be used for concentrate polishing. For solar evaporative systems, final management of concentrated brine is also required but is often achieved campaign style where the final residue in the pond is removed for further management, including off-site disposal, solidification or further drying and final disposal.

Ancillary systems that may be required for solar evaporative ponds include fencing and barriers to prevent people and wildlife from accessing the ponds. Wildlife hazing and deterrents should be incorporated into the design of the system, if necessary. Collection of appropriate data on wildlife in the area should be considered when developing other design criteria for the site, such as influent water characterization to determine if wildlife exposure is a concern. The design should also consider that the solids will have to be removed from the ponds intermittently and further managed or disposed.

Ancillary systems required for support of evaporative mechanical systems may include pH adjustment on the influent to the evaporator and antifoam addition. Storage tanks required include influent equalization; distillate storage and concentrate storage may also be required. Note that the distillate will be warm, in the range of 32°C to 43°C (90°F to 110°F), and the concentrate will be at near-boiling temperatures. For some types of mechanical systems, a boiler is required to produce steam, either for operations or start-up. The CIP system is typically

provided with the evaporator. Chemical feed is also required for two to three chemicals (antiscalant, citric acid or similar weak acid, and antifoam).

7.7.4.3 Typical Equipment and Process Flow Diagram

A solar evaporation system may include a series of lined evaporation ponds with support systems, including a feed pump, and spray evaporation system. Use of more than one pond allows one pond to be offline to remove solids while the other pond is still operational. Solids are typically removed campaign style and often require further processing such as solidification prior to final disposal. The lead time on solar evaporation systems can be relatively short and dependent more on liner availability and construction time. Enhanced solar systems using spray evaporators can have a lead time of up to eight weeks for the spray systems and controls. Weather stations can also be provided with spray systems to minimize overspray issues with wind. Couton and Timones (2017) provides a description of the principles of solar evaporation and schematics of a spray system with photos of the sprayers.

The addition of spray systems to enhance evaporation is relatively simple. The spray system produces higher evaporation rates and, therefore, the pond area required to achieve the target evaporation rate is smaller. Mechanical sprayers increase the air-water interface by spraying water droplets or mist above the pond. Sprayers may be installed in the pond on a flotation structure or on the perimeter berm. Automated on/off controls are frequently included to prevent windborne overspray and are controlled by an integrated weather station. While higher evaporation efficiency rates can be achieved relative to passive solar evaporation, drawbacks include drift and deposition of contaminants beyond the pond, high power use for pumping, and the need to “over-design” the spray system to account for occurrence of automatic shutdowns due to prevailing wind speed or direction.

For mechanical evaporators, there are several types with various types of heat exchangers (e.g., shell and tube, plate and frame), heat transfer surfaces, and configurations. Some of these types have been developed for product recovery rather than wastewater treatment and may have more operational impacts due to scaling water and other wastewater complications. Wastewater evaporators are typically powered by one of two methods:

- Mechanical Vapor Recompression (MVR) – The MVR evaporator is a highly energy-efficient evaporation system exploiting mechanical engineering principles of the heat pump. The water vapor (steam) produced by evaporation is recompressed to increase the pressure and, therefore, the temperature of the steam. The compressed steam is used to heat the influent water prior to being condensed and discharged as treated effluent. In comparison to an evaporator without vapor recompression and preheat processes, the MVR evaporator can be up to 10 times more energy efficient. Due to this intensive heat recovery, the make-up steam consumption for an MVR evaporator is nearly zero and is typically required only for start-up. Other than the start-up steam, the MVR requires electric power rather than natural gas. The general rule of thumb for power requirements is 0.1 to 0.2 kWh per gallon evaporated, with the higher power for more concentrated brine due to boiling point rise.
- Steam-heated – In this case, the energy required for evaporation is from steam, which means that excess steam at the site is required or a boiler must be provided with the evaporator. The boiler requires gas or other fuel. This type of evaporator is not as energy efficient as an MVR evaporator, using approximately 10 times the power to evaporate the same quantity of water.

The MVR evaporators generally have a higher equipment cost, but lower operating costs with longer lead times compared to the steam-heated evaporators. The steam evaporators require a condenser to recover water vapor and produce a high-quality effluent stream for discharge or reuse. If a condenser is not included, then the water vapor is not recondensed and is released to the environment. The MVR condenses the water vapor as part of the

energy recovery process and thus always produces a high-quality liquid effluent. Both MVR and steam-heated evaporators are manufactured in the following configurations:

- Falling film – As the name implies, this type of evaporator means the liquid being evaporated falls as a film on the heat transfer surfaces. The liquid influent to the system is at the top of the evaporator. This is a vertical shell and tube heat exchanger, and a thin film forms on the heat transfer tubes and falls down the heat exchanger. This type of evaporator is not efficient for salting and scaling liquids and is not a good configuration for most mining waters, particularly for brine. This type of evaporator is more commonly used for product recovery (dairy products).
- Forced circulation – This configuration is used for applications where crystallization or scaling may occur and, therefore, also may be used for brine and wastewater. The presence of some solids in the feed is acceptable. This type of evaporator also uses a shell and tube heat exchanger, and flow through the tubes is forced by an external pump rather than the natural convection that causes circulation in other types of evaporators. Turbulence is created, which increases the heat transfer surface area and efficiency of evaporation. Higher brine concentrations can be achieved, and the forced flow and turbulence also serve to minimize scale development on heat transfer surfaces.
- Rising film – The heat exchanger is a vertical shell and tube that produces steam and vapor within the tube, bringing the liquid inside to boil. The rising film results from the formation of vapor in the center of the tube that forces the remaining liquid to form a film on the tube wall. Liquids that may scale or crystallize should not be processed in rising film evaporators.

Note that crystallizers and spray dryers are included in the section on residuals (Section 7.10.2).

7.7.4.4 Operation and Maintenance Considerations

Operation and maintenance is fairly routine (e.g., liner inspection, pump maintenance, freeboard inspection, sampling) for solar ponds. With spray evaporators added to the pond system, the operational requirements are relatively low, but the sprayers should be monitored closely for a period to time to determine whether the automated system is controlling the operation of sprayers to prevent overspray. For manually controlled systems, the operation will have to monitor daily so that overspray does not occur; this should be included in operator duties. There will be some maintenance of the mechanical equipment, but it is low compared to a chemical precipitation system. Sludge removal is periodically required to maintain optimal capacity and operation. Removal of sludge by vacuum truck or similar is typically used to minimize the potential for liner damage. Sludge campaigns may occur once per year or at a different frequency depending on the system design.

Routine operations and maintenance of mechanical evaporation systems is simple compared to chemical precipitation systems. Systems checks are required and some routine maintenance of rotating equipment. Residuals that are in the range of 1% to 10% of the influent will require further handling and management. Non-routine maintenance and repairs may require specialized technicians.

7.7.4.5 Process Development and Testing Required

The process development and testing required is described in the paragraphs below for the solar pond, solar pond with spray evaporator and mechanical evaporator.

Solar evaporation – This technology is typically developed using long-term climate data that cover as long a period available and as close to the site as possible. The main challenge in the design of a solar evaporation system is good long-term site data. Key climate factors, such as wind, can change over a very short distance. In addition, there is variability from year to year, with some extreme years at the wet or at the dry end of the climate

spectrum. The system must be able to manage this variability, which makes the long-term data the key to system design rather than a short-term test.

Solar evaporation with spray system – Similar to the solar pond process design, the design of the ponds and sprayers is also dependent on climate data. Manufacturers have developed models for their equipment to calculate evaporation rates using local climate data. Site testing could be conducted using a rental spray unit if desired. Good water quality characterization is beneficial so the impacts of scaling, corrosion, or fouling can be evaluated.

Mechanical evaporation – The manufacturers of mechanical evaporation equipment will typically evaluate a small sample (approximately 1 gallon) of representative water and perform a boil test. From the boil test, they can determine the boiling point rise, estimated volume reduction, and whether antifoam will be required. Additional testing can be conducted by most manufacturers at their facilities or, in some cases, small pilot units are available for lease.

7.7.5 Ion Exchange and Adsorptive Media

Ion exchange (IX) and media absorption technologies are discussed together due to similarities in the treatment process and equipment required: both utilize packed columns and require regeneration (which generates liquid secondary wastes) or replacement (which generates spent resin/media). In general, these technologies are better suited to applications that require removal of constituents in lower concentrations. Contaminants are generally at influent concentrations of less than 1 to 3 mg/L, with removal often required to very low levels. Influent contaminant concentrations of 10 mg/L are considered high for applications other than softening. Softening by ion exchange or zeolite absorption removes calcium and magnesium at higher concentrations than other ion exchange applications. Ion exchange is used in the treatment of mining process water sources either as a primary treatment step or a polishing step to achieve low effluent concentrations or removal of targeted parameters such as nitrate or boron. There are some applications that utilize more of a fluidized bed approach to enhance contact between the resin or media and the water being treated.

7.7.5.1 Overview and Contaminants Removed

Ion exchange is the reversible exchange of target contaminant ions (e.g., sulfate, nitrate, ammonium, boron, calcium, magnesium, and several metals) between mine water and an insoluble solid (the ion exchange resin). It is a well-developed process for extraction of cations (e.g., calcium) or anions (e.g., sulfate or chloride) from contaminated wastewater. Ions in the wastewater exchange with ions on the resin; these ions often include sodium or hydronium (H_3O^+) for exchange of target cations and chloride or hydroxide for exchange of anions.

The reversible exchange involves removing the target constituents from the water stream to the ion exchange resin, which exchanges the counter ion from the resin structure. When the active sites on the resin are exhausted, the resin is regenerated by contacting it with a concentrated solution of the ion originally associated with the resin. The contaminant ion is incorporated with the regeneration liquor, which may require treatment prior to disposal. Unless the resin is highly specific to a target parameter, the exchange of ions is relatively non-specific and higher valence ions load preferentially to lower valence ions. In addition, concentration influences loading and removal efficiency. Sulfate is a common ion in MIW and often present at several hundreds to several thousands of milligrams per liter. Selenate ions can be removed by ion exchange, but selenate is often present in the tens to hundreds of micrograms per liter, i.e., several orders of magnitude lower than sulfate. Therefore, a general resin for removing anions from MIW will provide essentially no selenate removal.

Adsorption is a different mechanism than ion exchange, with the target constituent removed from solution and adhering to the solid media through sorption rather than an “exchange.” While the physical/chemical mechanism

is different, the two treatment technologies have many similarities, including the ability to regenerate many adsorptive media, the equipment used for the resin/media, and supporting equipment.

Ion exchange/media processes are very effective at removing target parameters to very low levels, with removal efficiencies typically in the range of 90% to more than 99% for target parameters. Ion exchange may also be used for softening (removal of calcium and magnesium) as a pretreatment to other processes where these cations may interfere. Additionally, ion exchange may be used as a polishing step after a main treatment process (such as chemical precipitation, RO or evaporation). Removal may be non-specific, removing all cations or anions rather than just a target parameter, or highly specific, such as boron removal by a boron-specific resin that does not affect other ions present in the water. In general, the removal efficiency and volume of secondary waste generated are influenced by the ionic strength and background matrix of the water being treated. Most applications generate from 0.5% to 10% of the forward flow in spent regenerant solution. The spent regenerant is a brine solution with a high concentration of the target contaminant.

Virtually any parameter could be removed by ion exchange/media processes, but the efficient removal for MIW treatment is highly dependent on the background water matrix and overall ionic strength of the water. Parameters that are typically treated by ion exchange/media processes in mining waters include the following:

- Calcium and magnesium – Removal of calcium and magnesium by ion exchange is known as softening. A general cationic resin or zeolite media can be used for softening.
- Boron, nitrate, and chromate can be removed by ion-specific resins.
- Ammonium – Ammonia can be removed in the form of the ammonium ion at pH values below 7 by specialty zeolite media; however, the ionic strength of the mine water does impact the efficiency of this application.
- Cyanide complexes with metals can be removed by activated carbon.
- Arsenic – Several media have been developed for arsenic removal, including titanium-based media, iron-based media, activated alumina, and other specialty media. The original focus of many of these products was drinking water treatment with removal of arsenic to very low residual levels.
- Manganese, iron, arsenic, sulfide, and radium can all be removed by manganese dioxide and greensand media. Regeneration of this medium is by an oxidant such as hypochlorite, and can be continuous or intermittent. The contaminants are removed as particulates by backwashing the media as indicated by the pressure drop across the media bed.
- Metals – Most metals of concern in mining waters (e.g., aluminum, cadmium, cobalt, copper, lead, mercury, zinc) are divalent or trivalent cations and can be removed by cation exchange resins or zeolite. Competing ions such as calcium and magnesium can be present at much higher concentrations and load on the resin/zeolite, and increase secondary waste generation.
- Phosphorus – Specialty reactive media are available to remove phosphorus and are continuously regenerated.
- Fluoride is removed by activated alumina. The capacity is impacted by alkalinity and is most effective at a pH of approximately 5.5. Activated alumina is regenerated by sodium hydroxide.
- There are emerging technologies using IX and media for selenium that are presented in Section 7.7.10.3.

Virtually any ionic species could be removed by ion exchange or adsorptive media, but not all applications are reasonable for this type of technology due to competing ions and other issues with the background water quality

matrix. These technologies are most effective for the treatment of lower-TDS, cleaner MIW, and as a polishing step. In some cases, use as pretreatment to another process is appropriate, such as with softening or manganese removal.

7.7.5.2 Pretreatment, Polishing Treatment, and Ancillary Equipment

Ion exchange and media systems provided in the most common system configuration of columns require relatively clean water prior to the column system. Pretreatment to remove TSS and oil and grease is required to prevent fouling of the media/resin and buildup of suspended solids within the bed. The resin/media bed is focused on removal of target dissolved constituents and should not be used for TSS filtration. Manganese dioxide media systems are backwashed to remove precipitated iron and manganese (or other precipitated target species); however, they also should not be used for TSS removal. The resin/media costs are generally high enough to deter use as a filter, but even if cost is not a driver, these systems are not designed for suspended solids removal, despite looking similar to a sand or multi-media filter. The particle size of the resin/media is not selected for suspended solids removal; solids can drive deeply into the bed, and the volumes of secondary waste will increase, and efficiency for the target parameters decrease.

There are some specialized applications or configurations that use either moving bed technology or mixed tank technology. The Higgins Loop is a well-known moving bed configuration developed for the nuclear industry and used in some wastewater treatment applications in the last 20 years, such as treatment of produced water in the Powder River Basin in Wyoming in the early 2000s.The mixed tank or continuous stirred tank reactor (CSTR) configuration is used in specialized applications.

Other pretreatment that may be required includes gross removal of target contaminants or competing parameters and control of scaling parameters and organics. The resin/media provides a very high surface area and if the mine water is scaling, precipitation can occur within the high surface area of the resin/media bed. Iron is another parameter that requires pretreatment to prevent fouling beds with iron precipitate. The exception to iron pretreatment requirements is if the media is manganese dioxide as the iron will then be removed and only require pretreatment (such as aeration) if the concentrations are high. Some resins/media change the pH of the water, and so the evaluation of potential scaling should include any potential pH changes within the column. The TDS concentration of the treated water can also increase depending on feed water composition and resin/media. If organics are present in the mine water, they may degrade resin structure depending on the organic present and they may encourage biological growth within the high surface area bed, with the resin/media providing surface area for biofilm development. Influent pH adjustment may be required to achieve a target operating range for the media/resin. Not all media/resins are impacted by pH, but some are, and the form of some parameters (ammonia/ammonium and sulfide) is more amenable to removal at certain operating pH levels.

Polishing treatment of effluents from ion exchange/media system is generally fairly limited since these systems are often themselves used as polishing processes. Some pH adjustment of the effluent may be required if the resin/media causes a pH change through the column or operates at a pH not within the effluent range.

Ancillary and support equipment for ion exchange/media systems may include fresh and spent regenerant tanks, chemical storage, makedown and feed for the regenerant. Secondary waste management includes either handling spent resin/media or spent regenerant solutions. For most systems, the liquid secondary waste is between 0.5% and 10% of the forward flow. This will be a brine stream and can be managed further by evaporation, solidification or if there are co-disposal options at the site. In some cases, there is the potential to recover or remove contaminants and regenerate the regenerant. Depending on the location of the mine, some off-site disposal, such as in an industrial liquid waste treatment facility or commercial deep well, may also be a viable option.

7.7.5.3 Equipment Required

In traditional IX systems, the ion exchange resin/media is contained in a column or series of columns; water flows by gravity or is pumped through a header lateral installed at the top of the column at a target hydraulic loading rate (Lph/m^2 or gpm/ft^2) for even flow distribution. A typical hub and spoke type lateral is shown schematically in Figure 7-21. Each of the spokes is made of slotted screen or has other fine openings for flow distribution. There are several other types of laterals. Flow is typically downflow to keep the column flooded and pressurized for even flow distribution. Upflow and fluidized bed configurations are also used in some applications. For absorptive media, there is typically a target contact time that establishes the size of the resin/media bed within the column. The resin/media volume is called the bed volume (BV) and the contact time is called the empty bed contact time (EBCT). Support systems include tanks for the fresh and used regeneration chemicals, pretreatment (if required), and pH adjustment (if required). Regeneration and associated rinses are often countercurrent (typically upflow) to the normal feed flow and require separate pumps as the flow rates may be different. In addition to regeneration and rinses, backwash may be required to remove fines from the bed.

Columns are often skid mounted and pre-piped and prewired to minimize field installation. Operation in a lead/lag configuration is typical to optimize resin/media utilization and minimize regeneration cycles. The lead column is operated to full exhaustion (or a target percentage), as indicated by the influent contaminant concentrations equal to the effluent. The lag column provides backup removal of any target constituent concentration that is not removed in the first column. Once the first column is exhausted, it is taken offline and regenerated. When returned to service, this regenerated column becomes the lag column. Two or three columns can be used for this configuration for either lead/lag operation or lead/lag/standby. The columns are pre-piped to allow either column to operate in the lead or lag position. These systems have the flexibility to operate in a one-, two-, or three-column configuration as well if the application requires that amount of media capacity. Figure 7-22 shows a three-column system with the piping in front of the columns designed so that any column can operate in the lead, lag, or standby position. The standby column is either being regenerated or freshly regenerated, and ready to go back into service when required. There is also backwash or regenerant piping shown as the bottom pipe into the column.

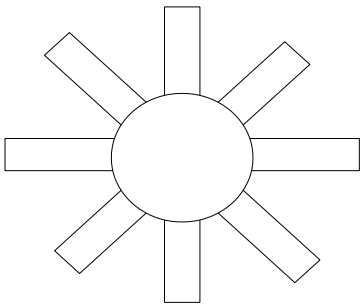

Figure 7-21: Hub and spoke type lateral schematic

Figure 7-22: Three-column IX system at mine water treatment plant (photo courtesy of IXOM)

There are some media systems that regenerate continuously rather than intermittently, such as greensand or manganese dioxide. The backwash stage to remove precipitated contaminants (manganese, iron, radium) is an intermittent process.

7.7.5.4 Operation and Maintenance Considerations

Ion exchange systems have low overall operational requirements. Operator attention is limited to routine checks for pressure and other instrumentation, sampling, ordering and maintain regeneration chemicals, and managing spent regenerant and backwash volumes. The system can operate unattended for long periods. The liquid waste from ion exchange or regenerable media is typically up to 10% of the forward flow. The spent regenerant is a brine that also contains a higher concentration of the contaminants of concern than the MIW. Methods for brine management include co-disposal, evaporation, solidification, and off-site disposal.

Regeneration cycles are initiated based on a number of triggers depending on the application. If the system is configured in a lead lag approach and the regenerant cycle time is approximately known, analytical results from samples taken between the two columns can trigger regeneration. When the influent to the lead column and the effluent from the lead column are equal in concentration, then the resin is considered fully loaded. To allow for a safety factor, regeneration is often triggered when the target constituent concentration in the lead column effluent is at a set percentage (such as 75%) of the influent target constituent concentration. This strategy allows some safety factor but minimizes regenerant (liquid secondary waste) volume by maximizing resin constituent mass loading. Other strategies for triggering a regeneration cycle include routine regeneration based on the volume of water treated or a set time period. These more routine triggers for regeneration are based on process knowledge, a constant influent concentration and flow and other factors.

Some annual cost information along with system limitations is provided in the Ion Exchange section of Reference Guide to Treatment Technologies for Mining-Influenced Water (EPA 2014). In addition, the ITRC site has information on the IX system installed at the Soudan Mine in Minnesota (ITRC 2010b). A cation IX system was installed to remove copper and cobalt from two mine drainages at this historic iron mine that is now a state park.

7.7.5.5 Process Development and Testing Required

Comprehensive water quality characterization is required for initial evaluation of this technology. The background matrix and concentrations of competing and fouling ions impact the removal of the target contaminants. Ion exchange manufacturers have robust modeling software that allows initial sizing of the system and determination of effluent quality, volume of secondary waste, time between regeneration cycles, and other related information.

Testing of ion exchange and media systems can be challenging because obtaining enough water for a meaningful bench test may be prohibitive. Whereas excellent information can be obtained with 5 gallons (19 L) of water for a bench-scale chemical precipitation test, the testing of ion exchange and media systems on the bench scale can take 10 to 20 times that volume. Bench testing generally starts with isotherm testing, which is general proof-of-principle testing that the contaminant will load on the resin or media. Small-scale column testing can be conducted, although simulating the hydraulic load rate requires very low flow and specialized laboratory pumps, the tubing is very fine bore and easily clogs, and the quantity of water and duration of the test are much greater than bench tests for other technologies.

Pilot testing is not always required; however, if a pilot testing program is planned, the pilot system should be set up at the site due to the quantities of water required. Pilot-scale systems will be easier to run than bench-scale because the tubing and equipment are larger and less prone to clogging and hydraulic problems. Adequate pretreatment should also be included in the pilot testing program. The system may have to operate for several weeks to months to obtain reliable data on breakthrough, cycle times, regenerant volume, and other pertinent information. If there are several resin/media options under consideration, this type of testing can provide a good head-to-head comparison.

The other factor in testing ion exchange or media systems is the treatment required to prepare the sample for the resin/media test. If the resin/media is a polishing step, then several other treatment steps may be required to prepare a sample for resin/media testing.

7.7.6 Biological (Selenium, Nitrogen Species)

There are several configurations of biological water treatment systems used for a range of purposes. For mining applications, the most common constituents that are removed by biological active treatment systems include nitrogen compounds (cyanide, ammonia, and nitrate), selenium, and in some cases other metals. Most biological water treatment processes require a carbon source for active growth and efficient operations; therefore, supplementation with some form of carbon is typically required in mining applications. Addition of phosphorus and other trace nutrients may also be required. Both aerobic (with oxygen) and anaerobic (no oxygen) processes are used in mine water treatment as well as anoxic (representing conditions without oxygen added but not necessarily with elimination of the presence of oxygen, as is required for strict anaerobic conditions).

7.7.6.1 Overview and Contaminants Removed

In addition to a carbon source, biological treatment systems must have the proper ratio of nitrogen and phosphorus to carbon for efficient microbial growth and contaminant removal. If the target contaminant of the biological treatment process is a nitrogen species, carbon and phosphorus amendments are required in appropriate ratios to the nitrogen. Oxygen is required for degradation of some contaminants and anaerobic conditions are required for other contaminants. While microbial activity can occur at extremes, the optimal temperature for biological activity is in the range of 21ºC to 32ºC (70°F to 90°F) for most processes. MIW is rarely within that range. For applications were the MIW is warmer, such as some underground or dewatering water sources, there is an upper bound and if temperatures exceed 40ºC (105°F), cooling may be required for efficient treatment. Mining water is often treated biologically at temperatures less than 24ºC (75°F), but the system must then be sized to accommodate slower biological reaction times. Colder water will require longer retention times

and larger equipment, so there is a tradeoff and, at some point, heating the water may be more cost effective on a life cycle basis. This should be evaluated during the conceptual evaluation and process development phases of the project. In some cases, colder water occurs when flows are lower, so the retention time in the system is longer anyway due to reduced flow. Bioreactors are generally designed for a target retention time at the coldest expected water temperature. Note that this temperature discussion applies to microbial growth required for efficient treatment of MIW for the target constituents of concern and does not imply that there are no microbes that thrive in extreme temperatures.

There are generally two types of biological treatment systems used for mine process water treatment:

- Suspended growth systems in which the microbial culture is well mixed and suspended in solution. This category includes lagoon systems, activated sludge, membrane bioreactors (MBRs), moving bed bioreactors (MBBRs), and sequencing batch reactors (SBRs). The microbial culture is generally well mixed within the bioreactor, and biological sludge is removed from the bioreactor in a variety of ways. For well-mixed tanks and lagoons, the effluent from the bioreactor has biological solids that must be removed from the water in a similar manner as for precipitated solids (Sections 7.7.7 and 7.7.8). In an MBR, the membrane retains and concentrates the biosolids to maintain a target average sludge age which is much higher than the average retention time in the bioreactor. A portion of the biomass is returned to the reaction tank and a portion is bled from the system for further management and disposal.
- Fixed film (or attached growth) systems in which the microbial culture is attached to a surface as a biofilm. This category includes packed bed reactors where the packing can consist of such materials as carbon or plastic packing. Packed bed systems can be fixed systems where the packing is placed in a column or tank and the water to be treated flows through the packing, or they can be fluidized bed or mixed tank systems where the packing is either fluidized in a column or well mixed in a tank. The biofilm can also grow on larger fixed surfaces, such as rotating disks called rotating biological contactors (RBCs). Other types of fixed film systems are trickling filters and similar, in which the biofilm may grow on rocks or other larger surface inert media. Biomass is removed from the system by way of sloughing. As the biofilm ages, portions slough off the surface or support media and are removed from the system for further management and disposal.

Constituents removed from mine water with biological treatment include the following:

- Nitrogen compounds treated aerobically include cyanide, ammonia, nitrite, and thiocyanate. Cyanide is oxidized biologically to ammonia. Ammonia treatment is called nitrification and converts the ammonia to nitrite and then nitrate. The microbial conversion of ammonia to nitrate via nitrification is the same process described in Section 7.8.1.1 for treatment of ammonia in a wetland system.
- Nitrate is treated anoxically by a process called denitrification. Microbial denitrification is also described further in Section 7.8.1.1. The oxygen present in the nitrate is consumed by microbes with the production of nitrogen gas.
- Selenium is treated anaerobically, being reduced to elemental selenium, and in active biological treatment is typically treated by a fixed film type configuration. Biological selenium removal is the most implemented type of active treatment technology for selenium. Based on a survey completed by NAMC, biological systems were included in 10 of 14 new selenium treatment plants installed between 2015 and 2018. This survey included several industries; however, five of the 14 applications were mining and of the five mining applications, four were biological treatment systems. The NAMC white paper (Golder 2020) has a tabularized comparison of biological treatment technologies (active, passive and in situ).

Metals/metalloids can also be removed by biological treatment, but this is not typically a primary active treatment method for analytes other than selenium. There are some exceptions, such as one of the first biological treatment systems for mine water at the Homestake Mine in Lead, South Dakota, where RBCs were used for cyanide and metals (iron, silver, copper, lead and mercury) from 1983 until 2002. The RBCs were refurbished and are currently operating to removed suspended metals and trace ammonia at the mine site which is currently operating as the Sanford Underground Research Facility (Broberg 2019).

Sulfate can also be removed biologically, but has not typically been the main target parameter for active biological treatment due to cost and efficiency. Biological sulfate removal occurs naturally and there are some commercialized biological systems that are of increasing interest for sulfate as discussed in Section 7.7.10.2. In addition, some metals inhibit microbial growth, and so metals and sulfate removal need to be evaluated on a case-by-case basis. Organics such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), and TOC can also be removed biologically; however, TOC is not a common constituent of MIW and typically mining applications require carbon supplementation.

7.7.6.2 Pretreatment, Polishing, and Ancillary Equipment

The extent of pretreatment required for a biological treatment system depends on the bioreactor configuration and whether there are any constituents present that will foul or plug the system or will inhibit microbial growth. In general, suspended growth systems such as lagoons or SBRs are fairly robust and can take some levels of TSS; however, plugging concerns with aeration systems should be considered in aerobic systems. An SBR is pictured in Figure 7-23. Fixed film systems with immobile packing may be impacted by TSS plugging the flow through the bioreactor. Similarly, oil and grease may cause issues with fixed film systems where some suspended growth systems may be impacted (e.g., MBRs) and some may not. Consideration of fouling and plugging of the bioreactor, aeration, system, pumps, and other mechanical equipment needs to be included in the evaluation of the mine water quality and the need for pretreatment. Other constituents that may impact biological treatment processes include scaling and fouling parameters (calcium sulfate, calcium carbonate, iron, and similar) that can deposit on fixed film surfaces, aeration equipment, pumps, and piping. Finally, elevated concentrations of some metals and/or TDS can impede microbial growth and require pretreatment.

Figure 7-23: Aerobic sequencing batch reactor (photo courtesy of Schreiber Water)

Polishing treatment equipment required in conjunction with biological processes may include the following:

- Solid-liquid separation of biosolids and further solids stabilization/management.
- Re-aeration of effluent from anaerobic system.
- Treatment of effluent for residual nutrients (can include removal of residual BOD, COD, nitrogen, and/or phosphorus, as well as reintroduction of DO) or parameters that may be produced in the treatment process, such as sulfide if sulfate is present and the treatment is anaerobic.

Ancillary systems include chemical storage and feed, aeration including blower and distribution system, solid-liquid separation, and solids handling as summarized below:

- Chemical storage and feed typically include a carbon source such as molasses, citrate, or a proprietary blend. Other chemicals may include acid or base for pH control, alkalinity control, and nutrient or micronutrient addition. For some applications, chemicals can be fed directly out of drums and totes, while in other applications bulk storage tanks are required. The storage requirements for the carbon source should be a factor in selection of the carbon source, as some require special consideration, including a minimum temperature, and some are explosive or flammable.
- Aeration systems may include a blower, piping, and distribution throughout the bioreactor.
- Solid-liquid separation can include equipment similar to chemical precipitation, and options include clarifiers, centrifuges, and filters.
- Solids management may also include equipment similar to chemical precipitation for solids dewatering, such as a centrifuge or filter press. Biosolids may also be managed in sludge drying beds and sludge digestors.

7.7.6.3 Equipment and Process Flow Diagram

The bioreactor is the main component of a biological treatment system and can be a pond, tank, or column that provides the target retention time. The pond, tank, or column can then be outfitted with the other systems and appurtenances required, including:

- Media if the system is a fixed growth system (e.g., MBBR).
- Membranes may be included externally or in the bioreactor tank if the bioreactor is an MBR that uses ultrafiltration membranes to separate and concentrate biomass. A portion of the biomass is returned or retained in the bioreactor and some is wasted, becoming the biosolids waste stream for further management.
- Mixing if the system is suspended growth or if it is a fluidized bed suspended growth system.
- Aeration if the system is aerobic. The aeration can be combined with the mixing or be a separate system. Aeration typically requires a blower, distribution system, and nozzles, diffusers, or some feature to provide small bubbles. These small bubbles can be in the category of coarse (3 to 50 mm) or fine bubbles (0 to 3 mm) bubbles. As a benchmark, a hole drilled in the pipe is usually 50 mm or more. There are advantages and disadvantages to both fine and coarse bubbles. The oxygen transfer is higher with fine bubbles, which requires less power. However, the diffusers are more susceptible to fouling and have a higher cost. The coarse bubble diffusers have less fouling and plugging problems, but consume more energy and provide less efficient oxygen transfer.
- Nutrient feeds that may include a carbon source, a nitrogen source, a phosphorus source, and/or a micronutrient source if these nutrients are not present in the influent water in the correct proportions to support microbial growth. There are many rules of thumb for the ratio of carbon to nitrogen to phosphorus (C:N:P), provided in references such as Metcalf and Eddy (Tchobanoglous 2014). Carbon (for this discussion: non-carbonate carbon) is rarely present in MIW and is required at approximately 10 times the concentration of nitrogen present. The carbon source can be a propriety carbon source or molasses, methanol, citric acid, and similar. Nitrogen is present in many MIW sources in the form of cyanide, ammonia, and nitrate. These concentrations may be just a few milligrams per liter to several hundred milligrams per liter, and so the carbon requirement could range from minor to fairly high. Nitrogen supplementation, if not present in mining water, is commonly provided by urea, ammonium nitrate, and similar nitrogen compounds. If needed, phosphorus is typically added in the form of phosphoric acid.

- Chemical feeds to maintain pH within the target range. Biological treatment systems may produce organic acid or alkalinity during some treatment steps and, therefore, may naturally increase or decrease the pH, which requires either acid or base addition to maintain the target pH range. Automated pH control and acid/base addition are included for many bioreactor systems. In addition, treatment for some target contaminants is most efficient in a certain pH range and so pH correction may be required.

These systems can be supplied by several manufacturers as packaged systems. The sizing is based on the retention time and/or loading rate, such as kilograms per day per cubic meter (kg/day/m^3) or pounds of contaminant removed per day per cubic foot of reactor (lb/day/ft^3). Note that water chemistry must be considered for sizing. For example, for biological selenium removal where nitrate is present, nitrate reduction must occur before selenium reduction can occur, and this may add to the size of the bioreactor.

The lead time is dependent on the size of the system and the configuration, but can be 4 to 12 weeks for aeration equipment, such as blowers and aerators/diffusers that may be installed in an in-pond lagoon system, or 6 months or more for a higher-capacity packed bed selenium treatment system.

7.7.6.4 Operation and Maintenance Considerations

Operational requirements for a biological treatment system depend on its configuration and size; however, on a comparative basis, the labour requirements are typically less than for a lime-based chemical precipitation system, but more than for an RO system. Power requirements are dependent on whether aeration and water heating are required, but are much lower than high-energy processes like evaporation. Nutrients can be one of the higher contributors to cost, particularly when carbon supplementation is required.

Operational challenges with biological selenium treatment systems are identified in the NAMC white paper on selenium (Golder 2020). Several considerations are discussed in the operation of packed bed fixed film systems. Some of these considerations are applicable to this bioreactor configuration and some are applicable to biological systems used in general for treatment of other constituents.

Residuals produced by biological treatment are biosolids. Aerobic systems and suspended growth systems produce more biosolids than anaerobic systems and fixed film systems (Tchobanoglous 2014). The volume of biosolids can be reduced further by adding a digestor, which is another biological reactor that digests the biosolids.

Maintenance requirements are not specialized, with most equipment being pumps, mixers, and other rotating mechanical equipment.

7.7.6.5 Process Development and Testing Required

Bench and/or pilot testing is generally recommended for biological treatment of mining water to refine process variables and determine design parameters, whether there are any inhibitory or toxic parameters present in the water, pretreatment requirements, and if effluent goals can be achieved. Testing for biological systems is more complex and requires longer testing periods than most other treatment processes because the biological culture generally requires time to acclimatize to the influent water. Each time conditions are changed to evaluate design parameters (retention time, nutrient doses, temperature, pH, etc.), the biological system must reacclimatize. Testing can, therefore, take several weeks to several months. The labour requirements for a bench or pilot system are often higher than for a full-scale system due to additional sampling locations and challenges operating and maintaining small-scale equipment and tubing. Several parameters must be monitored, including field parameters, the background water quality matrix, the nutrient levels, and the constituents of concern.

7.7.7 Gravity Separation (TSS, Oil and Grease)

Gravity separation is used at mine sites in a variety of applications, including for treatment of MIW. Much of the water treatment equipment is similar to that used in milling applications and other areas of a mine site, so this equipment category is known to most active mining sites. In addition, gravity separation is very common in many other municipal and industrial water treatment applications. Gravity separation may include simple settling ponds (with or without baffles), clarifiers, flotation, and centrifugation. In addition to removing TSS and oil and grease, gravity separation is often included in treatment trains that incorporate precipitation processes for removal of precipitated solids.

Gravity separation exploits the difference in the density of the contaminant to be removed and the density of the water. Most suspended and precipitated solids in mining applications settle well either unaided or with the addition of a coagulant and/or flocculating chemicals. In some suspended solids applications and for oil and grease, flotation is used for separation of the phases. Flotation is aided with the introduction of a gas (i.e., air, oxygen or other inert gas to provide extra surface area for flotation).

7.7.7.1 Overview and Contaminants Removed

The contaminants removed by gravity separation processes discussed in this section are TSS in the influent mine water, precipitated solids generated by oxidation and/or chemical treatment, and biosolids from a biological treatment step. Gravity separation is also effective in removing oil and grease and can include chemical addition to promote formation of larger particles or break emulsions. The gravity technologies discussed in this section are often used for gross removal and may be followed by a polishing filtration/membrane process discussed in Section 7.7.8.

Coagulation, flocculation, and gravity separation are widely used together for the removal of suspended particles from a waste stream. The following general discussion applies to particulates, although is also applicable for oil and grease, which is discussed at the end of this section. A chemical coagulant (such as alum, iron salts, or a proprietary chemical) is added to a well-mixed waste stream to neutralize surface charges and promote particle agglomeration. The agglomeration process (flocculation) may be enhanced with the addition of a polymeric flocculant, which allows smaller floc to agglomerate further into larger floc that separates from the liquid more effectively. While the addition of these chemicals may take place in a turbulent zone such as a rapid mix chamber, static mixer, or in a baffled channel or launder, the flocculation step is typically conducted in a slow mix chamber or other container where the particles can form, but are not allowed to settle. The rapid mix/slow mix zones are included for efficient mixing and floc formation which minimizes the chemical dose and residual in the effluent; however, these chemicals are added in-line, in ditches or similar lower technology systems when more simple pond systems are used.

While not required, the usage and required dosage of polymer can increase if less efficient polymer makedown and contact systems are used. Floc bricks or logs can also be used for in-ditch application and are specially designed for this type of application. The TSS or precipitated solids in many mine waters may not require coagulant and/or flocculent to aid in settling and should be evaluated with bench testing. The need for chemical settling aids is also driven by the clarity required, the use of the clarified water and whether more treatment or reuse follows, and other similar site-specific factors such as permit requirements. Following the coagulation/flocculation step, a gravity separation step can be used to effectively remove the solids from the liquid stream. Settling is the most common method used in mine water treatment applications for removal of suspended and precipitated solids, but flotation and centrifugation have also been used in mining applications. Settling equipment is sized according to the area required for settling, which should be based on bench-scale settling tests.

A range of clarifiers are used in settling applications in addition to settling ponds, which are used extensively in mining applications. While relying on gravity settling principles, this equipment has some differences and advantages/disadvantages that are application specific. Clarification equipment can include:

- Settling ponds - May be simple ponds that are existing and used for settling or specifically designed ponds to provide a target surface area for settling, provide storage for a number of months or year of settled solids, and may have curtains or baffles to direct flow and prevent short-circuiting. The surface area for settling is the top area of the pond.
- Circular clarifier - Circular tanks with a specialized clarification rake mechanism and cone bottom to aid in removing solids. Clarifier influent with suspended solids flows into the center feed well of the clarifier. Polymer flocculant can be added in the flash mix tank at the clarifier inlet to improve settling characteristics of the solids. Some clarifiers are configured so the polymer is added to the center well. The rake mechanism helps promote densification of the solids in the bottom of the clarifier. The side-wall depth should be sufficient to allow compression settling, which also creates a denser sludge. Treated water overflows a high elevation outlet in the settling unit, typically a launder, weir, or discharge pipe. The area of the tank is the area available for settling. Clarifiers are sized based on a target overflow rate or rise rate ($m^3/m^2/s$, m/h, or gpm/ft^2) or solids loading, whichever number results in a larger size. This type of clarifier is a mainstay of clarification for water treatment applications and is also a well-known piece of equipment at active mine sites for production (used as a thickener rather than a clarifier) and water treatment applications. This is the type of clarifier that is applicable for solids separation in the HDS process. Figure 7-24 shows typical circular clarifiers.
- Inclined plate clarifier – A smaller clarifier that provides an increased surface area for settling and a smaller footprint. Also known as lamella clarifiers, these clarifiers provide increased surface area through multiple closely spaced, angled plates installed in the clarifier vessel. The clarifier inlet is near the bottom of the vessel. Flow is upward, with the solids collecting on the plates and sliding down into a hopper bottomed collection tank. The clarified water exits through an overflow weir. Collected solids are pumped from the collection tank to be dewatered and/or disposed. Inclined plate clarifiers are available as stand-alone units or as plate packs, which are installed in concrete basins. Tube settlers are similar in principle to inclined plate clarifiers. Figure 7-25 shows an inclined plate clarifier.
- Ballasted clarifier – Consists of inclined plate or tube type configuration with the addition of particulates that aid settling. The particulates provide ballast, or a surface for the solids in the water source to adhere to, and a higher density to aid in settling. This generates larger particles, which settle more effectively. This decreases the footprint of the ballasted clarifier compared to a conventional clarifier. When the ballast and accumulated solids are removed from the clarifier, solids are washed off and the ballast is reused. The ballast requires periodic replenishment.
- Flotation – Removes suspended solids and oil and grease from influent water by injecting gas bubbles into the influent water and floating the solids and/or oil and grease. The bubbles adhere to the suspended matter or oil droplets, resulting in flotation where the “float” is skimmed and clarified water is produced. Finer bubbles produce more surface area for separation. Bubbles can be generated by an impeller, eductor or sparger. Air, oxygen, or an inert gas such as nitrogen can be used as the gas source. The flotation vessel is often a rectangular tank and can also utilize parallel plate packing similar to an inclined plate clarifier, providing more separation area. This category includes both dissolved air flotation (DAF) and induced gas flotation (IGF). The principles of separation are the same for either.

Figure 7-24: Circular Clarifier - two views (photos courtesy of WesTech)

Figure 7-25: Inclined plate clarifier (photo courtesy of WesTech)

Removal of oil and grease is similar to that of suspended solids. Some chemical addition may be required if the oil and grease is emulsified rather than free. Typically, when oil and grease is present in mining water, it is in a fairly low average concentration with some possible intermittent spikes of higher concentration. The main source of oil and grease in mine water appears to be lubricating and other oils from underground equipment. Often oil and grease can be skimmed from the top of tanks or ponds with booms. If dedicated treatment equipment is required, a phase separator similar to a lamella clarifier can be used while flotation is another good equipment choice. Instead of a settling area, a phase separator has a coalescing medium in which the oil droplets coalesce (merge) and rise, solids settle and treated water is produced. Generally, oil water phase separators can reduce oil and grease to the range of 10 to 200 mg/L depending on the influent concentration.

Geotubes® are another option sometimes replacing clarification; however, these are more commonly used for sludge management and are discussed in Section 7.10.1.

7.7.7.2 Pretreatment, Polishing, and Ancillary Equipment

Pretreatment requirements for solid-liquid separation processes are limited and fairly unusual. Gross TSS removal is often the first step in a treatment train if additional parameters beyond TSS require removal. Polishing may include conventional or membrane filtration and pH adjustment. Ancillary equipment would include the polymer makedown and feed system and coagulant feed system, if required. Rapid mix and slow mix tanks are required if polymer and coagulant are used. These are often supplied with most clarifiers; however, this should be confirmed. Additional solids handling is also required for the concentrated sludge stream and options may include ponds for storage and additional settling, sludge holding tanks, and dewatering equipment. A compressor or other gas-producing equipment is required with flotation systems.

7.7.7.3 Equipment and Typical Process Flow

In addition to the main tank (or pond) for the solids separation, the following equipment is required for a complete unit:

- Chemical feeds potentially for coagulant and flocculant. This includes makedown and feed for polymer and storage and feed for coagulant.
- Rapid mix and slow mix tanks or chambers and mixers. These are typically included with circular clarifiers, lamella clarifiers, and ballasted clarifiers.

7.7.7.4 Operation and Maintenance Considerations

Labour requirements for gravity separation are dependent on the equipment selected. Settling pond systems require very little routine operations support, but they do require campaign style solids removal and management. The lamella clarifier requires relatively little operator interface, while the circular clarifier, ballasted clarifier, and DAF/IGF all require more operator interface and a higher level of skill to maintain the clarity of the product water. All types of gravity separation may require that operators conduct jar tests to evaluate dose and alternative products for coagulation and flocculation if there is a change in influent conditions or effluent quality. Chemicals required are typically flocculant and coagulant, and the costs can be low to moderate depending on the dose required, which must be determined by jar tests on a case-by-case basis. The jar testing is typically intermittent, but may be required when there is an issue maintaining the sludge bed or effluent clarity.

Secondary waste from all gravity separation processes discussed in this section is sludge, which is typically in the range of 0.5% to 5% solids for predominately metal hydroxide sludge. Sludge that results from separation of influent TSS may be sediment and particulate that settles by gravity to a higher-percent solids than metal hydroxide sludge. Sludge from the lime HDS process is also typically much higher in solids content (often in the range of 15% to 30%) and may be even higher in some applications depending on the proportion of calcium sulfate and iron, aluminum and manganese metal hydroxides in the sludge. A solids dewatering process is generally required to achieve even higher solids contents and produce solids that pass the paint filter test for disposal.

Power requirements are fairly low since the mechanism of separation is gravity. Maintenance requirements are also fairly low since there is not a lot of mechanical equipment. Cleaning may be required to remove accumulated solids coating the surfaces of the equipment. High concentrations of iron, calcium sulfate, or calcium carbonate can precipitate on equipment surfaces. The rake mechanism on the circular clarifier will require some routine maintenance and will require specialized repair technicians for non-routine repairs. The flotation devices also have mechanical equipment to produce the gas bubbles.

7.7.7.5 Process Development and Testing Required

Gravity separation processes are well defined. The testing procedures are also well defined and significant data can be obtained with bench-scale testing. Jar testing and settling testing can be used to evaluate coagulant and flocculant type and dose, and then the identified products can be used in settling testing, which is also a bench-scale test.

7.7.8 Filtration and Membranes for Solid-Liquid Separation (TSS and Oil and Grease)

Similar to the gravity treatment processes described in Section 7.7.7, there are several filtration processes used for separation of suspended solids and precipitated solids. There are specialty filters used for oil and grease as well. Filtration is typically selected when lower levels of TSS are present or as a polishing step to gross TSS removal by gravity separation.

7.7.8.1 Overview and Contaminants Removed

Filtration is a broad category of process equipment aimed at removing particulates either at the filter surface or within the filter (called in-depth filtration). The filters are non-selective with respect to individual contaminants and remove TSS present in the influent water over the particle size rating of the filter media. Common forms of filtration for removal of TSS include screen filters, bag filters, multimedia and sand filters, and membrane filters (microfiltration and ultrafiltration). Similar to gravity separation as discussed in Section 7.7.7, chemical aids to increase the particle size can be coupled with some types of filtration. In general, the filters all provide a large surface area, so that MIW with a high scaling potential must be evaluated to minimize scaling of filter surfaces. Oil and grease removal is discussed at the conclusion of this section, so the following paragraphs address filtration for TSS removal. A brief overview of the types of filters available and generally used in MIW treatment applications include the following:

- Bag and cartridge filtration – Can treat a range of flow rates by providing housings that hold more bags or cartridges. Bags or cartridges are changed and disposed when the pressure drop across the filter reaches the target condition. Bags and filters come in a range of micron ratings down to one micron. This kind of filtration is typically used in short-term applications or where the TSS load is expected to be low or intermittent. These filters may be used in series with a larger filter, often in the range of 20 to 100 microns depending on particle size, followed by a finer filter in the range of 1 to 20 microns.
- Screen filtration – The screen size can be specified based on the application, with 10 micron being the typical lower size limit; however, some finer filtration can be achieved with the addition of a cloth over the screen. Screen filters are automatically backwashed and use filtered water for the backwash. The backwash must be managed further.
- Multimedia filtration – Tanks or columns filled with layers of media (anthracite, sand, and garnet) that have different density and will remain stratified after backwash, providing in-depth filtration. The three layers typically provide a little finer filtration compared to a sand filter, in the range of 10 to 25 microns. The filter is backwashed intermittently and the backwash must be managed further. Air scour is often included as part of the backwash cycle to loosen the bed. Polymer can be used in conjunction with multimedia filtration to enhance TSS removal.
- Sand filtration – Similar to multimedia filtration with tanks or columns filled with sand. The filter provides removal of particles larger than 20 to 40 microns and also produces a backwash that must be managed further. Sand filters can also be provided as continuous backwashing and moving bed. Polymer can be used in conjunction with sand filtration to enhance TSS removal.
- Membrane microfiltration (MF) and ultrafiltration (UF) – The equipment is similar to RO systems with skid-mounted membrane trains, a pump, and a cleaning skid. The MF and UF provide much finer filtration than the other types of filters discussed in this section, but only remove particulates and not dissolved parameters that RO systems treat. The MF membranes are in the range of 0.1 to 0.2 microns and the UF membranes provide even finer filtration. This technology is often used after chemical precipitation steps when very low effluent limits are applied or as pretreatment to RO or NF. No chemical coagulant or flocculant is needed with membrane systems. The removed particulates are retained and concentrated in a waste stream, called the concentrate, which is typically in the range of 2% to 10% of the forward flow.

Oil and grease can either be addressed by the gravity methods discussed in the previous section or with a specialized filter. The filters are typically used for removal of low concentrations of oil and grease or for polishing after the gravity treatment. Walnut shell filters and clay media filters both can provide removal of oil and grease to low residual levels. While the walnut shell filter media is contained in a flow-through pressurized vessel, the

operation of the filter is more complex than a multimedia or clay media filter. Conditioning of the walnut shell media is required prior to operation. The walnut shell filters are backwashed similar to media filters and the backwash must be managed further.

Clay, organo-clay, modified clay and similar media are all used for removal of oil from water in a column-type system similar to the media system described in Section 7.7.5. Some of the clay products are blended with anthracite media to increase the filter bed porosity. Once the media is spent, it is replaced and the spent media must be disposed. The spent media generally passes TCLP testing and can be disposed as a non-hazardous waste if sent off-site.

7.7.8.2 Pretreatment, Polishing, and Ancillary Equipment

Filters are used as both pretreatment and polishing treatment in various applications. The ancillary equipment required includes the following:

- Polymer makedown and feed, if used, for multimedia and sand filters or emulsion breaking chemicals for oil and grease removal
- Backwash supply tank and backwash pump, spent backwash tank for multimedia and sand filters, except for continuous backwashing sand filters
- Spent backwash tank for screen filters and continuous backwashing sand filters
- Concentrate bleed tank for MF and UF systems
- Backwash management either in a storage pond, return to front end of system, solids handling and dewatering or other option

7.7.8.3 Equipment and Typical Process Flow

The filter systems are all fairly simple, using a filter that is generally skid mounted and a feed pump, if there is not sufficient pressure from preceding equipment. The feed pump may be sized for flow through more equipment downstream or just the filter equipment, depending on the preceding or subsequent equipment. Except for bag and cartridge filters, all other filter types discussed in this section produce a liquid secondary waste stream that contains the suspended solids removed by the filter. Multi-media filters and conventional sand filters require a backwash supply and backwash pump as part of the system. Figure 7-26 shows a conventional sand filter and Figure 7-27 an ultrafiltration filtration system.

Figure 7-26: Pressure filters (photo courtesy of WesTech)

Figure 7-27: 102 m^3/h (450 gpm) ultrafiltration system (photo courtesy of Wigen Water)

7.7.8.4 Operation and Maintenance Considerations

The operational requirements of a well-designed filter are low compared to other water treatment technologies and may include the following:

- Labour – monitor pressure across filter, provide filter changes for bag and cartridge filters, initiate backwash or cleaning cycles if not automated, manage residuals (spent filters or backwash/concentrate stream).
- Power – pumping power for flow-through filters. The pumping power is higher for membrane filters than for other types of filters.
- Chemicals – polymer may be used to increase filtration efficiency; this is not required for membrane filters.
- Secondary waste – residual is a small volume liquid waste stream for all types of filters except bag/cartridge. For bag and cartridge filters, the secondary waste consists of spent bags/cartridges.

7.7.8.5 Process Development and Testing Required

These filtration processes are all well developed, and typically the filter is selected and sized based on the application, influent characterization, and flow rate. Process development includes good and complete characterization of the water and should include characterization for scaling and fouling parameters such as pH, calcium, sulfate, alkalinity, and iron in addition to TSS and other parameters. Initial bench testing may include bench-scale filter tests using a range of filter sizes to determine the particle size range. The data from this test are used to determine the required micron rating of the filter. The key parameter that is difficult to determine without field testing is the changeout frequency for bag/cartridge filters, cleaning cycles and concentrate volume for membrane filters, and backwash volume and frequency for the other types of filters.

7.7.9 Advanced Oxidation (Cyanide and other N-species)

An advanced oxidation process (AOP) is a destructive chemical treatment process where hydroxyl radicals are produced to modify or destroy target parameters. The chemicals most frequently used in the formation of hydroxyl radicals include ozone, hydrogen peroxide, and hypochlorite. Ultraviolet (UV) light can also produce hydroxyl radicals either alone or in combination with one of the oxidant chemicals. There are several variations using one or more of these chemicals and/or UV light. AOP processes are different than oxidation processes aimed at

precipitation because the goal of AOP is not oxidation of the target constituent but degradation or destruction. Oxidation to increase the oxidation state of a metal or compound to improve precipitation efficiency was discussed as part of precipitation in Section 7.7.2.

In addition to treatment of cyanide or other N-species, AOP can be used to convert selenite to selenate, and remove other reduced selenium-containing compounds. Teck has incorporated an AOP process in their Line Creek facility. The treatment system provides a 95% reduction of selenium; however, the majority of the residual selenium is present in the more bioavailable selenite form. The AOP system polishes the effluent by oxygenating the effluent and converting the residual low concentrations of selenium to selenate so the remaining selenium is less bioavailable (Hafke 2019).

7.7.9.1 Overview and Contaminants Removed

During chemical oxidation, one or more electrons transfer from the oxidant to the targeted pollutant, causing its destruction or conversion to a less bioavailable form. The process is used to treat toxic organic pollutants (which are not typically found in MIW), but is also effective to treat nitrogen compounds such as cyanide and ammonia that are more commonly present. The chemical oxidation processes require the addition of chemicals, most commonly alkaline chlorination, hydrogen peroxide (H_2O_2), and ozone (O_3). Another alternative is the photocatalytic oxidation, in which UV light is used to catalyze the oxidation reaction.

Persulfate is also used as an oxidant in AOPs; however, since its usage adds sulfate to the water, it may not be beneficial for mining applications where sulfate is already of concern. Potassium permanganate is often used for regeneration of greensand and manganese dioxide media, but is not as common for AOP. There are other chemicals, such as Fenton's reagent; however, ozone and hydrogen peroxide have the advantage in many mining applications because they do not add other ions to the treated water. Considerations for selection of chemical oxidants include:

- Chlorine and hypochlorite add ions to the water which may be detrimental to final effluent quality (e.g., chloride and sodium) and TDS can be increased. Many surface water permits have specific numerical limits on free residual chlorine.
- Chlorine and hypochlorite can cause formation of trihalomethane compounds (THMs) even when very low concentrations of organics are present. This is a concern primarily with drinking water and treatment of water where organics are targeted and may not be a consideration for MIW.
- Formation of unwanted by-products can occur, including chromate, nitrite, and bromate. Testing and selection of the AOP can control by-product formation.
- The dose of all oxidants is influenced by other parameters in the water that consume oxidants such as iron, manganese, other metals, alkalinity, naturally occurring background organic matter, and oil and grease.
- Excess oxidant may need to be removed prior to subsequent treatment processes or discharge, in a quench step.

Some oxidation processes are most efficient within a certain pH range, and so pH adjustment may be required in conjunction with chemical treatment.

Oxidation processes are non-selective and the radicals formed in the process will tend to react with any compound or chemical present. The effectiveness for removal of target compounds is typically determined by the specific water quality matrix. High background organic levels from naturally occurring organic matter (NOM) or other unregulated organics can increase the equipment and operational requirements. The presence of bromide or general NOM can result in the formation of undesirable by-products that are regulated. Nitrates and alkalinity

(carbonates) also consume oxidants. Higher chemical doses or power requirements may result when treating more complex or concentrated water matrices. Oxidation of chromium to hexavalent chromium is also possible and must be monitored. The effectiveness of the AOP relies on the production of hydroxyl radical (·OH) through the use of ozone (O_3), hydrogen peroxide (H_2O_2) and/or UV light. The true efficiency of ·OH generation is heavily influenced by a number of factors that are specific to the water quality being treated, such as pH, the relative concentration of oxidants, and the concentration of radical scavengers.

Cyanide and ammonia are the parameters most likely to be treated via an AOP in mine water treatment applications. Cyanide treatment effectiveness is impacted by the form of cyanide present in the mine water and the water pH. Chemical oxidation of cyanide is typically conducted under alkaline conditions. In general, free and weak acid dissociable (WAD) cyanides are readily oxidized. Oxidation of strong acid dissociable (SAD) cyanides (including iron-cyanides) is more difficult, requiring more reaction time and often an initial step to degrade the SAD cyanide bonds using photo-dissociation, a catalyst, or heat. For optimal treatment, laboratory testing must be conducted to determine the oxidant to cyanide dose, background oxygen demand, pH, oxidation/reduction (redox) conditions, reaction time, and effects of non-targeted compounds in the wastewater matrix. Generally, chemical oxidation of cyanide is carried out in a two-step system: stage one takes place at a high pH to oxidize cyanide to cyanate and stage two occurs at a lower pH to transform cyanate to ammonia or nitrogen gas. Formation of hydrogen cyanide gas is possible under certain reaction conditions, and pH values and safety procedures should be developed for both testing and operations to ensure this is prevented. AOPs have been used for cyanide treatment in the metal finishing industry for a number of years and the treatment chemistry and comparison of oxidants are well documented (EPA 2000). Botz et al. (2016) also provides a review of cyanide treatment technologies with a focus on mining. Young and Jordan summarize which oxidation processes are effective for four forms of cyanide in tabular format (Young and Jordan 1995). This table has been reproduced as Table 7-6.

Table 7-6: Effectiveness of oxidation on various cyanide species (reproduced from Young and Jordan (1995))

Oxidation Process or Chemical	**Effective for Oxidizing Specified Cyanide Form (yes, no or partial)**						
	Free Cyanide	Thio-cyanate	WAD Metal Complex (Cd, Zn)	WAD Metal Complex (Cu/Ni)	SAD Metal Complex (Fe)	SAD Metal Complex (other metals)	Polishing Required
Alkaline chlorination	Yes	Yes	Yes	Yes	No	No	Yes
Oxygen	Yes	Partial	Partial	No	No	No	Yes
Ozone	Yes	Yes	Yes	Yes	No	No	Yes
Hydrogen Peroxide	Yes	No	Yes	Partial	Partial	No	Yes
Hydrogen Peroxide (Cupric)	Yes	No	Yes	Yes	Yes	No	Partial
Hydrogen Peroxide (Kastone)	Yes	No	Yes	Yes	Yes	No	Partial
Caro's Acid	Yes	Yes	Yes	Yes	Yes	No	Partial
Sulfur Dioxide	Yes	Partial	Yes	Yes	Yes	Partial	Partial
UV/Ozone	Yes	Yes	Yes	Yes	Yes	Yes	No
UV/Peroxide	Yes	Yes	Yes	Yes	Yes	Yes	No
TiO_2 Photocatalysis	Yes	Yes	Yes	Yes	Yes	Yes	No

Breakpoint chlorination is a common oxidation process with a long history of use for treatment of many nitrogen-containing compounds. For ammonia treatment, breakpoint chlorination involves the addition of chlorine to wastewater to oxidize the ammonia nitrogen to nitrogen gas. Breakpoint chlorination can provide complete ammonia removal with precise chlorine dosing and pH controls. Breakpoint chlorination may also provide 80% to 95% removal of total nitrogen (Tchobanoglous 2014), although the required dose will then be higher than for ammonia removal alone.

Historically, breakpoint chlorination was often used with municipal drinking water systems where the water quality was good and removal of relatively low levels of ammonia was required. However, this technology is not as commonly used today for municipal drinking water treatment due to the negative impacts of disinfection by-products (chloramines) that can be formed. Application of breakpoint chlorination to industrial wastewater also is not common due to the typical increased chlorine demand from other constituents. Parameters that contribute to chlorine demand can include iron, manganese, sulfide, nitrite, and organic parameters, including algae and bacteria. The theoretical dose of chlorine (Cl_2) to ammonia is 7.6:1; however, in actual practice it is much higher due to the presence of other constituents that consume oxidant. The most effective pH for ammonia removal is generally in the range of 7 to 8, and reaction times up to two hours are typical. Dechlorination may be required if effluent toxicity is an environmental concern.

In addition to breakpoint chlorination, other advanced oxidation treatments may include use of ozone, hydrogen peroxide, ozone and peroxide combined, or chemical addition combined with UV light.

7.7.9.2 Pretreatment, Polishing Treatment, and Ancillary Equipment

The requirements for pretreatment and/or polishing treatment are dependent on whether the AOP is a stand-alone process or part of a treatment train and on its placement in the treatment train. In addition, the requirements are dependent on the oxidant selected and whether or not UV is included as part of the AOP treatment.

Pretreatment requirements for AOPs may include the following:

- Removal of fouling or scaling parameters such as iron, calcium carbonate, calcium sulfate, and similar. This is primarily of concern if UV is included since these parameters can reduce the efficiency of the UV lamps.
- Removal or reduction of parameters that consume oxidant such as NOMs, oil and grease, iron, alkalinity, sulfide, and similar parameters.
- Removal of TSS if levels are high or UV lamps are included in the AOP treatment.
- Influent pH adjustment as needed since there are optimal pH conditions for treatment of some parameters by some AOP methods.

Pretreatment processes often include gravity separation, filtration, oxidation and filtration, granular activated carbon, and pH adjustment.

Polishing can include treatment for removal of excess oxidant and/or pH adjustment. Excess oxidant can be removed by aeration in some cases, with addition of metabisulfite and/or addition of specialized carbon for oxidant removal.

Ancillary systems included with advanced oxidation processes include chemical storage and handling and solids management if filtration systems are part of the treatment train. The carbon systems are generally regenerated by the carbon supplier and, therefore, do not generate a secondary waste for further handling. Some mine sites are remote and return and regeneration of carbon may be more challenging and result in generation of secondary waste. Chemical storage for oxidants requires strict safe handling procedures, often separate storage areas and

specialized ventilation or outdoor storage. Materials used for construction must be considered carefully and for hydrogen peroxide, dark storage tanks are required to reduce degradation of the peroxide.

7.7.9.3 Equipment and Process Flow Diagram

The process and mechanical equipment required for most oxidation processes consists of tanks with mixing for chemical reaction along with any required equipment as described in Section 7.7.9.2. If the oxidation process includes ozone and/or UV light, then specialized equipment is required.

Ozone is an unstable gas that decomposes quickly to oxygen and, therefore, must be generated on site. Ozone generators are standard equipment for many applications and a range of sizes is available. Ozone is formed by the passage of high voltage alternating current through a gas stream containing oxygen (either air or oxygen).

UV systems for advanced oxidation are similarly packaged standard equipment sized for a range of flow rates (retention times) to deliver a target UV dose. UV is typically combined with chemical treatment (peroxide, chlorine, or ozone) that is added prior to the UV reactor.

7.7.9.4 Operation and Maintenance Considerations

Operational and maintenance requirements for advanced oxidation processes are mainly driven by the cost of the oxidant dose required for water treatment. AOP is commonly used for treatment of drinking water and contaminated groundwater and most often applied when the target contaminant concentration is a few milligrams per liter. For high concentrations of nitrogen compounds, AOP should be compared to other technologies on a life cycle cost basis. Key considerations for operational and maintenance requirements include the following:

- Health and safety issues related to handling chemicals and compatibility with other chemicals on site should be evaluated with SME input, and operations procedures developed to mitigate the potential safety concerns with the oxidants.
- Health and safety issues with treatment of cyanide and the potential to release hydrogen cyanide gas should be evaluated. At a pH of less than 9, cyanogen gas can form in the conversion of cyanide to cyanate.
- The cost of chemicals is often the major element of the annual operating budget.
- Labour requirements are low as residuals are typically not formed and chemicals do not require makedown.

7.7.9.5 Process Development and Testing Required

Evaluation and implementation of an AOP for treatment of mine process water requires good water quality characterization. If cyanide is the target parameter being treated, the determination of the form(s) of cyanide (e.g., free, WAD, SAD) is required. Characterization of the background water quality is also required and should include pH, TDS, alkalinity, iron, manganese, TOC, sulfide, ammonia, nitrite, and nitrate. In addition, bench-scale testing can be conducted similar to other jar testing to evaluate oxidant dose, pH, and other treatment conditions. If cyanide is present, this testing should be conducted in a hood to prevent exposure to hydrogen cyanide gas.

UV testing can be completed by many manufacturers, or UV transmissivity can be measured as part of the bench-scale testing.

Pilot-scale testing can also be conducted to further evaluate and confirm treatment conditions and to evaluate the need for pretreatment and any potential operational problems due to the water matrix.

7.7.10 Emerging Active Technologies Considered in MIW Treatment

There are many technologies that can be considered when evaluating the challenging problems associated with treatment of MIW. Some of these technologies have been well developed and are commonly utilized in non-

mining industries, and some have been evaluated on mine water, but not implemented at full scale or in very limited circumstances. These latter technologies are discussed in the following sections and a summary matrix is presented in Table 7-7.

Table 7-7: Emerging MIW Treatment Technologies

Technology	Type of Industrial Application	Technology Readiness Level
Ettringite Precipitation for Sulfate Removal	Mining, coal and other industry	Full Scale
Biological Sulfate Removal	Mining, coal and other industry	Field Scale and Full Scale
Ion Exchange and Media (for Selenium and Sulfate)	Mining	Early Full-Scale Application
Electrocoagulation	Metal finishing wastewater, shipyard runoff water, and food processing wastewater	Full Scale for other industries Bench Scale for MIW
Closed Circuit Reverse Osmosis	Industrial and Municipal	Early Full Scale
High-Pressure Reverse Osmosis	Industrial	Early Full Scale
Treatment and Extraction of Rare Earth Elements	Mining	Research and Development

7.7.10.1 Ettringite Precipitation for Sulfate Removal

Ettringite precipitation has been well studied and documented for the removal of sulfate to low residual levels (100 to 200 mg/L). The ettringite process is based on the addition of aluminum hydroxide in a high-pH environment, resulting in precipitation of ettringite (a hydrated calcium aluminosulfate mineral), as shown below:

$$6Ca^{2+} + 3SO_4^{2-} + 2Al(OH)_3 + 38H_2O \rightleftharpoons Ca_6Al_2(SO_4)_3(OH)_{12}\bullet 26H_2O + 6H_3O^+$$

Three commercialized variations of the ettringite precipitation process (SAVMIN™, cost-effective sulfate removal [CESR], and Outotec) have been developed and demonstrated. The primary steps include lime addition to pH 11 to 12, aluminum addition for ettringite precipitation, clarification, and pH neutralization. The differences in the processes include the number of precipitation steps, the chemical form of the aluminum additive, and recovery of aluminum in some cases. For MIW sources that have sulfate concentrations higher than at gypsum solubility, a gypsum precipitation step should precede the ettringite precipitation step to minimize the aluminum-based reagent dose required. There have been limited implementation and no reported long-term operating treatment plants using ettringite precipitation to achieve a low-sulfate residual. Compared to other treatment processes, the reagent costs are typically high while the sludge volume produced is also high. In addition, sodium is added to the treated water. Two packaged ettringite systems are available: the LoSO$_4$™ from Veolia (http://www.veoliawatertech.com/vwst-northamerica/ressources/files/1/33855,LoSO4-final-LR.pdf) and Outotec® Sulfate Removal Process (https://www.outotec.com/products-and-services/technologies/industrial-water-treatment/sulphate-removal-process/).

7.7.10.2 Biological Sulfate Removal

Sulfate is reduced to sulfide by sulfate-reducing bacteria (SRB) in a microbial process that is naturally occurring, but has had limited application as an active mine water treatment process. The process is anaerobic and a carbon source is required. Additional treatment for removal of sulfide is also required and an aerobic biological system can be used for sulfide management or iron coprecipitation. This technology was commercialized by Paques as the SULFATEQ™ process, with several full-scale installations that have been operational long-term (mid-90s) in various industrial wastewater treatment applications. However, mining applications have been limited. Sulfate is removed from various industrial wastewater sources that contain metals and sulfate with the sulfate concentration typically achieved in the range of 1,000 to 2,000 mg/L down to 500 mg/L or less. Reinsel (2015) reviews biological sulfate removal and includes three examples of packed bed systems with supplemental carbon (methanol or ethanol) installed between 2005 and 2012 at mine sites. There is also recent research and testing on active SRB systems (Du Preez et al. 2018, Hessler et al. 2018).

7.7.10.3 Ion Exchange and Media (for Selenium and Sulfate)

There are commercialized systems for treatment of selenium or sulfate using iron-based media and ion exchange with electrochemical treatment of spent regenerant. BQE Water has commercialized Selen-IX™ for removal of selenate by an anion exchange resin and then further treatment of the concentrated selenate in the spent regenerant by electrochemical reduction. There are currently two such full-scale treatment plants under construction: one at the Kemess Mine in British Columbia and the other at a mine in the US (Gleeson 2020). More detail and a photograph of a full-scale system are provided in the NAMC white paper (Golder 2020). Selenium removal using this technology is reported to be efficient in water with high sulfate concentrations.

BQE also offers a sulfate removal IX technology, Sulf-IX™. A fluidized bed reactor is used rather than a column system for IX contact with the mine water. The fluidization rise rate is calculated so that calcium sulfate precipitation does not occur on the resin beads. Calcium sulfate, gypsum, is a by-product. The system has been evaluated in a number of pilot and field trials.

The NAMC white paper (Golder 2020) on selenium technologies also presents work on zero valent iron and other iron-based media that are emerging for selenium treatment. One patented technology evaluated is the Pironox® Reactive Media System. The media contacts the influent water in mixed reaction tanks rather than columns and reduces the selenium to the selenite form. The media is effective for other metals as well, including mercury, chromium, copper, molybdenum, nickel, vanadium and zinc.

7.7.10.4 Electrocoagulation

The electrocoagulation (EC) process involves passing an electrical current through water, disrupting the ionic charges of dissolved species. Precipitation and coprecipitation of dissolved species result due to several mechanisms. One of the primary mechanisms is coagulation by iron or aluminum (depending on the electrode metal type) cations released from the corrosion of the anode. Since no chemicals are added, supplemental parameters such as sulfate or chloride are not of concern. The EC unit replaces the reaction tank and chemical feed systems used in conventional precipitation; however, downstream solids separation is still required. An EC system is shown in Figure 7-28, which presents two views including the complete system and the electrodes.

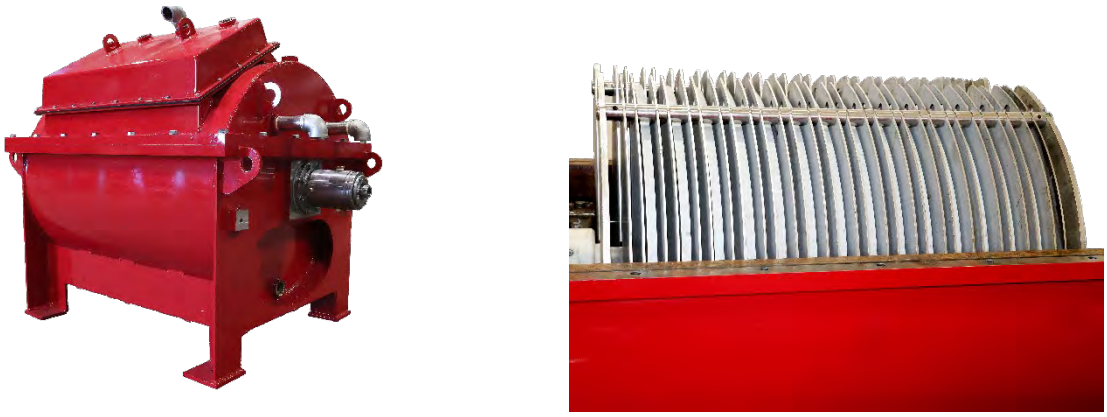

Figure 7-28: Electrocoagulation unit - 2 views (photos courtesy of Avivid Water)

EC has been used extensively in the treatment of metal finishing wastewater, shipyard runoff water, and food processing wastewater. In addition to metals removal, EC provides removal of other target contaminants in MIW, including TSS, oil and grease, and cyanide. New electrode materials are being evaluated for treatment of other contaminants as research and development continues to improve this technology. Other bench-scale research is conducted to evaluate removal of metals, nitrate, and sulfate using this technology (Nariyan 2017; Mamelkina et al. 2017, 2018, 2019).

EC can generally remove most metals encountered at mine sites, although only limited success with antimony and boron has been reported. In addition, it is not effective at low pH. In the past, EC equipment has focused on smaller industrial flows, and larger systems capable of treating the higher flows often present in mine water applications have required multiple units to achieve the desired treatment performance. However, larger systems from several manufacturers are becoming more standardized.

Typically, the capital equipment cost for EC is higher than for chemical precipitation for most MIW applications. In contrast, EC operating costs may be lower than those for chemical precipitation due to reduced requirements for labour and chemicals. Electrodes require replacement, and this cost can be an operating factor depending on local availability of metal material for electrode replacement, but it is typically less expensive than corresponding chemicals. Electrical power demand is likely higher and is inversely related to the ionic strength of the water being treated. Costs for electrical power may be high at remote mining locations.

7.7.10.5 Closed Circuit Reverse Osmosis

Closed circuit reverse osmosis (CCRO) is a specific configuration of RO technology that operates in a semi-batch mode and provides higher water recovery than conventional RO. Recovery in the range of 98% is achieved over a range of wastewater sources and the configuration minimizes fouling and scaling relative to conventional RO operations. Instead of operating in a continuous manner, with the influent flow split between continuous streams of permeate and brine, the brine discharge (flush) is intermittent in a CCRO system. The brine is produced batch-wise or as a flush. The brine is recirculated back to the influent in a closed circuit until the brine concentration, the recovery, or another indicator setpoint achieves a target value. The brine is then discharged from the system intermittently, similar to a cooling tower blowdown. Operating in this manner causes cycling of salinity (TDS), which disrupts, and therefore reduces, scaling and fouling. Operating at higher salinity on the brine side toward the end of a batch also inhibits microbial growth.

For conventional RO systems, on average, the permeate recovery obtained for MIW is often between 60% and 80%, with some applications able to achieve an 85% recovery. As an example, at a 75% recovery, a 100 m^3/h influent flow for conventional RO produces 75 m^3/h of permeate and 25 m^3/h of brine. With the CCRO system, the

100 m^3/h influent flow may produce 98 m^3/h of permeate and 2 m^3/h of brine. The CCRO systems have been used to treat a range of industrial and municipal wastewater sources. Desalitech, a Dupont company, has a patent on standardized CCRO design and proprietary operating software. They have implemented over 200 installations of the technology in the last seven years. A similar technology by IDE is called the MaxH20 system.

7.7.10.6 High-Pressure Reverse Osmosis

In addition to CCRO, there are other advances in membrane technology and treatment processes that are allowing production of higher concentration brines. Ultra-high-pressure membrane elements have been developed and commercialized that can operate up to 120 bar (over 1,700 psi; 12 MPa). Compared to a brackish water membrane with a maximum operating pressure of 41 bar (600 psi; 4.1 MPa) or a conventional seawater membrane with a maximum operating pressure of 55 bar (800 psi; 5.5 MPa), the ultra-high pressure is a significant increase. Brine concentrations of up to 100,000 mg/L have been achieved. This technology is also relatively new, but has been used in the treatment of a range of industrial wastewaters.

7.7.10.7 Treatment and Extraction of Rare Earth Elements

A team of researchers at Pennsylvania State University is developing an acidic MIW treatment process that utilizes carbon dioxide to precipitate rare earth elements as carbonates. The precipitation is accomplished in two steps at near-neutral pH. The treatment process is being called carbon dioxide mineralization and is intended to be a modification of traditional chemical treatment processes (Leotaud 2020). The recovery of rare earth elements from mine waters and mine water residuals has generated significant scientific and strategic interest (discussed in Section 7.11).

7.8 Passive Treatment Technologies

Passive treatment technologies for treatment of MIW are defined as biological and/or chemical processes that neutralize acidity and precipitate metals via oxidation or reduction using natural processes that do not require regular human intervention or maintenance. In general, a passive system should function for many years without a major retrofit to replenish materials and should be able to function with no or low electrical power.

Gusek (2008) provides a useful summary of the origin of passive treatment as applied to MIW in the US. The pioneering work of a group of researchers at Wright State University in 1978 documented water quality improvements in a natural sphagnum bog in Ohio that was receiving low-pH, metal-laden water. Complementing this research, a group at West Virginia University found similar results at the Tub Run Bog in 1982. Subsequently, researchers, practitioners, and engineers focused on developing the promising technology of using constructed wetlands to treat acidic drainage. Since the term “wetland” carries legal and regulatory connotations and does not quite describe structures like anoxic limestone drains or successive alkalinity producing systems, the term “passive treatment” was adopted.

Many elements can be treated in a passive treatment process, as outlined in Figure 7-29, which is the periodic table of elements for passive treatment, as developed by Gusek and Waples (2009).

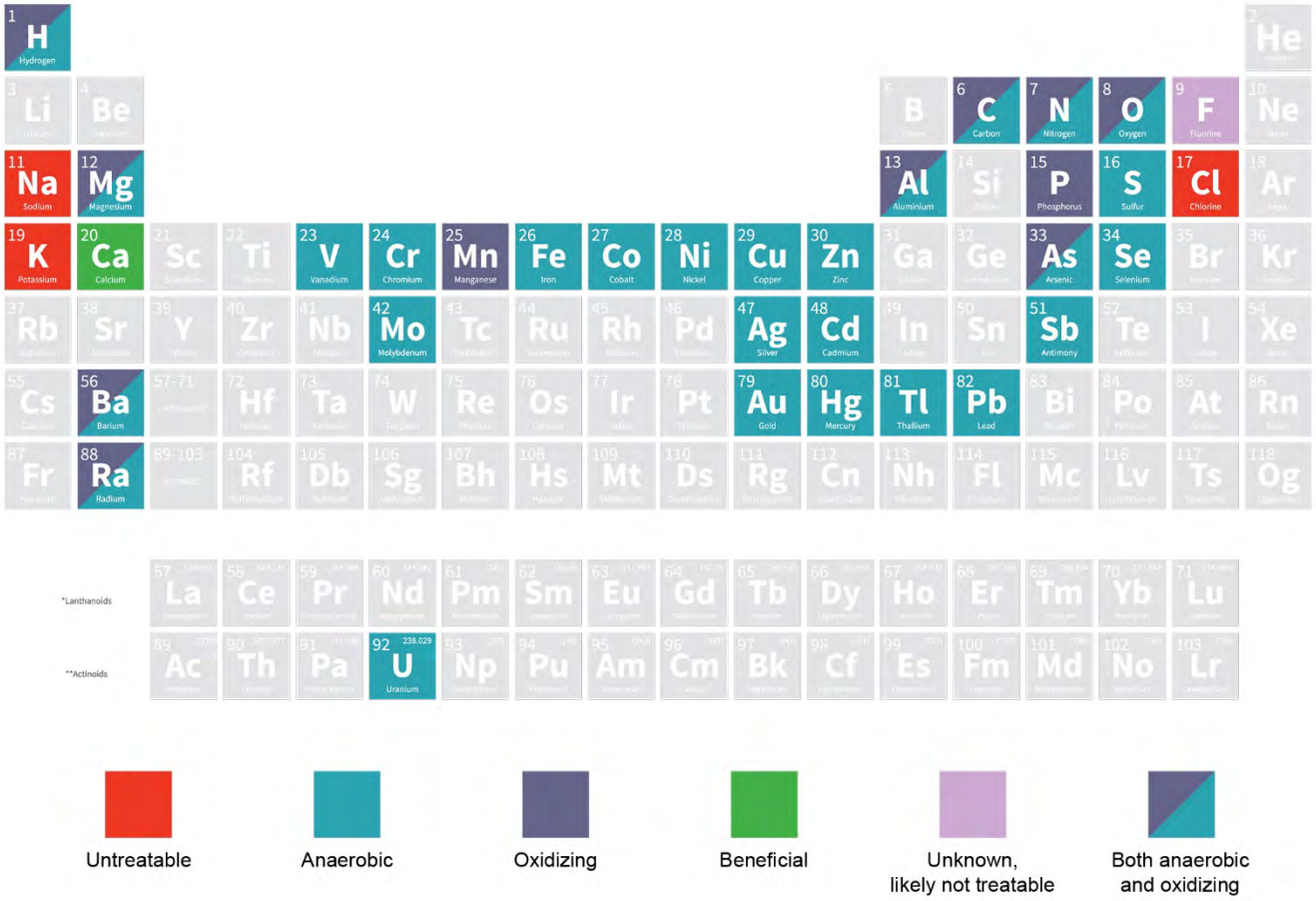

Figure 7-29: Periodic table for passive treatment

The generic categories of passive treatment systems are detailed in Table 7-8.

There are some variations of these technologies, such as steel-slag leach beds (SLB), which are a variant of the limestone leach bed included in Table 7-8 and limestone sand (LS sand). Both of these, and other similar technologies, are described in greater detail in Skousen et al. (2017).

The proven application of passive treatment technologies is to low-flow scenarios. Most successful passive treatment projects are treating less than 1,000 m^3 per day; however, there are examples of long-running systems at higher flows. The largest documented passive treatment system treated approximately 6,500 m^3 per day for lead and zinc removal starting in 1996 with limited maintenance, and discharge was in compliance for 19 years prior to being decommissioned (Gusek et al. 2000, 2007). Another long-running system (since 2011) that treats water at seasonal high flows of approximately 6,500 m^3/day is the Magenta Mine Passive Mine Water Treatment System installed at the Empire Mine State Historic Park near Grass Valley, California, which treats iron, manganese, arsenic and turbidity (Schipper et al. 2018).

Table 7-8: Generic Categories of Passive Treatment

Passive Treatment Technology	Application Niche in Mine Drainage
Aerobic wetlands (AeW)	Net alkaline; nitrogen compounds
Anaerobic wetlands (AnW)	Net acidic; high metal content
Biochemical reactors (BCR) - originally known as Sulfate reducing bioreactors (SRB)	Net acidic or neutral; elevated metals, selenium, nitrate, sulfate
Reducing and alkalinity-producing systems (RAPS) or vertical flow wetlands (VFW) – Originally known as successive alkalinity producing systems (SAPS)	Net acidic; high metal content
Anoxic limestone drains (ALD)	Net acidic; low aluminum, low iron, low DO
Open limestone drains (OLD) or open limestone channels (OLC)	Net acidic; high metal content, low to moderate SO_4.
Limestone leach beds (LLB)	Net acidic; low metal content
Iron oxidation ponds	Net acidic; high iron
Manganese oxidation beds (MOB) or Manganese removal beds (MRB)	Net neutral; high manganese

Hedin et al. (1994a) developed a decision support flowsheet to assist in the selection of an appropriate passive treatment technology. This was updated and adapted by Skousen et al. (2017). Gusek (2008) further updated the decision tree to include a wider range of chemistries for MIW as other versions primarily focused on aluminum, iron, and manganese (Figure 7-30). Trumm (2010) developed flow charts specifically for New Zealand conditions with selection of active and passive treatment. This adaptation includes both active and passive treatment and also specific accommodation for topography, site space constraints, climate, local environmental concerns and other challenges common to New Zealand.

Figure 7-30 is a useful tool that shows the steps and logic that can be used in determining a passive treatment train, similar to the development of an active treatment train. However, it should be noted that different flowsheets may result in different outcomes as none include all possible pathways. The process to develop a treatment train for each site needs to involve independent evaluation of the site-specific water quality, water quantity, and other site considerations (e.g., climate, space availability, existing infrastructure that can be utilized or repurposed, power availability, etc.) as well as the discharge requirements.

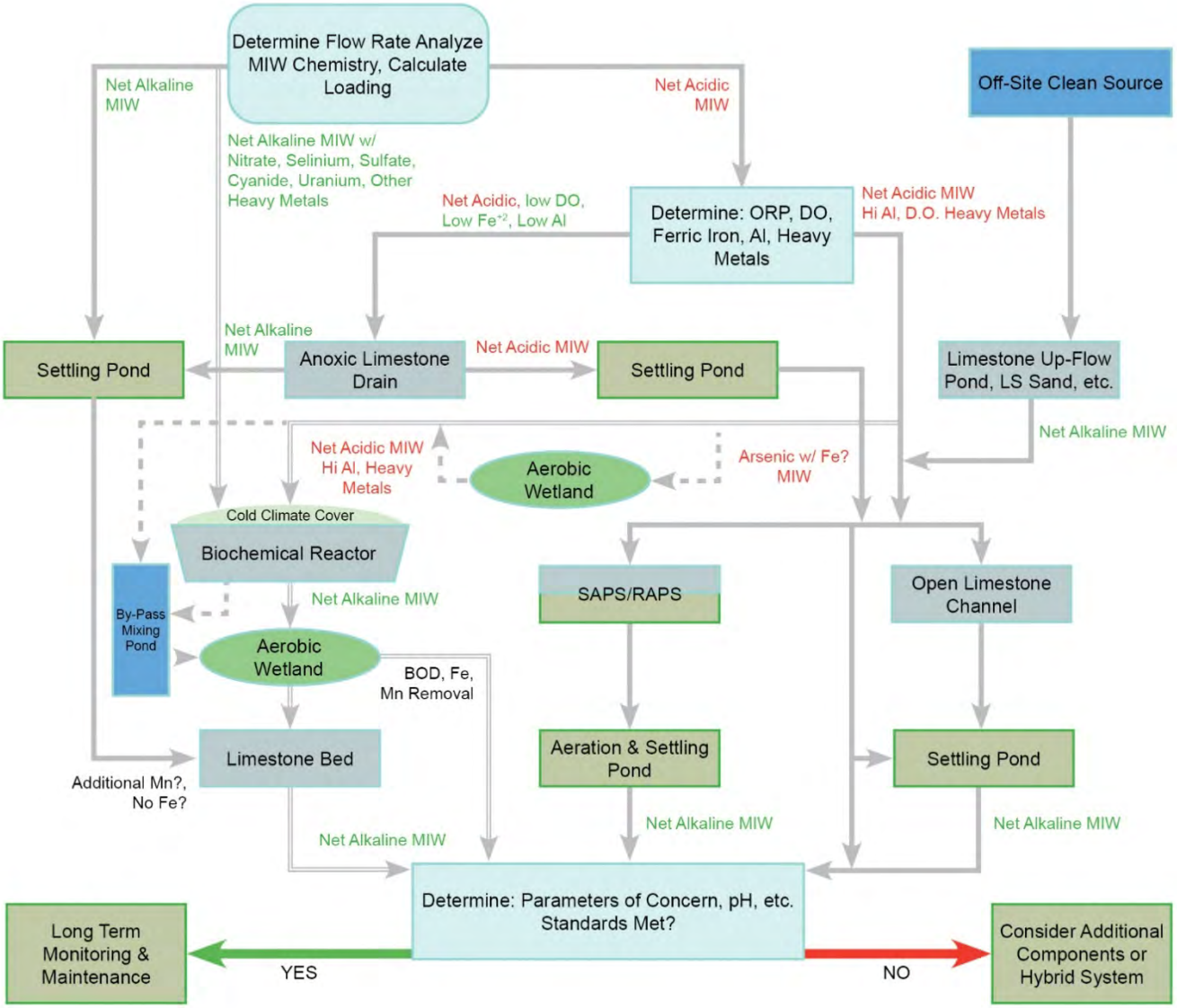

Figure 7-30: Decision flowchart for passive treatment technology evaluation (adapted from Gusek 2008)

The mechanisms of metal removal and retention in passive treatment systems are varied and include:

- Filtration of solids
- Oxidation at or near the water-surface interface
- Reduction via biological activity
- Precipitation as hydroxides and carbonates under aerobic conditions
- Precipitation as sulfide and hydroxy-sulfate (aluminum special case) minerals under anaerobic conditions
- Complexation and adsorption onto organic matter
- Ion exchange with organic matter
- Uptake by plants (phyto-remediation)

The precipitation of iron as hydroxide minerals may also assist in the removal of additional pollutants. Several ionic species, such as arsenic and molybdenum, coprecipitate or adsorb onto ferric hydroxide. There is evidence that some of these reactions can be microbially facilitated (LeBlanc et al.1996).

Although they may be economically attractive, passive methods also have limitations. They require a large footprint and are best suited to treating mine effluents with low acidity (<800 mg/L as $CaCO_3$) and low flow rates (<50 L/s) and, therefore, low acidity loads (Taylor et al. 2005). The effects of seasonal climatic changes, such as extended periods of low temperature or high flows during the freshet or rainy season, pose challenges to any water treatment system, but in particular to the design and operation of passive systems. Also, passive systems may not achieve the extremely low levels of some contaminants required with increasing frequency in regulatory jurisdictions. Some parameters are not removed, or are only minimally removed, by passive treatment, such as boron, chloride, sodium, potassium, calcium, magnesium, and TDS.

The challenges of passive treatment must be balanced against the cost advantages that passive treatment provide in many cases as well as the positive sustainability aspects of the technology. Like active treatment, passive treatment is the right fit for some situations and not for others and should be evaluated on a case-by-case basis for technical feasibility, regulatory acceptance, life cycle cost, and other project specific factors like any treatment technology or water management option.

Sections 7.8.1 through 7.8.7 provide brief overviews of the principal passive treatment technologies.

7.8.1 Constructed Wetlands

Constructed wetlands are the most widely used wastewater treatment option and have been implemented to treat a variety of contaminants in a variety of climates for several decades. They are designed to imitate the naturally occurring biogeochemical, geochemical, and physical processes of natural wetlands, and are constructed to maximize hydraulic efficiency and meet specific treatment goals.

7.8.1.1 Aerobic Wetlands

Aerobic wetlands are typically used to treat mildly acidic or net-alkaline waters with high iron concentrations, and have a limited ability to neutralize acidity. These wetlands are designed to introduce aeration to MIW to oxidize dissolved iron and provide sufficient residence time for hydrolysis and metal hydroxide reaction products to precipitate. Some metals/metalloids that may coprecipitate with iron oxides include arsenic, cobalt, copper, nickel, lead, zinc, cadmium, and chromium. Successful metal removal depends principally on the dissolved metal concentrations, DO content, pH, net acidity/alkalinity of the mine water, and the retention time of the water in the wetland. The pH and net acidity/alkalinity of the water are particularly important because pH influences both the solubility of metal hydroxide precipitates and the kinetics of metal oxidation and hydrolysis. If influent waters are alkaline and limited iron is in solution, aerobic wetlands can remove manganese. However, iron oxidation is a more efficient process and manganese oxidation does not occur until iron oxidation is nearly complete. For both iron and manganese, oxidation occurs both geochemically and biologically.

Aeration can be introduced passively to aerobic wetlands by simply cascading the MIW down a rock-lined channel or over a dam to encourage splashing and turbulence. MIW that contains less than 50 mg/L of dissolved iron and relatively low concentrations of manganese can often be treated simply using this form of aeration, followed by a pond or wetland for metal floc settling, if there is enough change in elevation to produce the required turbulence. No chemical addition is needed, and the water can typically be discharged safely without adversely affecting receiving streams. If the iron concentrations are higher, additional aeration steps can be incorporated into the design by inserting additional turbulence between the ponds or wetland cells. Since enhanced iron oxidation and hydrolysis are the keys to most MIW passive treatment systems, such turbulence steps are routinely added between wetland cells. For sites where the iron loading is particularly high, or where the change in elevation is

minimal, supplemental aeration may be necessary. At such sites, semi-passive systems have been constructed using gravity-, wind-, and water-powered aeration or neutralization processes, as well as some devices that require external electrical power, may be used to provide supplemental aeration. This is still often less expensive than conventional chemical treatment.

Aerobic wetlands typically include *Typha* (colloquially known as cattail or bulrush) and/or other wetland vegetation planted at variable shallow water depths and in relatively impermeable sediments composed of soil, clay, or mine spoil. Aquatic plants have aesthetic value and translocate oxygen to the subsurface through their roots, which promotes oxidation as well as facultative microbial activity. The aquatic plants also help to disperse the water flowing through the wetland, increasing residence time and aiding solid-phase metal removal via filtration and sedimentation. In addition, phytoremediation is a mechanism for contaminant removal in wetlands. The mechanisms for removal of contamination by aquatic plants includes uptake and concentration of contaminants in plant tissue, degradation of contaminants by various biological or chemical processes at or around the root zone, volatilization or transpiration of volatile contaminants from plants to the air, and immobilization of contaminants in the root zone (EPA 2014). While many studies have found that phytoremediation plays a minimal role in contaminant removal when compared to other treatment mechanisms in aerobic wetlands, it is well documented that wetlands with plants show a significant and positive effect of pollutant removal by providing sites for metal precipitation and/or sedimentation (Brisson and Chazarenc 2009, Yeh 2008, Pat-Espadas et al. 2018).

Wetlands can also be developed for the purpose of removing nitrogen via nitrification (conversion of ammonia to nitrate) or denitrification (nitrate removal via conversion to nitrogen gas), wherein temperature, ammonia loading rate, nitrate loading rate, and target discharge conditions are the major drivers for establishing wetland sizing (Crites et al. 2006). Ammonia (NH_3) is subject to nitrification in a two-step biological conversion, first being converted to nitrite (NO_2^-) and then to nitrate (NO_3^-). The initial step of converting ammonia to nitrite (Step 1) involves a type of bacteria called *Nitrosomonas*. After being converted to nitrite, the second step of the conversion, nitration, takes place (Step 2). In nitration, bacteria called *Nitrobacter* convert the nitrite to nitrate. An overview of the nitrogen cycle in a wetland is shown schematically in Figure 7-31. The equation for nitrification is as follows:

Nitrification: Step 1 – $NH_3 + 1.5O_2 \rightarrow NO_2^- + H^+ + H_2O$; Step 2 – $NO_2^- + ½O_2 \rightarrow NO_3^-$

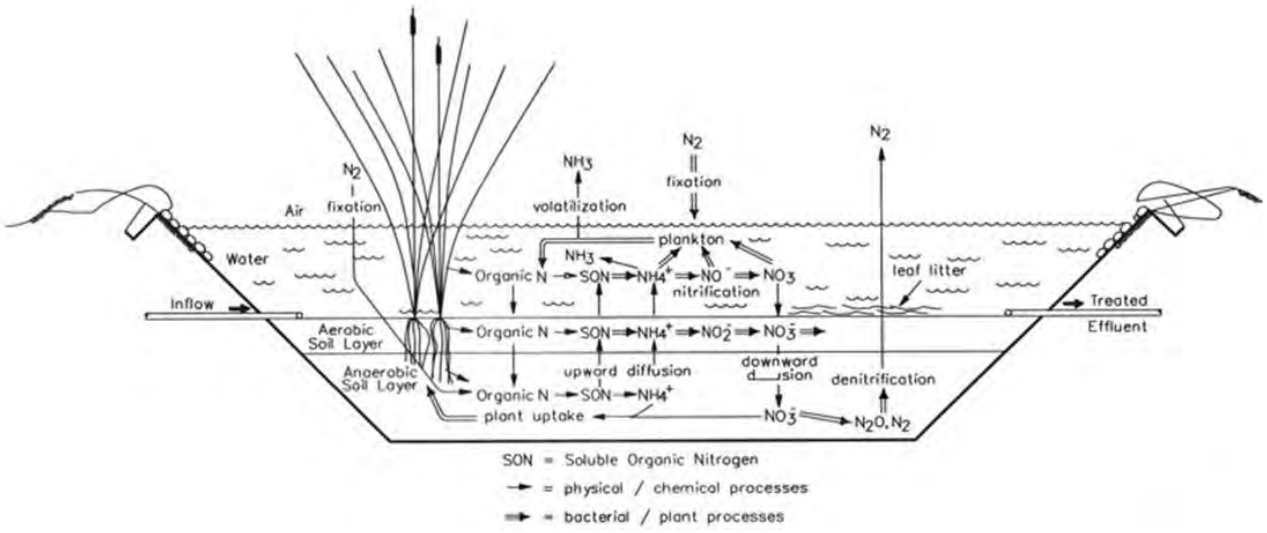

Figure 7-31: Nitrogen Cycle in Constructed Wetlands (taken from Campbell and Ogden 1999)

The amount of nitrification that takes place is temperature, oxygen, and pH dependent. The rate of nitrification decreases significantly as water temperatures approach freezing. The bacteria that perform nitrification, *Nitrosomonas* and *Nitrobacter*, are aerobes, so they require free dissolved oxygen to nitrify. Optimal pH ranges for nitrification are between 7.5 and 8.5, though nitrification still takes place as long as pH values are above 6.5.

The nitrate created via ammonia nitrification joins any of the other nitrate present in the water and is then available for denitrification. Denitrification is the biological reduction of nitrate to nitrogen gas (N_2) by heterotrophic bacteria. Since denitrifying bacteria are facultative, they can use either dissolved oxygen or nitrate as a source of oxygen for metabolism and oxidation of organic matter. Heterotrophic bacteria need a carbon source as food to live.

Denitrification occurs when oxygen levels in the wetland soil become depleted and nitrate becomes the primary oxygen source for microorganisms. This means that the process occurs under anoxic conditions (less than 2.0 mg/L of dissolved oxygen), primarily when the dissolved oxygen concentration is less than 0.5 mg/L, ideally less than 0.2 mg/L. It is important, however, that the conditions are not anaerobic, or completely void of oxygen, as facultative bacteria cannot survive in such conditions. Since facultative heterotrophic bacteria need carbon to live, as well as anoxic conditions (but not anaerobic conditions), wetland soils provide a good environment for denitrification to occur. Wetland sediments are anoxic and contain carbon from the wetland vegetation and will contain denitrifying bacteria when nitrate is present.

When the denitrifying bacteria break apart the nitrate to use the oxygen, the nitrate is reduced to nitrogen gas through nitrite, nitric oxide (NO) and nitrous oxide (N_2O) intermediates, as follows:

Denitrification: $4NO_3^- + 5CH_2O \rightarrow 2N_2 + 4HCO_3^- + CO_2 + 8H_2O$

Where CH_2O defines a representative carbon source.

Since nitrogen gas has a low water solubility, it escapes into the atmosphere as gas bubbles. Free nitrogen is the primary component of air; thus, its release to the environment does not cause concern. The rate of denitrification that takes place is temperature, dissolved oxygen, and pH dependent. The rate of denitrification drops significantly as water temperatures approach freezing while, as temperatures increase, rates of denitrification increase substantially. If dissolved oxygen is present, the bacteria will utilize that as a source of oxygen for metabolism and oxidation of organic matter before nitrate, which is why the dissolved oxygen levels stated above are preferred. The optimal pH range for denitrification is between 7.0 and 8.5.

A list of the important environmental design conditions associated with aerobic wetlands for removal of suspended solids and selected metals is as follows:

- Relatively shallow water depths to allow aeration of mine drainage
- Cascades to further enhance aeration
- Configuration and layout to promote favourable hydrodynamic flow conditions (prevent short-circuiting)
- Wetlands vegetation to assist in aeration of the substrate (wetlands vegetation has the capability to maintain aerobic conditions around the root/rhyzome area and can also promote favourable flow conditions)
- Sufficient residence time to allow the treatment reactions to take place
- Space for the settling and accumulation of the metal precipitates and solids
- Layout and screening against wind mixing and re-suspension of settled solids

- Promoting algal growth to further increase the pH and facilitate manganese oxidation and precipitation
- Sufficient bioavailable carbon in the soil, whether via soil amendment or from annual regeneration of detrital fragments resulting from the seasonal growth and death cycle of wetland vegetation, is needed to achieve nitrogen removal
- Piping and hydraulic controls to manage the water levels in individual wetlands cells

Aerobic systems can be constructed by planting *Typha* rhizomes in soil or alkaline spoil obtained on site, while others have been planted simply by spreading *Typha* seeds, with good plant growth after two years. However, it is best to use a mixture of appropriate emergent vegetation since this will allow the wetland to survive better in times of stress. For the same reason, the wetland cells should not be of uniform depth, but should include shallow and deeper areas and a few deep (1 to 2 m) spots. Most rooted aquatic vegetation cannot tolerate water depths greater than 50 cm and requires shallower depths for propagation. However, varying the depth will help promote wetland diversity (with respect to both plants and animals) and will help the wetlands survive droughts and storm events.

Often, several wetland cells and/or ponds are connected by flow through a v-notch weir, lined railroad tie steps, or down a ditch. Use of multiple cells/ponds can limit the amount of short-circuiting and the water is aerated at each connection. If there are elevation differences between the cells (as discussed above, to increase DO), the interconnection should be designed to dissipate kinetic energy and avoid erosion and/or the mobilization of precipitates in the next cell. Aerobic systems that have little emergent plant growth are better termed ponds than wetlands. Since sludge can be pumped from a pond more easily, aerobic ponds are typically placed before aerobic wetland cells to remove much, if not most, of the iron hydroxide precipitates. These ponds are usually sized for an 8- to 24-hour retention time (often encompassing as much surface area as the wetland cells that follow it) and are typically 1.5 to 2.5 m deep. To account for the accumulation of iron precipitates, the value of 0.17 g of iron per cubic centimeter can be used, so that the required retention time can be achieved independent of the volume required for solids deposition over a predetermined length of time (i.e., the cell design life – grams of iron accumulation per year of desired operation). It is recommended that the freeboard of aerobic wetlands/ponds be constructed at about 1 m to allow for the removal of iron. Observations of sludge accumulation in existing wetlands suggest that a 1-m freeboard should be adequate to hold 20 to 25 years of iron oxyhydroxide accumulation. Some of these iron precipitates have been characterized for potential recycling as pigment (Kairies et al. 2001, Hedin 2002).

Spillways should be designed to pass the maximum probable flow. Spillways should consist of wide cuts in the dike with side slopes no steeper than 2H:1V and should be lined with non-biodegradable erosion control fabric and a coarse riprap, if high flows are expected (Brodie 1991). Proper spillway design can preclude future maintenance costs associated with erosion and/or failed dikes. If pipes are used, small-diameter (<30 cm) pipes should be avoided because they can plug with litter and iron oxyhydroxide deposits. Pipes should be made of PVC or PE, or coated for long-term stability. More details on the construction of aerobic wetland systems can be found in Hammer's *Creating Freshwater Wetlands* (1992). The floor of the wetland cell may be sloped up to a 3% grade. If a level cell floor is used, then the water level and flow will be controlled by the downstream dam spillway and/or adjustable riser pipes.

Hedin et al. (1994a) reported typical removal rates of 10 to 20 g/d/m^2 for iron and 0.5 to 1.0 g/d/m^2 for manganese. Several groups have attempted to develop models that more effectively estimate the performance of treatment systems, especially for iron removal. Watzlaf et al. (2001, 2004) were able to model a system consisting of an aerobic pond, an aeration cascade, and a wetland using only the temperature-adjusted abiotic rate of iron oxidation. They found that the overall performance and the performance of certain sections of the system fell

within the 10 to 20 g/d/m^2 range, but that the performance of some sections was outside that range. Their model indicated that pH was the key factor limiting the rate of removal.

Kirby et al. (1999) used the same factors, but included the effect of bacterial iron oxidation to model a set of 17 ponds. They found that the relative importance of the biotic and abiotic mechanisms was determined mainly by pH, with the abiotic path predominating at the higher pH values. They further suggested that pH and temperature are the most important variables for determining iron oxidation rates and, therefore, iron removal rates. However, little can be done to control temperature in a passive treatment. The work by Kirby et al. (1999) suggests that increasing pH from 6.1 to 6.4, for example, greatly enhances oxidation, whereas doubling DO content (as long as oxygen is sufficiently high stoichiometrically to oxidize metals), pond volume, or retention time has considerably less impact on oxidation rates.

Dempsey et al. (2001) found that oxygen transfer was rate limiting in one system and that the amount of catalytic reaction provided by ferric hydroxide was the determining factor at a second site. While heterogeneous catalysis apparently plays a significant role in iron oxidation, it is difficult to increase concentrations of iron solids in a completely passive system. Such catalysis could be quite important in semi-passive or active treatment systems.

However, overall, it appears that the original estimate of Hedin et al. (1994a) of 10 to 20 g/d/m^2 remains a convenient pre-construction rule-of-thumb for estimating pond and wetland sizes for iron removal. Studies undertaken since then tend to support the findings in the majority of cases (e.g., Younger et al. 2002, Watzlaf et al. 2004). More recently, however, Kruse et al. (2009) suggested that retention time rather than surface area should be used to design such systems.

The layout and slope of aerobic wetlands should be designed to minimize disruption of the natural conditions when the wetland sludge is removed and substrate is replaced, while maintaining the above engineering considerations. Any design should account for the potential uptake of toxic metals to birds, riparian mammals, and amphibians, while enhancing the aesthetic quality of the project.

Many aerobic wetland systems have enjoyed long-term success and cost effectiveness. However, there have also been many failures, which have been very damaging to their perceived effectiveness. In general, systems that were not effective or failed were undersized, improperly designed, or both. The key, as with all water treatment systems, is to understand the limitations of each unit's operation, to have reasonable expectations, and to use conservative sizing criteria to attain specific water quality goals. Even undersized passive systems can be useful, discharging water with significantly lower concentrations of metal contaminants than were present in the inflow drainage. These improvements in water quality have significantly decreased the costs of subsequent water treatment at active sites and deleterious impacts from discharges at abandoned sites on receiving streams and lakes.

7.8.1.2 Anaerobic Wetlands

Anaerobic wetlands rely on chemical and microbial reduction reactions to precipitate metals and neutralize acidity. Anaerobic conditions are achieved by creating high biological oxygen demand by mixing the soil at the bottom of the wetland with organic substrate. This material is often then placed over the top of, or mixed with, a limestone bed that promotes generation of alkalinity as bicarbonate (HCO_3^-) via encouraging microbial sulfate reduction, which occurs under anoxic conditions when sulfate and biodegradable organics are available. Sulfate reduction can form solid-phase metal sulfides when acid-soluble metals are present, removing those metals and depositing them in the substrate.

Since anaerobic wetlands produce alkalinity, their use can be extended to MIW that is of poor quality, net acidic, low pH, high in iron, and high in DO (>2 mg/L). Microbial mechanisms of alkalinity production are of critical

importance to long-term MIW treatment. When wetlands receive high acid loads (>300 mg/L), the pH-sensitive microbial activities are eventually overwhelmed. Therefore, anaerobic wetlands are generally most successful when used to treat lower flows and/or MIW that has moderate water quality, resulting in acid loadings less than 300 mg/L. The available space is also a factor and must be considered in the evaluation to ensure that the area loading factor meets these requirements.

General guidelines for anaerobic wetland construction recommend a 30- to 60-cm layer of organic matter on top of a 15- to 30-cm bed of limestone, or a mixture of organic matter and limestone with a depth of 50 to 100 cm. The organic matter must be water permeable and biodegradable, and typically consists of material such as spent mushroom compost, straw, manure, or peat moss. The depth of water over the organic/limestone mixture varies. Some anaerobic wetland designs maintain shallow water depths of 10 to 30 cm as well as aquatic vegetation that prevents flow channelization and adds fresh organic material to the substrate. Alternatively, anerobic wetlands may be deep and lack vegetation as the translocation of oxygen to substrates through the roots of plants can interfere with anoxic conditions. When plants are not present, physical barriers can be installed to prevent short-circuiting, and regeneration of organic materials can be achieved manually rather than relying on detritus from decaying plant material.

Guidelines for system sizing recommend assuming an acidity removal rate of 3.5 g/day/m^2 when designing for regulatory compliance and 7 g/day/m^2 otherwise. However, performance data (Skousen and Ziemkiewicz 2005) demonstrated that anaerobic wetland performance is highly variable and that systems often neutralize acidity more effectively when treating higher influent acidity concentrations and loadings.

7.8.2 Biochemical Reactors (BCRs)

Biochemical reactors (BCRs) are engineered treatment systems that use an organic substrate to drive microbial and chemical reactions that reduce concentrations of metals, acidity, and sulfate in MIW. The organic substrate generally consists of a mixture of locally available organic materials (such as wood chips, hay, or manure) and can contain limestone to provide additional alkalinity. BCRs used for treating MIW are typically operated anaerobically (i.e., no oxygen) and are also referred to as “sulfate-reducing” bioreactors (SRBRs, SRBs). The microbial process of sulfate reduction converts SO_4^{2-} into H_2S in an organic-rich environment devoid of oxygen and releases sulfide and bicarbonate within the reactor as follows.

- $SO_4^{2-} + 2CH_2O \rightarrow H_2S + 2HCO_3^-$

The reaction results in the precipitation of target metals such as cadmium, copper, nickel, lead, and zinc as metal sulfides at pH values above 5.0. The bicarbonate also increases pH and promotes the removal of some metals as carbonates, such as $FeCO_3$ and $ZnCO_3$ under appropriate conditions. Carbonate material also suppresses the activity of fermentation bacteria, which are required in the bacterial consortium, but are not desirable in quantity since fermentation by-products can lower the pH.

Alkalinity also increases when limestone and dolomitic material react to neutralize acidity as follows:

- $CaCO_3 + H^+ \rightarrow Ca^{2+} + HCO_3^-$

In addition, the reducing environment of BCRs can be conducive to denitrification, selenium reduction, cyanide destruction, and uranium oxide precipitation.

BCRs can operate without external energy and chemical input and can often be sustained for extended periods of time without human intervention. Some characteristics and constituents of influent water can adversely affect bioreactor performance, so pretreatment is frequently necessary. For example, elevated concentrations of iron and aluminum both can produce sludges, which rapidly plug BCRs.

The key features of an anaerobic BCR are:

- A substrate bed containing a varied blend of natural material (e.g., wood chips, crushed limestone, plant residue, grass cuttings, hay, straw, manure, and compost).
- A surface pond (at least 150 mm deep), which floods the substrate bed and limits oxygen ingress into the BCR.
- Mine water flow distribution and collection system to promote a plug flow pattern (typically configured vertically) with limited risk of short-circuiting or dead zones.
- Flow and level control devices to control the water level and to prevent the substrate from being exposed to the atmosphere.
- Higher plant life may be present to assist with organic material supplementation, as wildlife habitat and for aesthetic appearance. However, vegetation may need to be suppressed in BCRs with a relatively thin (<750 mm) substrate layer because the oxygen infusion from the plant activity can impact the establishment of the required reducing conditions.

BCRs constructed in the 1990s were typically horizontal plug-flow cells that resulted in a significant amount of mine water flow across the cell surface. These were often referred to as compost wetlands (Hedin et al. 1994b). The current practice is to use a vertical flow configuration with untreated MIW introduced at the top of the cell and treated water collected from the bottom.

The mechanisms of metals removal vary depending on the specific metal, but they typically are a combination of the following:

- Sulfide precipitation
- Oxidation/hydrolysis (on the BCR surface if iron is present)
- Adsorption or co-precipitation (if iron or aluminum are present)
- Carbonate precipitation
- Absorption onto organic matter

A key advantage of BCRs is that the organic matter is typically found locally, as is the consortium of bacteria or inoculum that is used to populate the substrate. The optimum substrate design is normally determined through extensive preliminary field and laboratory testing.

BCR systems are frequently composed of two BCRs to facilitate long-term maintenance and are designed such that all flow can be temporarily directed to one BCR while the other is being regenerated. BCR effluent is fed into a single multiple-compartment aerobic wetland to remove excess nutrients and reoxygenate the effluent.

A cross section of a typical BCR is shown in Figure 7-32. In-depth information including calculation examples is provided at the ITRC website. (https://itrcweb.org/bcr-1/#4%20Design.htm#4._Design%3FTocPath%3D4.%2520Design%7C_____0)

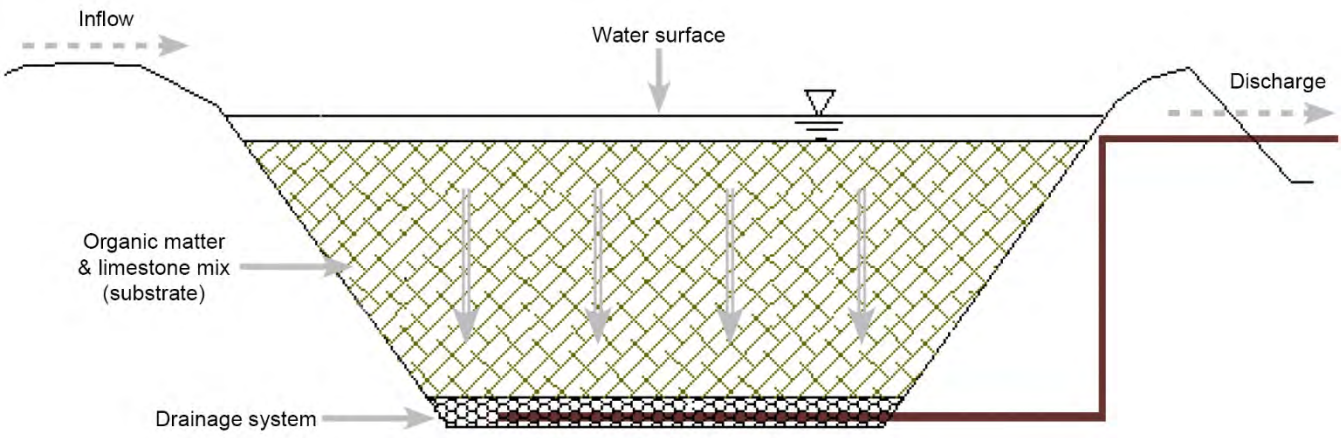

Figure 7-32: Typical BCR cross section

7.8.3 Reducing and Alkalinity-Producing Systems

Reducing and alkalinity-producing systems (RAPS) are a hybrid of biological and chemical/physical treatment processes. In a vertical flow wetland (VFW), MIW flows down vertically through an organic substrate layer followed by a limestone layer. Oxygen is consumed during flow through the organic layer, producing anoxic conditions and creating reducing conditions to convert iron to its ferrous (Fe^{2+}) state, which prevents coating of the underlying limestone with ferric hydroxide. Alkalinity is generated through the system both in the organic layer by sulfate reduction and in the limestone base. A series of perforated drainage pipes are installed below the limestone layer that convey water to an aerobic wetland or settling pond where iron and manganese can coprecipitate with metals.

RAPS are similar in construction to an anaerobic BCR, but the function of a RAPS is to reduce ferric iron to ferrous in a thin organic layer (as opposed to a much thicker substrate layer in the BCR) and then neutralize the acidity in a limestone layer installed beneath the organic layer. Sulfate reduction also takes place, which generates alkalinity, and can result in the precipitation of certain metals as sulfides. However, alkaline addition in RAPS is dominated by the limestone dissolution pathway. The acid neutralization potential afforded by a RAPS ranges from 35 to over 400 mg/L as $CaCO_3$. Sulfate reduction contributes an average of 28% (with a range of 5% to 51%) of the total alkalinity produced. The rate of alkaline addition for a single RAPS unit is about 40 to 60 g/d/m^2. The rate of alkaline addition for a second RAPS unit in a series is about one-half to one-third of the rate of the first unit.

RAPS can be a stand-alone treatment or can be coupled with other treatment systems to manage unique water quality situations. MIW with high metal loads can be sent through several RAPS in series, separated by sedimentation basins for metal floc removal. RAPS can also be used as pretreatment to reduce DO before the influent is introduced into an ALD. Since vertical flow constructed wetlands can nitrify, they can be an appropriate technology in the treatment process for wastewater with high ammonium concentrations.

In general, performance is highest after start-up, especially if fine limestone is added to the compost layer. These systems are prone to plugging, particularly if water has high aluminum concentrations, resulting in high maintenance requirements. Similar to constructed wetlands, VFWs can be designed to tolerate some freezing and periods of low biological activity. If the water contains DO or ferric iron, a RAPS will function better than an anoxic limestone drain.

This type of system was first implemented at Galax, Virginia, in the late 1980s to treat highly acidic, high iron water emerging from an abandoned pyrite mine (Hendricks 1991). In 1991, a second system of this type was

constructed to treat water being discharged by a coal processing waste landfill near Norton, Virginia (Duddleston et al. 1992). The term “successive alkalinity producing system (SAPS),” indicating that more than one of these units could be used in series to treat very highly acidic water, was applied to these systems by Kepler and McCleary (1994), who demonstrated a successful application at the Howe Bridge site in northwestern Pennsylvania. The Kepler and McLeary application received widespread notice and use of these systems expanded rapidly thereafter. Similar systems have also been referred to as vertical flow systems, vertical flow ponds, or vertical flow wetlands. Chemically, biologically, and physically, these systems behave similarly, and are all referred to here as RAPS since most applications involve just a single system followed by an oxidation pond to precipitate and settle iron from the alkalinity-buffered RAPS effluent.

A typical design involves a sedimentation pond or aerobic wetland to precipitate any suspended ferric hydroxide that may be present. This is followed by the RAPS, which is constructed by placing a layer of limestone (0.6 to 1.2 m thick) on the bottom of an excavated area. A network of perforated pipes is placed in the lower portion of this limestone layer. Organic material (0.15 to 0.6 m thick), which typically has been composted, is placed above the limestone and serves as the nutrient source for the iron- and sulfate-reducing bacteria. The composted organic material lies beneath 1 to 3 m of water (Figure 7-33); the water pressure helps force the water through the organic layer.

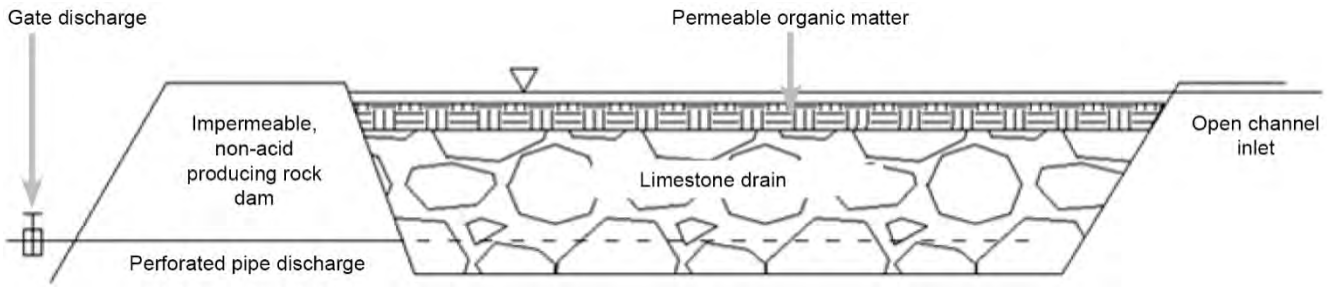

Figure 7-33: Profile view of a reducing and alkalinity producing system (RAPS) (not to scale)

RAPS are now more common than ALDs for treatment of MIW because they are appropriate for water that contains DO or ferric iron, which can armor the limestone in an ALD. It is thought that RAPS may also be more resistant to plugging by aluminum than ALDs because of their larger cross-sectional area and higher available head pressures (Watzlaf 1995). The Howe Bridge RAPS treated water for 11 years before being replaced. After 11 years, it was still able to pass 50% of the influent water through the compost and limestone layers. However, this system received less than 0.2 mg/L of aluminum. It appeared that the progressive reduction in permeability was due to the lack of a preliminary sedimentation pond; iron hydroxides precipitated on top of the compost layer, with an eventual accumulation of more than 15 cm of iron sludge on top of the compost. Reduced permeability can also result from storm-mobilized silt and other solids, as well as precipitation of metal sulfides within the organic layer. Thus, continued monitoring of the actual performance of these systems is warranted.

RAPS treatment efficiencies for acidity range from 0 to 800 g/day/m^2 (Jage et al. 2000, 2001; Ji et al. 2008; Kepler and McCleary1994; LaBar et al. 2008; Rose et al. 2003; Rose 2004a, 2004b, 2006; Rose and Dietz 2002; Rose et al. 2001; Skousen and Ziemkiewicz 2005; Watzlaf et al. 2000). A long-term acidity removal rate of 35 g/day/m^2 has been proposed by Rose et al. for design purposes after a review of more than 30 RAPS (VFWs) in the Appalachian region (Rose 2004a, 2004b; Rose et al. 2003, 2007).

In general, RAPS can be effective if properly designed and maintained. RAPS require frequent agitation or flushing to dislodge accumulated flocs, and if such maintenance does not occur, or even in instances where it

does, treatment efficiency goes down substantially with time. Kepler and McCleary (1997) reported on a flushing mechanism that allowed RAPS to resist clogging by aluminum. However, field experiments conducted by Watzlaf et al. (2003, 2004) indicated that, although it appears that significant solids are being flushed out, the actual amount is only a minor component of what apparently precipitated in the system, based on water quality records. So, if aluminum is present at significant concentrations in the MIW, this alkalinity-adjusting method should be avoided because of potential plugging.

7.8.4 Anoxic Limestone Drains

Anoxic limestone drains (ALDs) are buried cells or trenches filled with limestone into which anoxic water is introduced (Figure 7-34). The ALD must be sealed so that any ingress of atmospheric oxygen is minimized and the accumulation of CO_2 within the ALD is maximized. This is usually accomplished by burying the ALD under 1 to 3 m of clay. Plastic is sometimes placed between the limestone and clay as an additional gas barrier. In some cases, the ALD has been completely wrapped in plastic before burial (Skousen and Faulkner 1992). This can also help prevent clay and dirt from entering the pore volume from the bottom and sides of the excavation.

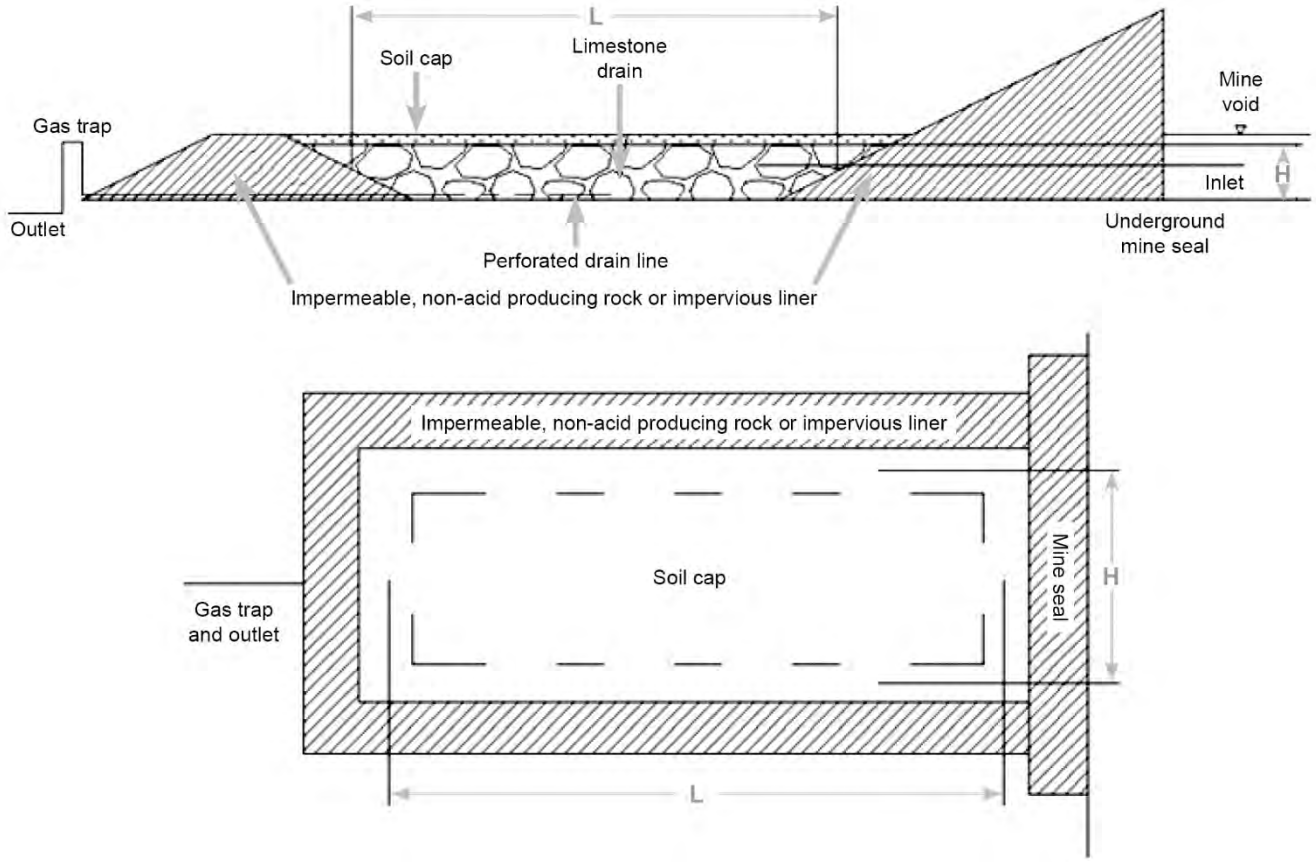

Figure 7-34: Anoxic limestone drain design

The limestone dissolves in the acidic MIW, raises the pH, and adds alkalinity. Under anoxic conditions, the limestone does not coat or armor with iron hydroxides because Fe^{2+} does not precipitate as $Fe(OH)_2$ at an acid or circumneutral pH. In addition to little or no DO and Fe^{3+}, aluminum concentrations must also be less than 2 mg/L or the ALD risks clogging.

Limestone with higher $CaCO_3$ content (>80%) dissolves faster than limestone with a higher $MgCO_3$ or $CaMg(CO_3)_2$ content (≈50% $CaCO_3$) (Watzlaf 1993). The limestone used in most successful ALDs contains 80 to

95% $CaCO_3$. Most effective systems have used 5- to 20-cm sized limestone. Some systems constructed with fine and small gravel limestone have failed, apparently because of plugging problems.

The ALD should be designed to inundate the limestone with water at all times. Clay dikes within the ALD or riser pipes at the outflow of the ALD will help ensure inundation. Also, the ALD discharge should be equipped with a plumbing trap to prevent air from entering the system. Finally, a pond must be constructed downgradient to capture all the iron that will precipitate once the neutralized water contacts the atmosphere. Typically, this pond is followed by additional ponds or wetlands to further enhance water quality. The dimensions of ALDs vary considerably. Narrower ALDs have the advantage of minimizing short-circuiting, but present a small cross section perpendicular to the flow and thus may be more prone to clogging. Wider ALDs may be less likely to suffer significant permeability reductions (clogging), but may allow short-circuiting to occur. Site conditions will often dictate the dimensions of the ALD.

Skousen and Ziemkiewicz (2005) evaluated 36 ALDs with a wide range of observed acid load treatment (0 to 130 t/year), but found no apparent relationships between ALD effectiveness and the pH of the influent water or residence time. On average, 86 g of acidity per ton of limestone was removed per day. Zipper and Skousen (2010) observed that these systems' alkalinity-generating performance increased in response to increasing influent acidity and residence times. However, Hedin et al. (1994b) found that treatment effectiveness decreased as calcite saturation was approached. When properly designed, ALDs perform well over the expected lifetimes and are the most consistently efficient and cost-effective passive treatment systems in terms of the cost per metric ton of acid removed (PA BAMR 2009, Ziemkiewicz et al. 2003).

However, longevity of treatment is a major concern for ALDs, especially in terms of water flow through the limestone. Unless there is no Fe^{3+}, DO, or aluminum present, eventual clogging of the limestone pore spaces with precipitated aluminum and iron and/or gypsum is predicted at many sites (Nairn et al. 1991). Selection of the appropriate water and environmental conditions is critical for long-term alkalinity generation in an ALD. Like wetlands, ALDs may be a solution for MI treatment for specific water conditions or for a finite period, after which the system must be replenished or replaced.

Tracer studies have indicated that while ALDs approximate plug-flow systems, some short-circuiting occurs, and dead areas do exist. Calculated retention times, using 49% porosity, were in fairly good agreement with the median retention times of the tracer tests (Watzlaf et al. 2004). Water quality data are essential to determining the applicability of an ALD, and flow data provide the basis for sizing an effective ALD for the desired design life. Approximately 15 hours of contact time between mine water and limestone in an ALD is necessary to achieve a maximum concentration of alkalinity. To achieve 15 hours of contact time within an ALD, 2,800 kg of limestone are required for each liter per minute of mine water flow. For example, an ALD that discharges water with 300 mg/L of alkalinity (the maximum sustained concentration thus far observed in an ALD effluent), dissolves 1,750 kg of limestone (90% calcium carbonate) in 10 years for each liter per minute of mine water flow. Therefore, a limestone bed should contain 6,200 kg of limestone for each liter per minute of flow (equivalent to 26 tons of limestone for each gallon per minute of flow). This assumes that the ALD is constructed with 90% $CaCO_3$ limestone rock and has a porosity of 49%. The calculation also assumes that the original MIW does not contain Fe^{3+} or aluminum. The presence of these ions could result in faster rates of limestone dissolution due to the generation of acidity during hydrolysis. More importantly, they have the potential to limit limestone dissolution and cause a significant reduction in permeability that could very well lead to failure (as previously discussed). A more detailed discussion of limestone dissolution rates is given by Cravotta and Watzlaf (2002).

To summarize, the success of ALDs depends on the following:

- Iron must be in the reduced ferrous (Fe^{2+}) form because ferric iron (Fe^{3+}) will armor the limestone material (if not, use a RAPS, as described in Section 7.8.3).
- No free oxygen (<1 mg/L) must be present; otherwise iron (Fe^{3+}) precipitation will take place (see RAPS in Section 7.8.3), if water is oxygenated).
- Low aluminum concentration (<2 mg/L) because any aluminum hydroxide precipitates will clog the limestone bed.
- A vent for excess CO_2 formed in the ALD

ALDs continue to be a component of passive treatment. Palmer et al. (2012) evaluated ALDs for treatment of mildly acidic (pH 5.4) mine drainage from an abandoned mine in Andean Boliva. A parallel system treating lower pH water used the open limestone drain technology described in the next section. The project was Phase 1 of a reclamation project for two of the highest channels of the Rio Junckucha. Phase II of the passive treatment project is targeting passive treatment systems for the Upper Rio Junckucha (Hess 2016).

7.8.5 Open Limestone Drain

Open limestone drains (OLDs), also known as open limestone channels (OLCs), are designed to introduce alkalinity via the dissolution of exposed limestone on the bottom and sloped sides of a limestone drain. OLDs are effective for a wide range of acid and metal loadings, and work best on slopes >20%. When acidic MIW passes over the OLD, it is neutralized and oxidized, leading to the precipitation of metal hydroxides. Past assumptions held that limestone armored or coated with iron or aluminum hydroxides ceased to dissolve. However, Ziemkiewicz et al. (1994, 1997) reported that armored limestone was still somewhat effective (50% to 90%, compared to unarmored limestone), and that seven OLDs reduced acidity in ARD by 4% to 62% compared to a 2% acid reduction in a sandstone channel. They suggested that OLDs would be useful in abandoned mine reclamation projects where one-time installation costs can be incurred and regular maintenance is not possible.

Long channels of limestone, which compensate for the reduced efficiency of armored limestone, can be used to convey MIW to a stream or other discharge point. Based on flows and acidity concentrations, cross-sections of stream channels (widths and heights) can be designed with calculated amounts of limestone (which will become armored) to treat the water. However, the design and operation of the limestone drain require special attention to accommodate the inevitable armoring and coating of the limestone.

The following features of open limestone drains are recommended:

- Steep drain slopes of >20%
- High flow velocities to scour settled solids and clean precipitates from the limestone surfaces
- Ability to periodically flush the OLD and clear accumulated precipitates and solids
- OLDs are most effective when used where the MIW is most acidic (typically upstream of other passive treatment systems). Treatment efficiency decreases as pH increases above 3.0.

7.8.6 Limestone Leach Beds

Limestone leach beds (LLBs) are small basins filled with coarse limestone that are designed to provide at least 30 minutes of residence time. They can be constructed at the upwelling of a seep or in an underground mine discharge. They can be also used to pretreat water with low pH (<3.0) and DO (<1 mg/L) in either an upward or downward flow strategy. The latter are more prone to clogging. Black et al. (1999) reported that a 30-minute

residence time in LLBs was sufficient to remove about 50% of the acid load from slightly acidic water (pH 6.0, ≈20 mg/L of influent acidity). They also found that 30 minutes of contact with limestone removed much of the proton acidity in pH 3.0, metal-free water. Ziemkiewicz et al. (2002) reported that LLBs were useful at the upstream end of OLDs since they shortened their required length, improved the OLDs' service life, and were easily serviced. LLBs can also be used as stand-alone systems. Self-flushing systems can be incorporated into LLBs to better control residence time while providing more effective floc removal.

A flushing technique that has been used for LLBs to effectively treat high-aluminum discharges is described by both Hedin et al. (2013) and Wolfe et al. (2010). These systems are designed so that a bed of limestone gravel 1 m or more thick can be filled with acidic MIW and then flushed as required by opening a valve to allow rapid flow of the treated MIW out of the LLB and into a settling pond.

Trumm et al. (2018) compared manganese removal by LLBs compared to a slag leaching bed (SLBs) for treatment of tailings water seeps and mine rock contact water at the Waihi Gold Mine in New Zealand. The pilot system included two parallel trains, with each train pretreating the water for iron removal using a vertical flow reactor (gravel beds for oxidation, precipitation and filtration of iron) followed by either the LLB or SLB for manganese removal. High removal of iron was achieved and the removal of manganese in the SLB depended on the type of slag used and the increase in pH while the LLB provided 23% to 32% manganese removal.

7.8.7 Manganese Oxidation Beds

Manganese oxidation beds (MOBs) appear similar to alkaline leach beds, but they are positioned as the final step in a successful passive treatment system of MIW. MOBs are also known as manganese removal beds (MRBs). MOBs support the growth of a bacterial/algal consortium. The initial precipitation of MnO_2 or similar compounds is slow, but is apparently aided by the bacterial activity. Because MOBs are intended to facilitate manganese oxidation, the limestone cannot be completely inundated; the general rule is the surface of the limestone is above the normal operating liquid level. Both research and experience have indicated that the bacterial/algal organisms are naturally occurring and will typically colonize the bed within six to eight weeks (Brant and Ziemkiewicz 1997, Rose et al. 2003). Once the bacteria oxidize the manganese and induce manganese oxide precipitation, the mineral surface catalyzes additional manganese oxidation (auto-catalysis). The algae employ the MnO_2 formed to provide hold-fasts to rocks in the flowing water and appear to facilitate manganese removal.

MOBs only function as a polishing step in a passive treatment system because they are only effective after virtually all iron has been removed, since dissolved Fe^{2+} chemically reduces manganese, causing it to re-dissolve. Also, while MOBs allow manganese to be inexpensively removed at circumneutral pH, manganese is sometimes only regulated as a surrogate for other more toxic metals, as stated in the CMD section of Chapter 2. Where that is the case, the presence of such metals may argue against the emplacement of a MOB unless the removal of those metals has also been addressed.

7.8.8 Emerging Passive Technologies

The technologies discussed in this section are more appropriately considered emerging applications of proven passive technologies than ab initio applications. Some of these technologies have been well developed and are commonly utilized in non-mining industries or in mining, but not commonly for the constituent described in this section. In addition, some of the technologies discussed in this section have been evaluated on mine water, but not implemented at full scale or in very limited circumstances.

7.8.8.1 Passive Sulfate Removal

While sulfate reduction and metal sulfide precipitation are both integral to metal removal in BCRs, BCRs have not traditionally been used for sulfate removal. In general, passive treatment has not been considered an option for sulfate treatment. However, pilot testing indicates BCRs can be designed to maximize biological sulfate reduction

to sulfide, metal sulfide precipitation, and then removal of excess sulfide. Two methods for removal of excess sulfide have been reported: iron precipitation via sulfide polishing cells (SPCs) (Pruisner et al. 2020) and a two-stage process that includes an oxidation pond and a pebble-bed pond (Neale et al. 2018).

SPCs can be used to remove sulfide and minimize oxidation of residual sulfide back to sulfate to achieve sulfate removal at low sulfate concentrations (<250 mg/L). SPCs provide sulfide removal via iron coprecipitation or sorption. The SPCs are composed of an iron source and an inert spacing material, which can consist of a variety of materials depending on what is available on or near the site (wood chips, gravel, etc.). SPCs are typically designed based on estimated sulfide levels in the BCR effluent and resulting frequency of media replacement. A demonstration-scale passive system that incorporates multiple passive stages has been in operation treating MIW at a coal mine on Vancouver Island in British Columbia for more than five years (Pruisner et al. 2020). This system is designed to remove sulfate at influent concentrations of a design target of 800 mg/L to less than 300 mg/L. The average sulfate influent from the first four years of operation was 591 mg/L and the system effluent was 287 mg/L.

The biological sulfate reduction (BSR) evaluated by Neale et al. (2018) is also a BCR-type system that has been evaluated during bench-scale testing and currently pilot-scale testing for treatment of sulfate in acidic MIW. Influent concentrations were approximately 3,000 mg/L and effluent concentration in the range of 90 to 140 mg/L in the bench testing. Pilot results at the time the 2018 paper was prepared were showing similar results.

7.8.8.2 Passive Uranium Removal

BCRs are emerging as a potential mechanism for passive uranium removal. A full-scale treatment system is currently operational at a former vanadium mine in Colorado. BCR passive treatment is removing uranium, Ra-226, and selenium from MIW collected from two mine adits. The full-scale system was designed based on bench-scale testing and included two constructed wetlands to polish the BCR effluent. Uranium was reduced from 2.6 mg/L to 0.42 mg/L, radium-226 from 1.2 Bq/L to 0.11 Bq/L, and selenium from 0.22 mg/L to 0.006 mg/L. (Pruisner et al., 2020).

7.8.8.3 Passive Treatment Systems for Cold Climates

Passive treatment of MIW in cold climates has gained a lot of traction over the past 10 years. Specific studies have been performed in Canadian locations such as Cape Breton, NS (Kalin and Scribailo 1989), Elliot Lake, ON (Fyson et al. 1991), and Smithers, BC. (Sobolewski 1996). Many Yukon mines (i.e., Minto Mine, Casino Mine, Faro Mine, United Keno Hill Mine, Brewery Creek, Eagle Gold, and Wolverine Mine) are in the process of completing research to develop passive systems for treatment of mine impacted water (Ness et al. 2014). Golder partnered with the US Environmental Protection Agency on a successful multi-year pilot passive treatment which was operated in a cold climate at an elevation of 3,300 m at a site that receives over 7.5 m of snow per year (Gallagher et al. 2012).

Golder conducted a bench-scale study on treatment of MIW in the Upper Peninsula of Michigan and observed high levels of treatment. In addition, prior to its decommissioning, the Antamina Mine in Peru had the highest operating wetland in the world and monitoring data indicate that it was effectively treating MIW (Strachotta et al. 2009). In Canada, a demonstration-scale constructed wetland for treatment of wastewater from the Minto Mine (Contango 2017) showed consistent removal of nitrate cadmium, copper, molybdenum, and selenium during a one-month trial period after a one-year commissioning period.

These studies, taken as a whole, indicate that many of the contaminants in MIW can be effectively treated in cold climates despite low temperatures. However, site-specific design criteria need to be established given the cold climate, short operating season, and limited long-term data available. Every case must be studied separately based on the composition of wastewater, land availability, hydraulic loading, and effluent limitations.

7.8.9 Development of a Passive Treatment Train

Similar to developing an active treatment train, many passive treatment technologies that are applied for removal of target contaminants require pretreatment or post treatment to produce treated water that can be discharged or reused and for efficient operations of the primary treatment process. For instance, TSS or dissolved iron should be removed prior to a BCR system or many of the systems where plugging could occur. Often, aerobic polishing is required to reduce BOD added by a BCR or sulfide generated by anaerobic processes when sulfate is present in the water. Several of the articles reviewed for this section incorporate more than one passive treatment process. Nairn et al. (2011) discuss passive treatment in general and specifically the evolution of two passive treatment trains in Oklahoma. The system consists of 10 passive processes and the function of each process and target parameter(s) are summarized in the paper. Two years of operating data are also presented.

Nairn also evaluated enhancing passive treatment systems with aeration. While the aeration could be conventional aeration making the system semi-passive, this study involved aeration powered by renewable energy, utilizing solar-power with the ability to store energy to aerate existing passive pond systems (Nairn et al. 2018). An assessment of other forms of renewable energy was conducted as well.

7.9 In Situ and In-Mine Treatment Technologies

In situ and in-mine treatment of mine water can be undertaken in many different ways and configurations, and the terminology used to describe these applications is open to interpretation. Technologies that address covers or spreading of alkaline material across mining-impacted land and mine waste are not addressed in this section. Technologies that focus on prevention of acid mine drainage formation are also not considered here, although some MIW treatment technologies may also provide some long-term control of acidic mine water formation. This section is focused on water treatment, and the terms “in-mine” and “in situ” as used in this section pertain to treatment in the underground workings or in-pit treatment. Of the technologies discussed, only in-pit treatment is a developed technology that has been implemented as a full-scale mine water treatment technology at numerous mine sites and for a number of years. The in-pit category includes treatment of surface impounded water whether in the pit, a lake, pond, or other impoundment. The other technologies have been studied and evaluated on a pilot or demonstration scale but have no or limited full-scale implementation.

In situ treatment and in-mine treatment generally all include some type of chemical or supplement addition, require power for the chemical addition, and may require power for mixing. Either biosolids or precipitated solids are formed that settle in the mine workings or pit. Treatment is often batch or intermittent rather than continuous, requires very little equipment, does not require a utility hookup if power is not available (diesel pumps and generator can generally be used for the campaign-style treatment), ongoing labour requirements are minimal and may not be needed between treatment campaigns. The common challenge to most in situ and in-mine treatment technologies is to obtain good mixing and contact between the treatment chemical and water to be treated.

7.9.1 Alkaline Injection

Treatment of MIW by injection of an alkaline source into the mine has met with mixed success. The techniques included in this section are not intended to be routine treatment, which is discussed in Section 7.9.3. The challenges to practical mine scale applications include the following:

- Flow and transport characteristics of the mine waste material, which can be described as a pseudokarstic aquifer due to the presence of interconnected preferential flow paths
- Introducing a lime slurry, sodium hydroxide, or any other alkaline solution in a manner that will ensure distribution and effective contact with acid-producing zones or water bodies. In some cases, alkaline by-products such as coal combustion residuals (CCR) or sludges have been used.

Full-scale trials have been conducted in West Virginia surface coal mines (Donovan et al. 2000), with some success reported. Alkaline waste in the form of a grout from CCRs was reported in a study supported by the Electric Power Research Institute (EPRI 2001). A lobe of the Omega Mine located in West Virginia was filled with alkaline CCR grout in 1998. Monitoring approximately nine months after the injection program showed some reduced contact of water and air with acid forming material in the mine. However, buffering of acidic mine drainages did not occur as expected. Continued monitoring and results reported in 2004 showed some decrease in contaminant load, but grouting was just one of the factors that contributed to contaminant decline, with decline of pyrite oxidation considered a major factor (Perry and Rauch 2004).

There are several other articles from the 1990s and early 2000s on this type of treatment strategy of acid mine drainage in coal mines in the eastern US. Some of these articles refer to using alkaline water treatment sludge, CCRs or other waste materials to grout and stabilize old coal mine workings. The Office of Surface Mining, Reclamation and Enforcement (Department of Interior) has a Mine Drainage Technology Initiative (MDTI). The MDTI evaluated in situ underground ARD treatment (Aljoe and Hawkins 1993). According to the MDTI website, the Omega Mine is one project being monitored. At the Keystone Mine, addition of sodium hydroxide to the mine pool was also tested. Prior to the field testing, a hydrological study of the Keystone Mine and Friendship Mine was conducted to determine the mine with the most favourable conditions. Keystone was selected for a number of reasons, including the high level of detail of the mine maps (which were later determined to be incorrect). The conclusion for both the Keystone and Friendship mines based on the testing was that the mine pool was too large and the expense greater than expected. No further in situ work or testing was performed at either site on in-mine treatment.

Skousen et al. (2018) contains a section reviewing Alkaline Amendments to Abandoned Mines that provides several additional examples. There are also several Australian examples presented in “Preventing Acid and Metalliferous Drainage” (Australian Commonwealth 2016, Acid Solutions 2020).

7.9.2 In-Pit Treatment

In-pit treatment includes treatment of mine water that collects and is stored in an open pit. Treatment typically involves the spreading and dispersion of an alkali material across the accumulated water surface for precipitation of metals and neutralization of pH. Addition of carbon and other amendments to encourage microbial growth is another form of in-pit treatment. Biotreatment targets parameters such as ammonia, nitrate, selenium and other parameters treated efficiently biologically or aims at biological sulfate reduction to create reducing conditions for precipitation of metal sulfides. Challenges in achieving effective in pit water treatment include the following:

- Effective contact between the added chemical and pit water
- Efficient use of available chemicals
- Maintaining aerobic conditions for biological treatment of ammonia and other parameters that require oxygen for effective treatment
- Long-term dissolution of precipitated metals from the sludge layers (for alkali precipitation)
- Poor control of the pH and redox conditions in all parts of the pit lake to achieve the target treatment objectives
- Temperature variation through seasons and cooler water temperatures. In particular, biological treatment will be impacted by water temperature
- Stratification and potential subsequent turnover of the pit lake

- Constant inflow of poor-quality water

In spite of these challenges, in-pit treatment is regularly implemented due to its cost, effectiveness, and logistical advantages. Totsche et al. (2018) describe 15 year of experience in Germany with the neutralization of 17 acidic mine lakes.

In-pit treatment can be evaluated on the bench scale to determine treatment targets and dose targets. Equipment required may include equipment for chemical mixing, dosing, and application. Many techniques are utilized for adding chemicals to pit lakes, including injection in a slip stream pumped from the lake, spray broadcast from the shore, broadcast as a liquid or powder from a boat, and similar methods that can be utilized campaign style. Aeration, if required, can be provided either by using floating aerator/mixers, similar to anaerobic lagoons. Floating aerators/mixers can also be solar powered. Treatment often requires an initial campaign, allowance for several days or weeks of reaction time, and then sampling of the water at several locations and depths to determine if treatment goals have been achieved. Additional campaigns of chemical addition may be required. In some cases, a single treatment or campaign is sufficient and in other cases, treatment may be required every few years. At the White King/Lucky Lass Superfund Site, the White King Pond is treated with lime intermittently to control pH. The White King and Lucky Lass are former uranium mines approximately 1 mile apart near Lakeview, Oregon. The first campaign was conducted in 1998/99, with subsequent campaigns in 2004 and 2009 (ODEQ 2020).

Two options for portable and mobile chemical mixing and dosing are shown in photographs in the leading practice handbook “Preventing Acid and Metalliferous Drainage” (page 164, Figures 31 and 32) developed by the Leading Practice Sustainable Development Program of the Australian Commonwealth (Australian Commonwealth 2016). That reference also provides a good overview of in-pit treatment and challenges. Another overview of pit lake treatment by in-pit bioremediation is provided by Martin et al. (2006) in work presented in 2006 at the BC MEND ML/ARD (Metal Leaching/Acid Rock Drainage). Five case studies are included with some success stories and some mixed results in a technology overview of In Situ Treatment of Mine Pools and Pit Lakes (ITRC 2010c). Other studies reported in the literature include evaluation of biological remediation of pit lakes (Lund and McCullough 2009) and bench-scale testing to support in pit treatment for arsenic (Barabash and Nicholson 2019a).

7.9.3 Underground Treatment

Underground treatment takes place in the underground workings of mines rather than in-pit treatment and includes mine water treatment techniques that add chemicals to the underground mine water pool on a routine or semi-routine basis. Once the chemical has been added, the underground mine is used for mixing and settling in a similar manner as the pit for in-pit treatment. There is increased interest in in-mine treatment due to technical advances in geophysics, hydrology, geochemistry and other geotechnical areas in the last 15 to 20 years that allow improved understanding of water flow through and associated geochemistry in the underground workings. Costs of long-term conventional active water treatment are well documented from a number of private and public acid mine drainage treatment facilities and provide a benchmark for evaluation of in-mine treatment.

The water treatment portion of an in-mine treatment project is a small component of the overall technical evaluation. A true team effort is required, including hydrology, geophysics, geochemistry, and mining engineers to characterize and define the problem and cooperate on the best method to enhance contact between treatment chemicals and either the rock or mine water. Developing this technology at an active mine may be an advantage as the mining engineers and hydrologists at the mine can contribute to the success of the testing. The development would have to include long-term planning and field testing in areas of the mine no longer active.

In 2005, an in-mine bioremediation demonstration project included addition of alkalinity, organic carbon, and carbon dioxide into the Tide Mine in Western Pennsylvania (Houston et al. 2005). The alkalinity and organic

carbon were intended to stimulate microbial growth, anaerobic conditions, and biological treatment of the mine pool. The carbon dioxide injection into the atmosphere above the mine pool was intended to maintain anaerobic conditions within the mine. Tracer studies were included in the demonstration test to characterize the hydraulics of the mine pool. Over the study period, the pH increased in the mine pool from 2.5 to over 6 and subsequent monitoring showed the pH remaining above 5 due to microbial activity. Acid mine drainage was controlled for the three months of the test period. A similar treatment strategy was implemented at the Schwartzwalder Uranium Mine in Colorado, although in this case the in-mine treatment is used as a pretreatment to an active treatment system (Harrington 2016). A pretreatment campaign in 2013 provided initial reductions of uranium, molybdenum, and selenium, removing the bulk of the load prior to active treatment. While active treatment continued, a second pre-treatment campaign was not required until late 2016. A combination of in-mine treatment and diversion of groundwater with sale of water rights for municipal use is being implemented at the London Mine in Colorado (Blevins 2019). The State of Colorado is currently conducting pilot testing of in-mine treatment using sodium hydroxide addition at the Captain Jack Mine near Nederland, Colorado (CDPHE 2019b). Neutralization with sodium hydroxide and addition of ethanol and nutrients to promote microbial growth is being evaluated in the Corona Mine Tunnel at the Corona and Twin Peaks mercury mines in California (Tsukamoto 2016).

Another form of underground treatment, pioneered by Taylor et al. (2018), is the so-called inert atmosphere technology. This technology has been developed and implemented at two decommissioned mine sites in Australia, with state government support. It involves the partial or total removal of oxygen from mine void atmospheres, and replacement with an inert gas phase, starting with the mapping and isolation of all significant air entry points into the mine void. This usually includes features such as shafts, adits, declines, stopes, glory holes, subsidence zones, highly fractured areas, and drill holes. Air entry control works need to retard oxygen (air) addition to the mine voids, but not prevent water discharge. Once air entry points have been managed, the oxidation of sulfides within the mine passively lowers internal oxygen concentrations. Case study results from the Nevada gold mine in New South Wales, Australia, clearly demonstrate the benefits of the inert atmosphere technology for lowering pollution discharges from decommissioned underground mines at low cost and low risk. The success of this new technology also highlights the importance of incorporating key air entry and drainage control works into closure planning regulation for active underground mines worldwide.

7.9.4 Permeable Reactive Barriers

Permeable reactive barriers (PRBs) are designed to encourage bacterial sulfate reduction and metal sulfide precipitation and have the potential to treat MIW. PRBs are proven and well developed in support of groundwater remediation and have been used since the 1990s for treatment of organics. Treatment media, such as zero valent iron (ZVI), is installed in a continuous subsurface trench that is perpendicular to the subsurface flow. See https://clu-in.org/techfocus/default.focus/sec/Permeable_Reactive_Barriers%2C_Permeable_Treatment_Zones%2C_and_Application_of_Zero-Valent_Iron/cat/Overview/, https://itrcweb.org/Guidance/ListDocuments?TopicID=19&SubTopicID=23, and https://ois-isrp-1.itrcweb.org/ (Appendix D7) for additional information on the technology. Additional information from an Australian perspective is provided in a guidance document developed in 2016 (CRC CARE 2016) and available online at https://www.crccare.com/files/dmfile/CRCCARETechnicalReport25-Permeablereactivebarriers.pdf . Contaminants typically associated with MIW that have been treated successfully include sulfate, ammonia, nitrate, phosphate, selenium, uranium, chromium, and arsenic. Implementation at mine sites has been limited and includes a pilot-scale test at a smelter in Montana and two uranium mill tailings cleanup sites (EPA 2014). Shabalala et al. (2014) review PRB technology for treatment of MIW; examples provided for mine sites include two pilot-scale PRBs installed in Eastern Europe at uranium mines. Three papers were presented at the 2018 IMWA conference on

evaluation of PRBs to treat seepage contaminated with arsenic, cobalt, and iron at the Goldcorp Red Lake Gold Mine:

- Crozier et al. (2018) – hydrogeological, geochemical and geotechnical considerations impacting PRB design
- Helsen et al. (2018) – results of tracer test work conducted to confirm contaminant flow paths
- Martin et al. (2018) – evaluation of groundwater plume distribution and contaminant behaviour

These examples demonstrate the multi-disciplinary approach that should be taken in evaluating PRB technology for implementation at mine sites. However, PRBs are a well-known and proven technology in non-mining applications.

As noted in “Preventing Acid and Metalliferous Drainage” (Australian Commonwealth 2016), PRBs are better suited to relatively low acidity and metal load, such as the downgradient interception of a broadly dispersed plume. The longevity of a PRB will depend on the contaminant loading relative to the volume of treatment amendment installed.

7.9.5 Saturated Rock Fill

Saturated rock fill (SRF) is an in situ, fixed-film, biological treatment technique using a backfilled mine pit as the bioreactor vessel and mine rock as the fill which also serves as the surface area for biofilm growth. As the void spaces are filled with water, becoming saturated, the biofilm develops. Microbial growth is enhanced by addition of a carbon source and nutrients. Anaerobic-anoxic conditions are created which are optimal for microbial selenium treatment. The system becomes a bioreactor with a long retention time when mine water is injected along with the carbon source and nutrients into the SRF. Treated water is produced for polishing treatment and/or discharge.

The SRF concept has been developed by Teck (Karbashewski et al. 2019) for selenium and nitrate treatment. Teck initially identified reduction of selenium and nitrate concentrations was occurring naturally at areas of their Elk Valley operations (Bianchin et al. 2013). Subsequently, they developed the technology through laboratory- and pilot-scale testing that started in 2011. Positive test results for selenium and nitrate removal led to a demonstration-scale 10,000 m^3 per day treatment system installed in 2017. Two years of successful operation have resulted in plans for expansion to a treatment capacity of 20,000 m^3 per day.

7.10 Management of Residuals

All mine drainage treatment technologies produce some residues (e.g., sludge, brines, and spent media) or emissions (e.g., gases). These residues and emissions contain the elements and compounds removed from the mine drainage and the additives and supplements dosed in the treatment process. An understanding of these residues and emissions and their management is required to provide a fully functioning water treatment system. Considerations related to residue management include:

- Relative production in terms of volumes and masses
- Typical characteristics in terms of chemical composition (e.g., hydroxide, sulfide, and NP) and physical properties (i.e., consistency, volatility, and dewaterability)
- Hazardous classification and rating
- Potential environmental impacts
- Disposal options and cost

The treatment residues can be broadly classified into the following two categories:

- Sludge, which is a slurry or dewatered cake containing precipitates of diverse composition
- Brine, which contains soluble salts in high concentrations

Other residues, such as spent treatment media, commonly are a relatively low volume compared to sludge or brine, and disposal and management options for sludge are assumed to apply to spent media. Emissions are not typical for mine water treatment systems. Sulfide is generated by some anaerobic biological treatment systems and when present in the off-gas, is generally managed by aeration, precipitation with iron, or absorption on media.

The remainder of this section addresses sludge and brine management.

7.10.1 Sludge Management

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

7.10.1.1 General Considerations

To design the most appropriate sludge management strategy for a site, several factors need to be considered. The principal considerations are the mass of sludge produced, whether the mine is operating or closed, the dewatering ability of the sludge, sludge density (moisture content), sludge volume, chemical and physical stability, sludge composition, disposal location availability, and economics (Zinck 2013). Permitting requirements have to be evaluated in determining a sludge management strategy, and may include geochemical and geotechnical considerations.

The ability of a sludge to dewater may limit the options available. Sludges that can dewater without mechanical assistance will not only reduce the area required for disposal, but also make 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. These characteristics are linked directly to the water treatment process that generates the sludge and to the raw water chemistry (Zinck 2013).

The considerations provided above are from reports completed for MEND. MEND has completed a number of evaluations on sludge stability and disposal to support and improve sludge management and disposal:

MEND Report 2.36.1b – In-Pit Disposal of Reactive Mine Wastes: Approaches, Update and Case Study Results, October 1, 2015 – This report evaluates in-pit disposal of several mine waste sources, including water treatment sludge. A summary of 12 case studies is provided (Arcadis 2015). Of the 12 case studies presented, there are three with sludge, including sludge and mine rock, sludge and tailings, and tailings, sludge and mine rock.

MEND Report 2.32.1 – Acid Mine Drainage – Status of Chemical Treatment and Sludge Management Practices, June 1, 1994 (SENES 1994). While this report is more than 20 years old, it does contain information on dewatering of sludge and typical percent solids that can be achieved from different dewatering processes.

MEND Report 2.42.2a – Characterization and Stability of Acid Mine Drainage Sludges, May 1, 1997 (Zinck 1997). Sludge generated from the treatment of ARD was characterized and evaluated for the effects of natural sludge aging. Sludge samples were collected from 11 mine sites (base metal, uranium, gold, and coal mines). The sludge samples were collected of both fresh sludge and aged sludge. Chemical and physical factors that affect long-term stability were determined.

MEND Report 3.42.2b – The Effect of Process Parameters and Aging on Lime Sludge Density and Stability, February 1, 1999 (Zinck et al. 1999). This study used pilot plant testing to evaluate the impacts of several operational parameters (sludge recycle rate, chemical dose, etc.) on sludge density and leachability. Other operational and water quality impacts were also studied in bench-scale and pilot scale testing. In addition to sludge characteristics, the impacts on other process design parameters such as settling rates were evaluated.

MEND Report 3.42.3 – Review of Disposal, Reprocessing and Reuse Options for Acidic Drainage Treatment Sludge, January, 2005 (Zinck 2005). This report provides an overview of sludge disposal options, including conventional (disposal in mine workings, with mine rock, landfills, etc.) and less known practices such as reprocessing sludge, metal recovery, stabilization, solidification and other potential sludge management options. The report also provides recommendations for additional work and identifies characterization and research gaps.

MEND Report 3.43.1 – Review of Mine Drainage Treatment and Sludge Management Options, March 1, 2013. (Zinck and Griffith 2013). This review is based on both a survey of mine sites (providing 52% of the data) and literature review (representing 48% of the information). Information from over 100 sites from all over the world is incorporated. Information on treatment process, chemicals used, treatment issues, cost, and other information is presented for a large number of water treatment operations. Sludge management information includes disposal practices (sludge pond, mixed with tailings, landfill, smelter, etc.) and disposal costs.

MEND Report 3.44.1 – Characterization and Prediction of Trace Metal Bearings Phases in ARD Neutralization Sludges (Martin et al. 2013). Sludge samples from seven Canadian mines were examined microscopically along with influent/effluent water chemistry and sludge chemistry. The trace metal bearing phases were identified based on high-resolution microscopy and the relative proportions of sulfate (sulfur), iron, aluminum, magnesium, and manganese were determined to be most relevant. This information may form a framework for prediction of “sludge type” from the influent chemistry. The sludge type identification can then inform the selection of the long-term sludge disposal and storage and environment.

MEND Report 3.90 AT-1 – Investigation of Metal Hydroxide Solubility from Sludge in Acidic Mine Water Conditions. (NB Coal, 1997). This document reports on the use of fresh and aged (1 to 3 years) sludge from a coal mine water treatment plant and the acid mine water as the leach solution. Leaching of the sludge/mine drainage was conducted for 10 cycles of 2 weeks each. Tests were also conducted with two samples treated with amendments prior to the leaching cycles. The study evaluated the dissolution of sludge into the acidic mine water and whether the lime demand of the water is impacted if it has been in contact with the sludge.

The MEND reports provide information that should be incorporated into sludge management planning and operations of sludge disposal facilities. In addition, there are factors in the design and operations of the water treatment system that have been shown to affect solids separation, sludge disposal and long-term stability. The impact of water treatment system operating parameters on sludge density, particle size, and long-term leachability is also presented in these reports. The reports are based primarily on surveys of Canadian mine operations and research and testing on samples collected from participating mines.

7.10.1.2 Sludge Dewatering

Sludge from a clarifier, DAF, pond, UF or MF membrane system, or biological treatment system may require dewatering prior to disposal. Some sludge is disposed directly after the solid-liquid separation step and some is further dewatered to remove free water and reduce the volume that must be disposed. Typical sludge dewatering options include:

- Sludge Drying Beds – Sludge drying beds rely on gravity and evaporation to dewater solids. The beds consist of lined and bermed areas with a porous bed such as sand with an underdrain. Filtrate is collected

and returned to the treatment train. Drying beds are impacted by weather and precipitation unless a greenhouse-type structure is built over the bed. Allowing freeze and thaw cycles may also improve the final sludge cake density. Sludge is deposited in 0.5-m raises and the beds are usually sized for several months of storage. Sludge is removed in campaigns from the bed manually or with a loader or other equipment. A large area is required relative to other sludge management options.

- Filter Press – Filter presses consist of multiple parallel recessed plates which are compressed together to seal the plates by hydraulic force. The recessed plates are lined with a filter cloth. Sludge is pumped into the center of the filter press plates into the recessed cavities. The water is forced through the filter cloth with the sludge being retained between the plates. Filter presses operate as a batch process with typical operational cycles between one and three hours. After completion of each cycle, the hydraulic pressure is released, the plates separated, and the cake is dropped. An operator is required during operation to facilitate cake removal. Filter presses are one of the more common types of sludge dewatering used in mining applications. The equipment is highly reliable and generally achieves higher dewatered cake solids than other dewatering equipment. The equipment can generally be maintained by plant personnel and is typically installed on a platform so that a roll-off can fit underneath and dewatered sludge can dump directly into the roll off.
- Belt Press – A belt press is a continuous process that requires less labour than a filter press and relies on both gravity dewatering and a pressurized dewatering zone. Polymer is required and the system can be operated in an automated mode. The systems have a low energy requirement. The mechanical equipment and belts can be maintained by plant personnel, and typically produces higher dewatered cake solids than a centrifuge, but lower than a filter press.
- Vacuum rotary-drum filter – This is a rotating drum with a filter media. Part of the drum is submerged as it slowly rotates with suction on the drum inward toward the center. Dewatered sludge is removed by a scraper blade as the drum rotates and the filtrate is collected in the center of the drum. The labour requirement is lower than for a filter press and the solids content of the final cake is also typically somewhat lower than that produced by a filter press.
- Centrifuge – The centrifuge relies on centrifugal force to achieve solid liquid separation and is highly effective for compressive sludges that settle well. There are several types of centrifuges available; however, the basket type is used in mining and metal processing applications. A basket-style centrifuge operates similar to a washing machine in spin cycle. As the centrifuge spins, solids are retained on a filter cloth and filtrate is driven through the filter cloth by centrifugal force. The centrifuge is operated as a batch process, with the solids being skimmed from the cloth and discharge from the unit between cycles. Centrifuges have high capital cost, specialized maintenance requirements, and higher power requirements than most of the other sludge dewatering systems. There are some applications where there is an advantage to a centrifuge, such as dewatering of biosolids. The lead time for a centrifuge is typically longer than for other dewatering equipment.
- Geotubes® – The geosynthetic sleeve of fabric that makes up each tube is filled with sludge via a pump. Two major factors are at play in geotextile filters: solids liquid separation and filtration. Hydrostatic pressure forces water through the geotextile fabric which can be collected and returned to the process. Geotextile filters can be housed in roll-off waste containers, which can reduce handling requirements, and in a bermed lined area. Several bags can be manifolded together, and the bags are generally considered replaceable. Similar to sludge drying beds Geotubes® have a relatively low capital investment requirement and high surface area requirement. Geotubes® can be deployed and made operational on a very short timeframe. Information on mine applications is provided in recent articles by Kim and Kim (2017) and Stephens (2019).

As with other components of the treatment system, the selection of dewatering equipment should be based on an overall evaluation of life cycle cost. Consideration of capital cost, space required, labour required and final volume of sludge requiring disposal will all be factors.

7.10.1.3 Sludge Disposal

Various options are available for sludge disposal, as follows:

Pond disposal

Sludge management involves three principal 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. 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. Due to the thixotropic nature of sludges (i.e., viscosity decreases as shear strength increases), pond failure could present some concerns, although generally not to the same extent as with tailings impoundments. 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 typically enough to sustain a moderate pH for decades, even centuries (Zinck and Griffith 2013).

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 then 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 (Zinck 2013).

Co-disposal with Tailings

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 ingress and lowering 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 high (Zinck 2013).

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 contact with atmospheric oxygen completely. Some of the issues related to the application of a sludge cover on tailings are cracking and preferential channeling. Therefore, sludge needs to be disposed in a manner by which the particles will not segregate, such that the sludge and the underlying tailings remain saturated (Zinck 2013).

Sludge Disposal with Mine Rock

Disposing sludge with mine 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 mine rock piles is being adopted at some sites. While results show that sludge is not effective as a capping material, this method was found to be a low-cost final disposal option because the sludge filled pore spaces and voids within the mine rock pile (Coleman et al. 1997).

Disposal in Underground 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, underground disposal could have the additional benefit of reducing the acidity of the mine water. 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)

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 cadmium, zinc or nickel content in this manner may or may not be economic or environmentally acceptable depending on the contact effectiveness and ratio between the sludge and acidic mine water, the alkalinity of the sludge, and the acidity of the mine drainage (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. Some excellent work on this option has been described by McNee et al. (2003), McNee (2004) and Arcadis (2015).

7.10.2 Brine Management

Brine disposal is much more challenging than sludge disposal as the target contaminants are typically concentrated, but often present at their solubility limit. The brine may be a slurry that contains crystallized contaminants that can easily resolubilize when in contact with water. Further treatment of the brine by chemical precipitation was discussed in Section 7.7.3 and is not included again in this section. This section deals with brine that cannot be further processed by the technologies described in Section 7.7, such as RO, evaporation, or chemical precipitation.

The management and disposal options for brines include similar technologies and disposal options discussed for sludges. However, the waste stream has a smaller volume and is more concentrated. Some common technologies and disposal options include:

- Incorporation into a mine waste or tailings stream. In most cases, the disposal location should be isolated hydraulically because contaminants from the brine stream are highly concentrated and soluble. Co-disposal with paste tailings is another option that may be viable if there is a paste plant onsite.
- Solar evaporation ponds with or without a mechanical spray system. This is the same technology described in Section 7.7.4; however, the evaporation rates may decline due to the concentration of the brine. There may be increased labour requirements due to the potential for fouling from the concentrated water. The goal is to achieve dryness which also may be a challenge in a passive pond as crust layers can form. Once dry, the residue requires final disposal in a segregated covered cell, other hydraulically isolated cell, or appropriate off-site disposal. Note that the residue salt produced from solar evaporation will be higher in final

volume than the same brine treated in a mechanical crystallizer as there are waters of hydration associated with residue from solar evaporation.

- Discharge and dilution in a sanitary sewer have been an option in the past. However, this approach is becoming less acceptable to municipal system operators. In addition to requiring a discharge permit, this option is only viable if the mine water treatment system is located near a town or city with large enough treatment works to accept the brine.

- Mechanical evaporative crystallization generating a highly concentrated (75% or greater solids content) final residue is one of the more commercialized options. As with the solar pond option, the dry residue must be disposed properly. Although the technology has been around for decades, it has become more of a waste disposal option in the last few years with many commercialized systems and standard designs available. There are also energy efficient options similar to those described in Section 7.7.4 for evaporators. Crystallizers are also available with MVR technologies, improving the energy efficiency of the process. Further cost savings in the final crystallization step can be achieved by reducing the volume sent to the crystallizer as much as possible. Man et al. (2018) present an economic analysis of two cases using crystallizers to treat brine and achieve solids for disposal. One case uses a conventional RO technology with a 70% recovery and then evaporation/crystallization of the brine while the second case uses electrodialysis/RO to increase the RO recovery to 90% followed by a crystallizer. Detailed capital and operating costs are provided for both cases and while the pretreatment and RO capital costs are much higher, there is an even larger savings in the crystallizer capital cost for the second case. Costs are also provided by Petschel and Drummond (2018) for several cases of brine treatment with a crystallizer including different fuel sources, with RO, without RO, freeze crystallization and combinations of freeze crystallization with conventional evaporative crystallization. This evaluation showed no advantage to the RO volume reduction and concluded that conventional crystallization was preferred. However, the economics for the freeze crystallization were similar. The Petschel and Drummond evaluation took place at a lower flow rate than the work by Man et al. and demonstrated that the scale of a project can impact the technology selection on a life cycle cost basis. An evaporative crystallizer is shown in Figure 7-35. This is a single unit with a capacity of 100 m^3/day of freshwater removed. The grey cone tanks under the unit are brine tanks and each module of the evaporator has its own brine tank. The residual from a crystallizer is approximately 10% water and passes a paint filter test.

- Freeze crystallization should be considered an emerging technology. However, it is being considered more often in brine management evaluations. In freeze crystallization, ice crystals of pure water are formed as brine is slowly cooled. The ice crystals can be separated from the residual brine, which is even more concentrated. Pure water is recovered as the ice melts and salt begins to crystallize as the brine concentrates further. The freeze process is more energy efficient than conventional evaporative crystallizers. This technology has been evaluated in numerous papers that have focused both on desalination applications for recovery of drinking water (Zambrano et al. 2018, Hammer et al. 2016, Kaplan et al. 2017) and waste brine management (Petschel and Drummond 2018, Man et al. 2018, Randall et al. 2011, Hartog et al. 2019).

Figure 7-35: Evaporator crystallizer (photo courtesy of Saltworks)

There are other options, such as deep well disposal, off-site hauling, and solidification, that may be appropriate in some applications.

7.11 Resource Recovery

Sustainability goals, cost, and liability limitations have motivated evaluation of alternatives to disposal in handling and management of treatment residues such as sludges and brines. The recovery of useful and saleable products is increasingly researched and sustainable alternatives pursued. Options for the recovery of useful products from the treatment process waste streams that have been commercialized include the following:

- BQE Water Inc. provides two sulfide-based technologies that precipitate metal sulfides from which metals such as copper and zinc can be recovered. The source of the sulfide can be biologically produced from sulfate in the mine water or added as a treatment chemical. This technology has been in use at the Wellington-Oro mine since 2008 and Merta (2019b) provides operational details and cost information, including the impact of the zinc recovery. Paques has a similar commercialized technology and metal recovery with both biologically-produced sulfide or chemical sulfide sources. Sanchez-Andrea et al. (2016) describe an acidic MIW treatment system in the Dominican Republic with a copper recovery plant. This plant is an example of the biologically-produced sulfide process by Paques installed at the Pueblo Viejo gold mine.
- Both companies have designed several full-scale treatment plants that have been operating for more than ten years. While the metal sulfide removal process can be implemented in a range of mining applications, the metal recovery component may or may not be economically viable and will have to be determined on a case-by-case basis.
- Several papers are available that highlight the potential of recovery of iron-based products from acid mine drainage treatment sludges with beneficial uses, for instance as adsorbents, water treatment chemicals, raw materials for pigments, fertilizer, and other commercial products (Michalková et al. 2013). EnvironOxide™ is a commercial producer of iron oxide from three coal sites with MIW in Western Pennsylvania. Three commercial products are offered in bulk shipments, bulk bags (typically 2,000 pounds or 907 kilograms), or 50-pound bags (23 kg). The three products are for pigments, soil remediation, and phosphate retention. The initial 1,000 tons of the material was manufactured in 2001 in a proof of principle test described by Hedin

(2002) and used by a paint manufacturer. Iron oxide sludge recovery from a passive treatment system at a Pennsylvania coal mine is also described in Hedin (2016), with costs provided for the iron oxide recovery. Costs are also presented for the installation and operation of the passive treatment system and sludge removal and handling. Sludge dewatering is through use of Geotubes®.

- Red mud, the residue generated from refining bauxite into alumina by the Bayer process, has been evaluated for several years for the potential to recover useful products. Several absorbent type wastewater treatment materials have been developed or are in development, such as the products by Virotec (2020) https://virotec.com/services/reagent-manufacturing/. In addition, treated red mud has been used to make building materials, with both Alcoa (2012) (https://www.alcoa.com/australia/en/pdf/kwinana_refinery_ltrms_report_2012.pdf) and Virotec developing products.

Research and development of potentially viable alternatives to disposal for MIW brine and sludge residues include the following:

- Building and construction-related materials, such as gypsum, can be recovered using lime, magnesite and CO_2 bubbling to treat acid mine drainage (Masindi and Shingwenyana 2018a, Masindi et al. 2018b). The recovered gypsum was of high purity. The study also showed that other valuable commodities, such as Fe-hydroxides, can be obtained. Further treatment of the clarified water after mineral recovery using RO produced high quality drinking water. Recovery of aluminum and iron from MIW at a coal site and synthesizing Al/Fe polycationic-nanocomposite material was also evaluated through bench experiments and the product was used for chromium and arsenic removal (Meudi et al. 2018).
- Batch treatment testing showed that addition of iron-rich mine sludges (mine tailing sludge and MIW treatment sludge) improved the efficiency of anaerobic municipal wastewater treatment (Bose and Tiwari 2019).
- A patent (US10351482B1; Nanis et al. 2019) for “Mine waste source for bio-mineral fertilizer to remineralize agricultural soil” was granted in July 2019. Per US103514821B1, solid and liquid fertilizers are obtained by digesting mine waste and process tailings in combination with bio-waste plus selected bacteria under anaerobic conditions. The process extracts mercury, arsenic, gold, silver, lead and cadmium to produce the fertilizer. Research is also being conducted to evaluate phosphate addition to HDS to stabilize metals (manganese, nickel, and zinc) in the sludge and improving the material as a plant nutrient source (Sukati et al. 2018).
- The West Virginia Water Research Institute was awarded a project from the US Department of Energy to scale up the Rare Earth Recovery Project which began as a pilot plant in 2018. The system will include a new acid mine drainage treatment plant and recover rare earth elements. The pilot system was summarized in a presentation in 2019 (Stephens 2019).
- A similar research effort to the West Virginia Water Research Institute is to modify conventional active treatment for MIW to recover rare earth elements while treating the water, as discussed by Leotaud (2020)

Research and development in resource recovery is motivated by sustainability goals as well as cost. Reduction of waste sludge and brine products, which require perpetual handling and disposal, lowers costs, potentially produces a revenue stream, and reduces associated long-term environmental liabilities.

The key aspects of successful by-products recovery in the treatment of mine drainage are as follows:

- The target by-products must be selectively removed by minimizing the coprecipitation of compounds that would degrade the quality of the by-products.
- By-products recovery, as a project objective, may have an impact on the mainstream treatment process in terms of unit treatment, process selection, and sequence of treatment processes.
- Chemicals (reagents) dosing to the mainstream treatment process must take into account the impact on the potential for of the generation of by-products and their composition.

Factors that must be considered in addition to the cost of the resource recovery and production include the logistics and demand for the product. Lower value products, such as calcium sulfate (gypsum) that are generated in large quantities, may not have the price flexibility to withstand additional transportation charges from remote mine sites, but may be a reasonable option in mine sites that are located closer to urban areas and other manufacturing. The ability to centralize recovery facilities and process residues from more than one mine will also improve the chances for viability of resource recovery projects. The commercialized iron oxide facility in Pennsylvania is a good example of the benefits of a centralized facility in a region with multiple potential sources and markets.

7.12 Approach to Costing

Preparing capital costs and annual operations and maintenance costs of treatment plants is similar to the approach for determining the nature of the treatment train and requires establishment of the cost estimate basis. Factors that impact the cost estimate basis can include the following:

- Life cycle of the treatment plant and required duration of water treatment. A life cycle period is assumed for process equipment based on performance of recommended maintenance and upkeep, experience with similar process equipment, regulatory acceptance, and other factors. Twenty years is a common life cycle period assumed for comparative evaluations; however, other time periods may be used or included in the evaluation according to experience, company policy, expected life of mine (and/or treatment system) or other considerations.
- Battery limits of the cost estimate – Do the costs include only the items within the treatment plant (or shown on the process flow diagram) or do costs include such items as a road to the plant, power to the plant, collecting and transfer of water to the plant, transfer of treated water to reuse location or discharge location? Is the equalization pond included in battery limits for the treatment plant, discharge structure (diffuser or similar is used), transfer and disposal of residuals including sludge and/or brine, storage of chemicals and spare parts?
- Building requirements beyond housing the process equipment such as accessibility (to comply with Americans with Disabilities Act or equivalent), shower and locker room facilities required, will the “look” of the building have to match the surroundings, and other similar project specific criteria.
- Level of cost estimate – The level and purpose of the cost estimate should be established. Is the cost estimate used to compare treatment alternatives and is it a rough order of magnitude estimate, or is it an engineer’s estimate of probable cost? The Association for the Advancement of Cost Engineers (AACE) International (AACE 2020) publishes guidelines for a Class 1 through Class 5 estimate, with Class 1 a very tight (+15% to -10%) estimate and Class 5 (+100% to -50%) for concept screening purposes.
- Other factors that impact the capital or operations costs should be identified. This can include aspects such as preferred or negotiated rates that many mining companies have for building materials (piping, liner, etc.) and chemicals (lime, ferric sulfate or chloride, and similar). Unusual delivery and construction constraints,

such as delivery only occurs seasonally each year via truck or materials must be delivered by air, are an important consideration. A construction season may be short due to extreme cold, rain, and similar and so the plant assembly must be broken into two or more construction seasons. Local wages that are unusual and high or low based on the area will affect costs, as does land cost or treatment plant siting. Although for most mining applications cost of land is typically not included in the project cost, this may be a factor in some locations. If life cycle costs are being prepared, a discount and inflation rate should be included. Several cases can be prepared that evaluate the impact of discount rate selection on the life cycle costs. Discount rates can be a controversial topic both within organizations and with NGOs and regulatory agencies.

Once the basis for costing is established, the capital and annual operations and maintenance costs can be developed using a number of sources, including direct quotes for process equipment and materials. Estimates from contractors or in-house by construction engineers based on experience or manuals/software such as RSMeans are used to develop the more rigorous cost estimates (typically Levels 1, 2 and 3) for the installation and construction phase. There are also factors for construction based on total equipment cost or similar that are available in references such as Perry's Chemical Engineers Handbook (Green and Southard 2018). The general categories that should be included in a capital cost estimate are the following:

- Process equipment – Components shown on the process flow diagram (for Class 4 and 5 estimates) and the piping and instrumentation diagram (P&ID) for tighter estimates. This includes the main process equipment such as pumps, tanks, mixers, chemical storage and feed, residuals handling (dewatering for sludge or evaporation for brine), and disposal facility (if in the battery limits). For tighter estimates, this will include the instrument list.
- Materials – This can include material take-offs for quantity and size of pipe, tubing and hoses along with the fittings, pipe supports, cabling and wires, transformer and other electrical equipment, programmable logic controller, and all other components required to render the process equipment functional. This can also be a factor based on process equipment depending on the level of cost estimate.
- Tax and freight on equipment and materials.
- Installation/facility cost includes several major categories, such as the building or structure to house the treatment system and space for workers and onsite laboratory (if needed), site work, foundations, construction labour, equipment installation, and electrical installation. This can also be a factor or a detailed estimate depending on the level of the cost estimate required.
- Indirect costs, including contingency and the indirect cost for the general contractor.
- Engineering, including design and construction management.

Many of the bullets above can require tens to hundreds of lines on a spreadsheet depending on the level of cost estimate and complexity of the treatment system. A passive treatment system will have minimal process equipment and materials, but could involve a lot of installation and site work. However, overall the cost estimate for a passive treatment system will typically be simpler than that for an active treatment system.

Annual operations and maintenance costs are developed in a similar manner, but with different categories. Major O&M cost elements should include:

- Operations labour – Depending on the complexity of the system, this could be one person visually inspecting a passive system once per week and collecting monthly or quarterly compliance samples (depending on the permit requirements). For more complex treatment plants with higher flow, there may be round-the-clock

operations with a site manager, lead operator, shift operators, maintenance technician, and sampling technician. There may also be the need to assign some office support for engineering and compliance.

- Utilities cost – These can include electricity, natural gas, propane, diesel (for generator provided power). Potable water and sewage fees may also be included depending on the location of the plant and the discharge mechanism for treated water.
- Chemical costs – For any treatment process, the costs of the chemical(s) required should be accounted for. For a lime HDS plant, these often include lime, oxidant, acid or carbon dioxide, ferric sulfate (chloride), and polymer. Other chemicals can include antiscalants for membranes, cleaning chemicals for membranes, regenerant solutions for ion exchange, and similar.
- Consumables for treatment, including replacement media or sand, replacement membranes, replacement bags or cartridges, and similar.
- Waste disposal costs are not always included in mining applications if such options as transfer to tailings or in the mine workings are viable. In some cases, an on-site disposal facility is constructed while in other cases waste may be hauled to a local off-site facility. In addition to disposal costs, other costs may include transportation, sampling and analysis, and reporting.
- Costs for sampling supplies and labour, sample shipping and chemical analysis can be significant.
- Analytical work may be required for process control purposes or for sampling required by the discharge permit. This may be completed onsite or offsite, depending on requirements.
- Maintenance includes routine maintenance such as replacement of pump seals or changing the oil in a piece of equipment. Other routine maintenance items include changing pH probes per manufacturer's recommendations, which is typically one to two years. Maintenance costs can be estimated as a percentage of process equipment, a lump sum, and/or experience on other projects. Non-routine maintenance includes repair or replacement of equipment that breaks accidentally such as dropping a pH probe when conducting routine cleaning.
- Contingency – Depending on the required level of the cost estimate, degree of design and availability of pertinent information, inclusion of a contingency may be appropriate.

If the life cycle cost estimate includes operations for more than 20 years (or the established design life of the treatment system), periodic replacement of the treatment system must be included in the costing effort.

MEND has completed studies on best available technologies economically achievable (BATEA) in MEND report 30.5.1 titled "Study to Identify BATEA for the Management and Control of Effluent Quality from Mines" (Pouw et al. 2014).

7.13 Treatment in the Context of Mine Closure and Post Closure

The approach to mine drainage treatment during and after closure of mining operations must be placed in context with respect to the following factors:

- Changes in mine drainage flow and quality
- Climate change over the long term
- Long-term operations and maintenance
- Capital replacement cost

- Non-mining water user requirements
- Involvement from non-mining stakeholders

Mine drainage volumes requiring treatment may increase or decrease after mine closure. The opportunities for consumptive on-mine water usage decrease after closure, potentially resulting in increased excess mine drainage volumes. On the other hand, completion of rehabilitation work after closure may decrease the ingress of water into old mining operations, resulting in decreased excess mine drainage.

Management and support for long-term, post-closure operation and maintenance of mine drainage treatment facilities may be limited. Passive treatment technologies are, therefore, considered more beneficial in the post-closure situation than active treatment technologies, where applicable.

Mine planners should consider post-closure water treatment system land requirements in the design of tailings storage facilities and mine waste dumps so that space is available, when needed, and post-closure water treatment does not become a major design constraint that forces the implementation of active treatment technologies. For example, a mine rock dump might be configured in a way that leaves adequate room at the toe for collection and passive treatment of residual seepage. A similar design protocol should be followed for tailings dams and other mine waste facilities that may generate drainage in the long term, in some cases in perpetuity.

The design life of post-closure treatment facilities should be based on geochemical model predictions of the long-term mine drainage flow and quality.

Replacement of capital infrastructure and equipment items must be taken into account for continued post-closure treatment. Mine drainage flows and associated pollutant loads are typically projected to continue for a considerable period after mine closure. In some cases, this long-term projection for continued treatment may even require a reevaluation of the appropriate treatment approach and technology as research and technology development takes place.

Communities and other non-mining economic activities may rely on the long-term availability of mine drainage. Such reliance is not necessarily negative because the transfer of mine drainage treatment facilities to a third party may assist in the sustainability of a post-mining situation. For instance, the Emalahleni Local Municipality in South Africa receives a substantial part of its drinking water supply from a mine water reclamation plant (Gunther et al. 2008).

The early involvement of non-mining stakeholders to identify and implement post-closure beneficial and economic use of mine drainage will assist in developing appropriate treatment infrastructure.

7.14 Case Studies and Sources of Additional Information

Case studies related to MIW treatment have been developed and are presented in many public-domain sources. Section 7.14.1 presents sources of additional and more in-depth information on MIW treatment and residuals management. Section 7.14.2 summarizes some of the case studies available, including links to the sources that provide more information on active and passive treatment technologies.

7.14.1 Sources of Additional Information

Information on mine water treatment is abundant in the literature and on the internet, and much of it provides supplemental information to this chapter. In addition to the specific articles and documents referenced in this chapter, the following sites or documents are recommended:

- The INAP website has several relevant resources including links to many other scientific and mining related websites, INAP workshops such as a sulfate treatment workshop held in 2014, a water treatment workshop

in 2009, a research report on treatment of sulfate in mine effluent, and other relevant information. https://www.inap.com.au/

- The Mine Environment Neutral Drainage (MEND) program has completed many in-depth studies on mine water treatment and residuals management. The MEND site and specific documents of interest are below:
  - MEND Report 3.43.1. As already mentioned in Section 7.10.1.1, this report surveyed mine drainage treatment and sludge management practices and collected information on over 100 sites. Survey results are provided on practices for mine water treatment and residuals management. Treatment issues, chemicals used, capital cost information and operating cost analysis are discussed (Zinck and Griffith 2013).
  - MEND Report 3.15.1. This report provides an overview of membrane separation technologies directed toward mine water treatment. Both dissolved membrane processes, RO and NF, and particulate processes, UF and MF, are discussed. Membrane bioreactors are also included. Costs (based on 2008 numbers) and case studies are presented (Mortazavi 2008).
  - MEND Report 3.50.1. This report reviews treatment technologies and identifies best available technology economically achievable for MIW by mining subsector. Sixteen technologies are reviewed and evaluated, including cost information (Pouw et al. 2014).
  - The treatment page on the MEND site includes the documents listed above plus 17 others. Both active treatment and passive treatment, as well as aspects of residuals management are covered in these documents. http://mend-nedem.org/category/treatment/
  - The Technology Transfer and Case Studies page on the MEND site includes several documents that are relevant to treatment. http://mend-nedem.org/category/technology-transfer-and-case-studies/
- Leading Practice Sustainable Development Program for the Mining Industry in Australia supported the development of “Preventing Acid and Metalliferous Drainage” (Australian Commonwealth 2016). This document was developed by a working group of experts and has information on both active and passive treatment, including case studies. https://www.industry.gov.au/data-and-publications/leading-practice-handbook-preventing-acid-and-metalliferous-drainage
- BC MEND ML/ARD Annual Workshop proceedings typically contain several mine water treatment papers. The proceedings can be found on their website (http://bc-mlard.ca/). For instance, the 2019 proceedings include one presentation on in-pit treatment (Barabash et al. 2019b), one on HDS treatment (Aubé 2019), one on biological nitrate and selenium treatment (McKevitt 2019), and one on saturated rock fill (Klein et al. 2019).
- The proceedings from the International Mine Water Association (IMWA) Conferences represent a useful resource. The proceedings from the 2019 conference in Perm, Russia are available online and comprise 11 treatment-related papers, including three on passive technologies while the remainder discuss active technologies, many of them developmental innovative ones. https://www.imwa.info/imwaconferencesandcongresses/proceedings/306-proceedings-2019.html
- The proceedings from the International Conferences on Acid Rock Drainage (ICARD) are similarly applicable. The proceedings from the 2018 ICARD/IMWA Congress contains many papers on mine water treatment, several of which are referenced throughout this document. https://www.imwa.info/imwaconferencesandcongresses/proceedings/303-proceedings-2018.html

- Geological Survey of Finland Mine Closure website. This website presents an overview of basic principles and best practices of many aspects of mine closure, including mine water treatment. The water treatment section includes an overview of several technologies (active, passive, and in situ), case studies, and research areas. https://mineclosure.gtk.fi/water-treatment/
- The Society of Mining Engineers Webinars present information on both active and passive mine water treatment. https://www.smenet.org/publications-resources/resources/webinars
- The American Society of Mining and Reclamation (ASMR) website has links to the proceedings from their annual conferences, links to Reclamation Matters and the journal, and links to other relevant sites. https://www.asrs.us/
- Mine Water Treatment Technology Selection Tool: User's Guide prepared for the South African Water Research Commission. March 2017. http://www.wrc.org.za/wp-content/uploads/mdocs/TT%20711_final%20web.pdf This is an application with background information in the user's guide that provides information on many of the technologies presented in this chapter plus freezing technologies and emerging technologies. Flowsheets are included for many treatment processes as well as sites where the technology has been implemented. Criteria for technology selection are discussed, and the preliminary steps and information required to launch the application.
- The Interstate Technology and Regulatory Council (ITRC) maintains a Mining Waste Treatment Technology Selection page and links to descriptions of active and passive treatment technologies and several case studies for both. https://www.itrcweb.org/miningwaste-guidance/
- The International Council on Metals and Mining (ICMM) published a report in 2012 that included several water treatment case studies. https://www.icmm.com/website/publications/pdfs/water/water-management-in-mining_case-studies
- The proceedings from the International Water Conferences are a useful resource. https://eswp.com/water/conference-archives/

7.14.2 Case Studies for Active and Passive Treatment

Table 7-9 summarizes several case studies on MIW treatment and provides links to on-line sources for more in-depth information (if available). The case studies focus on active and passive treatment technologies.

Table 7-9: Summary of MIW Active and Passive Treatment Case Studies

Location, Site or Mine/Company	Technology	Scale	Dates	Link
				Active Treatment
Queensland, Australia Mount Morgan Mine Site	Lime HDS	75 L/s	Commissioned in 2006, upgraded in 2013	See case study 11 https://www.industry.gov.au/sites/default/files/2019-04/lpsdp-preventing-acid-and-metalliferous-drainage-handbook-english.pdf
eMalahleni, South Africa Anglo America Coal, multiple mines	Multiple stages of precipitation (influent and brine), ultrafiltration, RO, solids dewatering. Potable water reuse	60 ML/day	Commissioned in 2007 with capacity increases in 2011 and currently (2020) in progress	See case study 12 https://www.industry.gov.au/sites/default/files/2019-04/lpsdp-preventing-acid-and-metalliferous-drainage-handbook-english.pdf https://mineclosure.gtk.fi/emalahleni-water-treatment-plant/ https://www.icmm.com/website/publications/pdfs/water/water-management-in-mining_case-studies
Colorado, US Wellington-Oro Mine	Sulfide precipitation	180 L/min (avg) 1600 L/min (peak)	2008 - ongoing	https://mineclosure.gtk.fi/wellington-oro-mine-water-treatment-plant/
British Columbia, Canada Britannia Mine	Lime HDS	1050 m^3/h	2005 - ongoing	https://mineclosure.gtk.fi/britannia-mine-british-columbia-canada/
Adelaide, South Australia Brukunga Pyrite Mine	HDS (converted from LDS)	Full Scale 15 kL/h to 63 kL/h	LDS 1980 2004 (ugrade) -	http://www.energymining.sa.gov.au/minerals/mining/former_mines/brukunga_mine_site https://papers.acg.uwa.edu.au/p/1152_66_Scott/ https://www.energymining.sa.gov.au/__data/assets/pdf_file/0006/245616/Notes_for_Visitors_to_the_Brukunga_mine_2012.pd
Hokkaido, Japan Toyoha Mine, JX Nippon Mining & Metals	HDS (converted from LDS)	Full Scale	2008 and expanded in 2011	https://www.icmm.com/website/publications/pdfs/water/water-management-in-mining_case-studies
South Dakota, US Homestake Mine, Barrick	RO and biological selenium	Full Scale	2006 - ongoing	https://www.icmm.com/website/publications/pdfs/water/water-management-in-mining_case-studies
British Columbia, Canada Elk Valley Coal Mine	Biological, ballasted clarification	7500 m^3/h		http://bc-mlard.ca/files/presentations/2019-21-MCKEVITT-continuous-improvement-west-line-creek-plant.pdf
Durham, United Kindgom Dawdon	HDS (iron, TDS - 40,000 mg/L)			https://www.gov.uk/government/case-studies/dawdon-mine-water-treatment-scheme https://waterprojectsonline.com/wp-content/uploads/case_studies/2009/Dawdon-Minewater-Treatment-Scheme-2009.pdf?looking=water-company
Multiple sites and examples at ITRC website	Various	various	various	https://www.itrcweb.org/miningwaste-guidance/case_studies.htm
				Hybrid - Active and Passive
Durhan, United Kingdom Horden	Aeration and reed beds (pH, salinity, iron)			https://www.gov.uk/government/collections/coal-mine-water-treatment
Cornwall, United Kingdom Wheal Jane	Active treatment - HDS, several metals. Passive treatment - several technologies evaluated. Natural attenuation	350 L/s (active)	Active since 2000	https://www.claire.co.uk/component/phocadownload/category/3-case-study-bulletins Brown, M., B. Barley, H. Wood, 2002. Mine Water Treatment-Technology Application and Policy. IWA Publishing. Whitehead, P.G. and H. Prior, 2005. Bioremediation of acid mine drainage; an introduction to the Wheal Jane wetlands project. Science of the Total Environment 338:15-21.
Northern Territory, Australia Mt. Todd	Pit Lake treatment - neutralization			https://vistagold.com/images/mttodd/MT_Todd_Restart_Mining_Engineering_April2016.pdf

Passive Treatment				
Joensuu City, Finland Hammaslahti Copper Mine	Biological		Late 1990's - 2005	https://mineclosure.gtk.fi/hammaslahti/
Kaavi, Finland Luikonlahti Copper Mine	Open Limestone Drains, Wetlands		2008 - 2013 (years for data reported)	https://mineclosure.gtk.fi/luikonlahti/
Western Finland Vihanti/Lampinsaari Mine	Wetland Pools			https://mineclosure.gtk.fi/vihanti/
Yukon, Canada Minto Mine	Wetland Treatment System	Pilot and Demo	2013-2018	https://www.yukonu.ca/sites/default/files/inline-files/Pilot_bioreactor_2_yrs_monitoring_-_Minto_-_2016.pdf http://bc-mlard.ca/files/presentations/2018NL-4-BOUCHARD-Wetland-Treatment-System-Minto.pdf
Ontario, Canada Campbell Complex, Goldcorp	Engineered Surface Flow Wetland	10,000 m^3/day	Operating since 2002, period of study 2011-2013	https://www.imwa.info/docs/imwa_2015/IMWA2015_Martin_165.pdf
Cumbria, England, United Kingdom Force Crag	Vertical Flow Ponds, Wetland (Zinc, lead, NMD)	Full scale (up to 24 L/s)	Operating since 2014	https://www.gov.uk/government/case-studies/force-crag-mine-water-treatment-scheme https://www.imwa.info/docs/imwa_2015/IMWA2015_Jarvis_235.pdf
Colorado, US Argo Tunnel Mine Water Treatment/Superfund Site (Colorado Department of Public Health and Environment)	Pulsed Limestone Bed (Note the Active Treatment Plant is described in detailed case studies)	Demo - 230 L/min	2004 - 2007	https://www.itrcweb.org/miningwaste-guidance/cs41_argo_tunnel.htm
Wales, United Kingdom Taff Merthyr	Iron			https://www.gov.uk/government/case-studies/taff-merthyr-mine-water-treatment-scheme
Multiple sites and examples at ITRC website	Various	various	various	https://www.itrcweb.org/miningwaste-guidance/case_studies.htm

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AACE	Association for the Advancement of Cost Engineers
Al	aluminum
ALD	anoxic limestone drain
AOP	advanced oxidation process
AMD	acid mine drainage
ARD	acid rock drainage
As	arsenic
ASMR	American Society of Mining and Reclamation
B	boron
Ba	barium
BC	British Columbia
BCR	biochemical reactor
BOD	biochemical oxygen demand
Bq/L	Becquerel per liter
BV	bed volume
C	carbon
ºC	degrees Celsius
$CaCO_3$	calcium carbonate
CaO	calcium oxide, quicklime
$Ca(OH)_2$	calcium hydroxide, hydrated lime
CCP	coal combustion product
CCR	coal combustion residuals
CCRO	closed circuit reverse osmosis
Cd	cadmium
CDPHE	Colorado Department of Public Health and Environment
CESP	chemically enhanced seeded precipitation
CESR	cost effective sulfate removal
CIP	clean-in-place
Cl	chloride

Cl_2	chlorine
cm	centimeter
CMD	coal mine drainage
CO_2	carbon dioxide
COD	chemical oxygen demand
Co	cobalt
Cr	chromium
CSIR	Council for Scientific and Industrial Research
CSTR	continuous stirred tank reactor
Cu	copper
DAF	dissolved air flotation
DO	dissolved oxygen
EBCT	empty bed contact time
EC	electrocoagulation
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
EWRP	eMalaheleni Water Reclamation Plant
FBR	fluidized bed bioreactor
Fe	iron
Fe^{2+}	ferrous iron
ft^3	cubic foot
GARD	Global Acid Rock Drainage
$g/day/m^2$	grams per day per square meter
g/t/day	grams per tonne per day
gpm/ft^2	gallons per minute per square foot
H	horizontal distance
H_2O_2	hydrogen peroxide
H_3O^+	hydronium ion
HCO_3^-	bicarbonate ion
HDS	high density sludge

Hg	mercury
H_2S	hydrogen sulfide
ICARD	International Conference on Acid Rock Drainage
IGF	induced gas flotation
IMWA	International Mine Water Association
INAP	International Network for Acid Prevention
ITRC	Interstate Technology & Regulatory Council
IX	ion exchange
Kg	kilogram
kwh/gal	kilowatt-hours per gallon
lb	pound
L	liter
L/s	liters per second
LDS	low density sludge
LLB	limestone leach beds
Lph/m^2	liters per hour per square meter
m	meter
m^3/h	cubic meters per hour
MBBR	moving bed bioreacor
MBR	membrane bioreactor
MDTI	Mine Drainage Technology Initiative
MEND	Mine Environment Neutral Drainage
MF	microfilter
Mg	magnesium
mg/L	milligrams per liter
MIW	mining-influenced water
mL	milliliter
ML	million liters
ML/ARD	metal leaching/acid rock drainage
mm	millimeter

Mn	manganese
Mo	molybdenum
MOB	manganese oxidation bed
MRB	manganese removal bed
MR	mine rock
MRS	mine rock stockpile(s)
MVC	mechanical vapor compression
MVR	mechanical vapor recompression
MWRP	Middleburg Water Reclamation Plant
N_2O	nitrous oxide
N	nitrogen
Na	sodium
NAMC	North American Metals Council
NaOH	sodium hydroxide
ND	neutral drainage
NF	nanofiltration
NGO	non-governmental organization
NH_3	ammonia
NH_4^+	ammonium
Ni	nickel
NO_2^{2-}	nitrite
NO_3^-	nitrate
NO	nitric oxide
NOM	naturally occurring organic matter
NP	neutralizing potential
NF	nanofiltration
O_3	ozone
ODEQ	Oregon Department of Environmental Quality
·OH	hydroxyl radical
OLC	open limestone channels

OLD	open limestone drains
O&G	oil and grease
O&M	operations and maintenance
OWRP	Optimum Water Recovery Plant
P	phosphorus
Pa	Pascal
Pb	lead
PE	polyethylene
PFD	process flow diagram
P&ID	piping and instrumentation diagram
PRB	permeable reactive barrier
psi	pounds per square inch
PVC	polyvinyl chloride
Ra	radium
RAPS	reducing and alkalinity producing systems
RBC	rotating biological contactor
RO	reverse osmosis
SAD	strong acid dissociable
SAPS	successive alkalinity producing systems
Sb	antimony
SBR	sequencing batch reactor
SD	saline drainage
SDI	silt density index
Se	selenium
SLB	steel-slag leach beds
SME	Society of Mining Engineers
SO_4	sulfate
SPC	sulfide polishing cell
Sr	strontium
SRB	sulfate reducing bioreactor

SRF	saturated rock fill
TCLP	toxicity characteristic leaching procedure
TDS	total dissolved solids
THM	trihalomethane
TMT	trimercapto-s-triazine,trisodium salt
TOC	total organic carbon
TSF	Tailings Storage Facility
TSS	total suspended solids
U	uranium
UF	ultrafilter
USEPA	United Stated Environmental Protection Agency
UV	ultraviolet
V	vertical distance/
VFW	vertical flow wetland
WAD	weak acid dissociable
WET	whole effluent toxicity
WR	Waste rock
ZVI	zero valent iron
Zn	zinc